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Nanosecond Laser Processing of Diamond Materials

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Abstract

Laser processing of synthetic diamonds for tooling application has been industrially established since the early 2000's. Though there are many publications dealing with the interaction between laser radiation and diamond materials using scientific laser sources, there are no comprehensive studies available for achievable ablation rates using industrially wide spread nanosecond laser sources. This paper will focus on the investigation of laser ablation results for various polycrystalline diamond materials using a NIR laser source with maximum pulse energy of 1 mJ and tunable pulse width between 10 and 240 ns. Single pulse ablation results for different laser parameters show that the ablation depth for polycrystalline diamonds is limited by absorption of laser radiation in the plasma plume. The plasma plume is visualized by high speed photography and correlated to the ablation results.

Keywords: Laser ablation, diamond materials, short pulse, nanosecond, graphite

1. Introduction

The outstanding properties of cutting tools made of diamond materials make these tools ideal for machining light metals, FRP and wood in economically efficient operations. However the degree of hardness and the level of wear resistance present enormous challenges throughout the processes involved in manufacturing the cutting tools. Low material removal rates and heavy abrasive disk wear make conventional finish machining operations through grinding, both costly and time consuming. Laser processing offers the big advantage to effectively run without any tool wear.

Synthetic diamonds are produced either by high pressure high temperature processing (HPHT) or chemical vapor deposition (CVD). Both manufacturing techniques are able to produce monocrystalline diamonds (MCD) as well as polycrystalline diamonds (PCD). Most diamonds used for tooling applications are HPHT-PCD. Figure 1 shows a typical process chain for a diamond tool manufacturing process. PCD blanks manufactured by HPHT usually are disk-shaped consisting of a cemented carbide substrate with a PCD top layer. Single PCD cutting inserts are manufactured by cutting the PCD blank into pieces by either wire electrical discharge machining or laser cutting. The cutting process results in a thermally affected rim zone

which has to be removed before using the tool. In a next step the cutting inserts are brazed on tool holders. The brazing process causes dimensional and angular errors which also have to be removed to achieve a high shape accuracy of the diamond tool. In a final finishing step the affected rim zones as well as the brazing errors have to be removed and the macro geometry (corner radius, clearance angle) and the micro geometry (cutting edge, chip breaker) have to be manufactured.

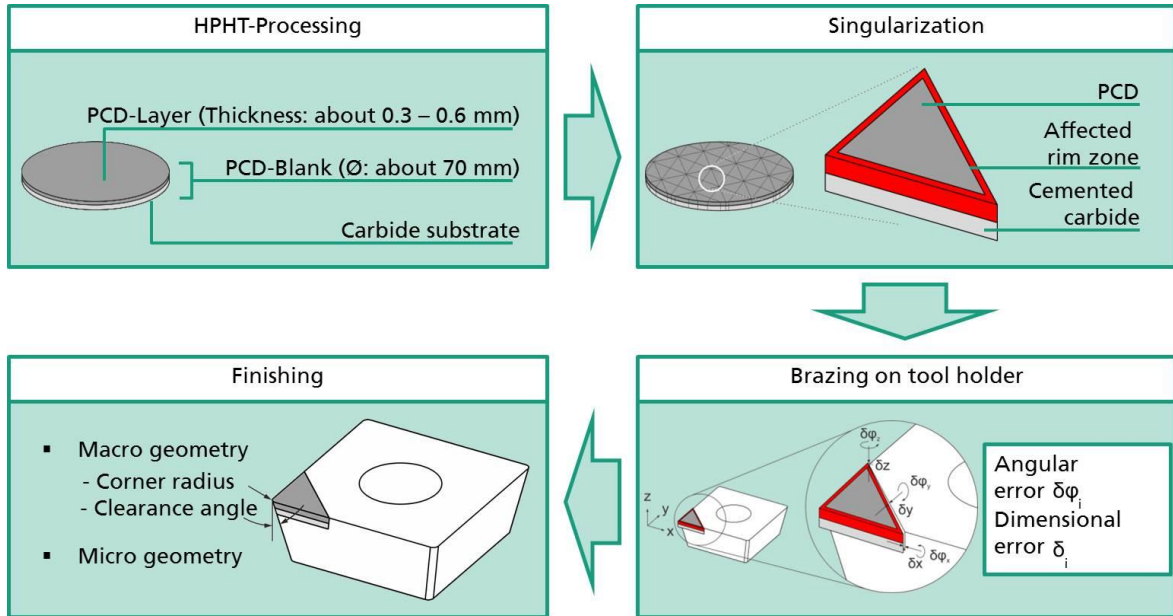


Fig. 1. Process Chain for Diamond Tool Manufacturing

Conventional machining techniques for the finishing step are grinding as well as electrical discharge machining. Since the early 2000's laser processing has been industrially established as finishing technique. Single laser pulses are positioned next to each other creating grooves into the material. By repeating groove by groove whole layers can be removed. The PCD material allowance is removed layer by layer. The first layers are usually removed using a parameter setting with high ablation rates and poor surface quality. The last layers are removed with low ablation rates but high resulting surface quality. From the laser point of view there can be distinguished between two different processes: ultrashort pulse laser ablation and short pulse laser ablation. Ultrashort pulse laser ablation refers to a process with pulse duration of less than 10 picoseconds. Within this period of time the laser beam material interaction is limited to interaction between electrons. A heat transfer and thermal equilibrium between electrons and crystal lattice takes place after approx. 1 nanosecond. The energy is deposited into the material without heating up the material in a macroscopic scale. Short pulse laser ablation refers to pulse duration in the nanosecond time scale. The energy is deposited into the material while the material is heating up, melting and evaporating (see figure 2).

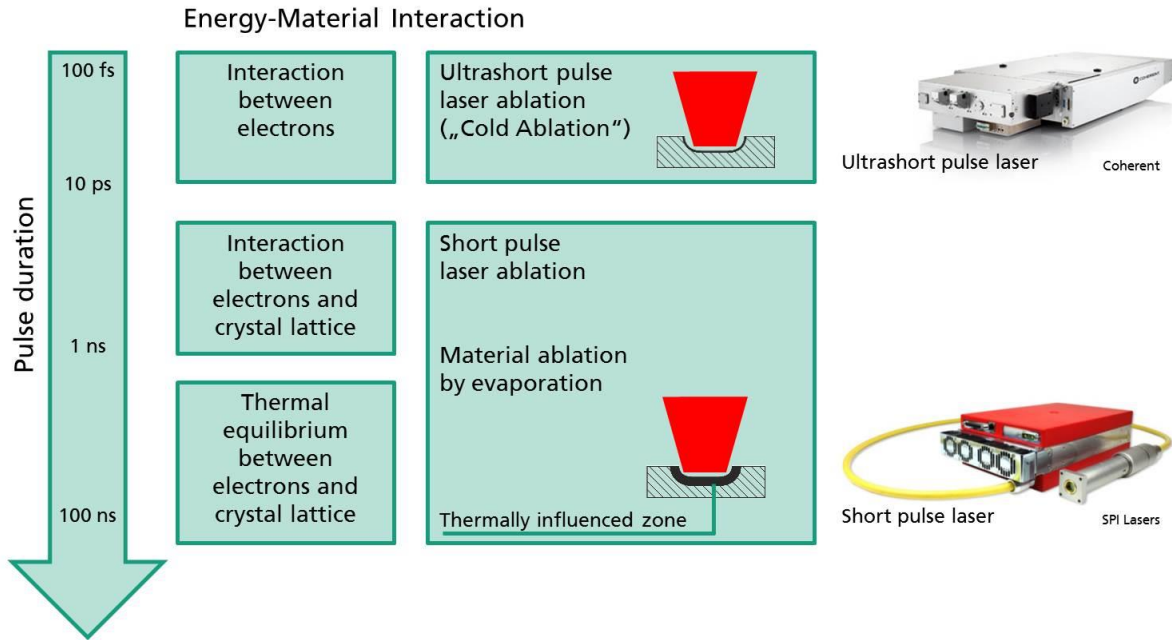


Fig. 2. Classification of Ultrashort Pulse and Short Pulse Laser Ablation

The absorption characteristics of short pulse and ultrashort pulse laser radiation in diamond materials differ considerably. Basic requirement for absorption of laser radiation in pure, monocrystalline diamond is an excitation of electrons from the valence band, which requires bridging the bandgap (figure 3). Diamond has a very high bandgap E_b between the valence band and conduction band approximately 5.5 eV after Wilks et al., 1991. The required energy for bridging the bandgap may be provided by individual photons only if the wavelength is less than approximately 225 nm (UV). However, the laser sources used for material processing have a wavelength of about 1064 nm (NIR) or 532 nm (green). In an ideal, pure diamond laser radiation of wavelength 1064 nm or 532 nm cannot be absorbed. However, absorption in real diamonds is enabled by imperfections, additives, grain boundaries or gas inclusions.

In the case of multiphoton absorption an electron can be excited by multiple photons. For multiphoton absorption, a high temporal and spatial photon density I_{ph} is required. Focused laser radiation of ultrashort pulse laser systems usually fulfils these requirements.

In contrast to diamond graphite has advantageous absorption properties. Valence and conduction bands are close to each other and overlap at some positions, resulting in negative values for the band gap. Therefore, graphite is considered as a material with good absorption properties. Depending on surface properties and temperature the absorption levels up to 98% can be obtained (Bulgakov et al., 1999). For this reason, graphite is often applied as a powder or spray in laser materials processing to improve the absorption properties of highly reflective materials.

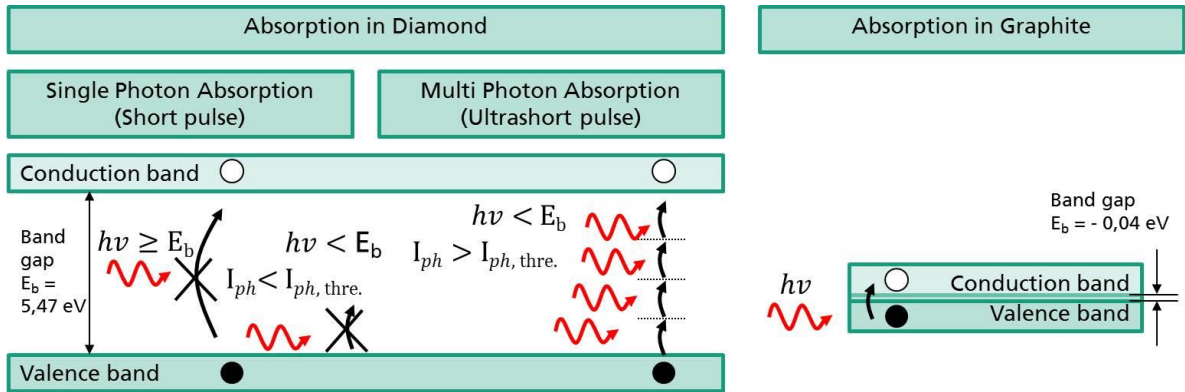


Fig. 3. Absorption Behavior of Diamond and Graphite

2. Model for Short Pulse Laser Ablation of Diamond

As mentioned above short pulse laser radiation is absorbed in diamond by imperfections, additives, grain boundaries or gas inclusions. The energy is deposited into the surface of the diamond material and is generating heat. The heat is transported into the depth by thermal conduction. After reaching the graphitization temperature of about 2000 °C the carbon phase changes from diamond to graphite. After further energy input by laser irradiation the graphitized surface layer reaches vaporization temperature at around 4000 °C. The graphite evaporates and carbon vapor expands with high pressure. As a consequence of the evaporation laser radiation is absorbed by carbon particles in the plume leading to plasma formation. Further laser radiation is partially absorbed in the plasma plume. After laser irradiation has stopped a crater has formed in the material. On the bottom of the crater a graphite layer can be found.

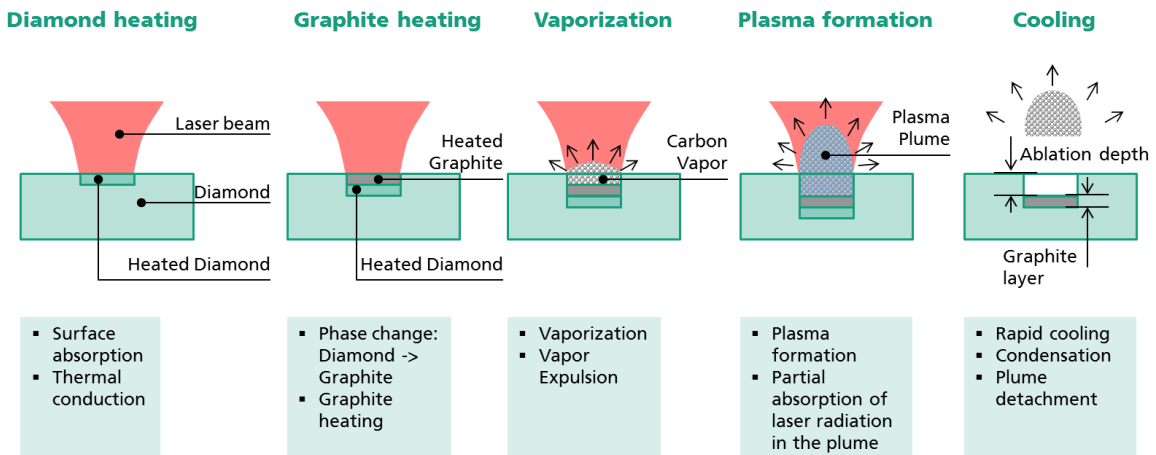


Fig. 4. Simplified Model for Short Pulse Laser Ablation of Diamond

The thickness of the graphite layer again depends on the pulse duration. Kononenko et al., 2005 have demonstrated an analytical and experimental relation between pulse duration and thickness of graphite layer (see figure 5). For ultrashort pulse laser ablation the thickness of graphite layer is proportional to the absorption properties of graphite. There is no relation between pulse duration and graphite thickness due to the fact that heat conduction starts after the end of the laser pulse (as shown in figure 2). For short pulse laser processing the thickness of graphite depends on the pulse duration and thermal properties of graphite. For laser pulses of 200 ns pulse duration the graphite layer can reach a thickness of 1 μm . The Fraunhofer IPT has experimentally proved the relation (transmission electron microscopy image on the right side in figure 5) for a pulse duration of 220 ns. After laser processing of PCD a graphite layer with a thickness of 0.8 μm was found by analyzing a thin lamella prepared by focused ion beam (FIB).

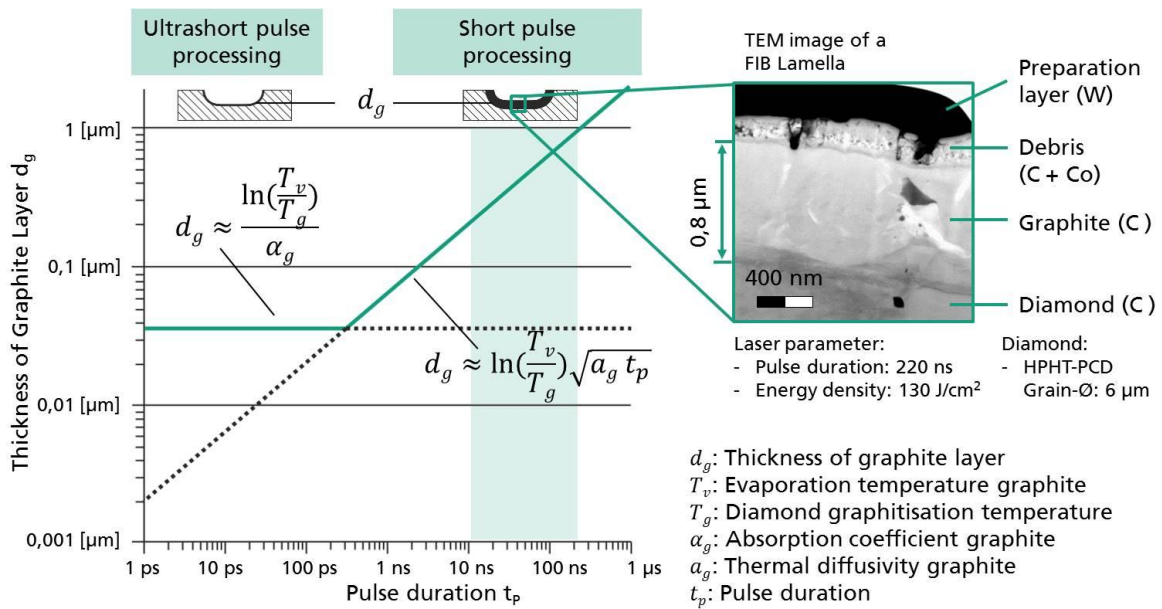


Fig. 5. Thickness of Graphite Layer after Laser Processing based on Kononenko et al., 2005

3. Ablation Results for Polycrystalline Diamond

Different polycrystalline diamond materials were investigated after single pulse laser irradiation under variation of pulse energy (results see figure 6). It was found out that the ablation depth for cobalt-free CVD-PCD is higher than for cobalt-containing HPHT-PCD. The reason for the differences between the materials is the different thermal conductivity. The thermal conductivity for medium grained HPHT-PCD is between two to four times lower than for CVD-PCD. Low thermal conductivity leads to a fast heating at low values of fluence and consequently to evaporation and ablation even at low values of fluence. For higher values of fluence the heat cannot be conducted fast enough into the depth of the material to reach evaporation temperature. High thermal conductivity leads to a higher ablation threshold. For the parameters shown in Figure 6 ablation of CVD-PCD requires a fluence of 20 J / cm². The achievable ablation depth at higher values

of fluence is higher than for HPHT-PCD due to better thermal conductivity (1000 -1200 W/mK for CVD-PCD compared to 500 – 560 W/mK for HPHT-PCD).

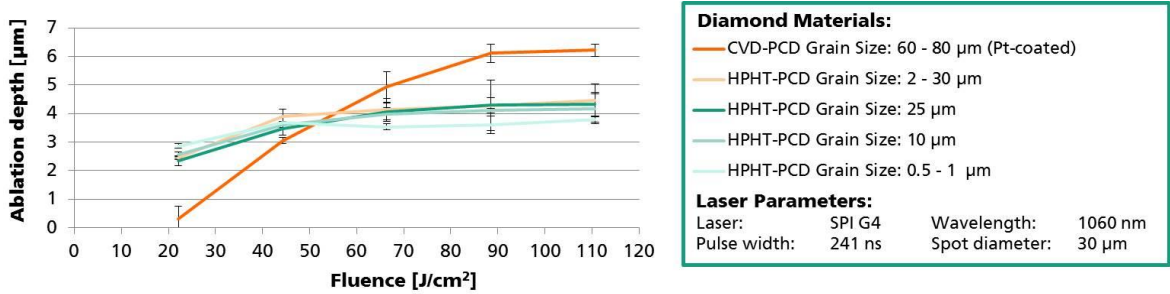


Fig. 6. Single Pulse Ablation Results for Different Diamond Materials

It can be further observed that the ablation depth is limited for higher values of fluence for all PCD materials. As shown in figure 4 laser radiation is absorbed in the plume after material has been evaporated. This effect is further analyzed by two experiments. First experiment (figure 7) shows the plasma formation during single pulse laser ablation for different values of fluence. For that purpose a CMOS camera is installed and synchronized with the laser source. It is obvious that the size of plasma plume is scaling with fluence. The plume size variation for different diamond materials is insignificant (not shown).

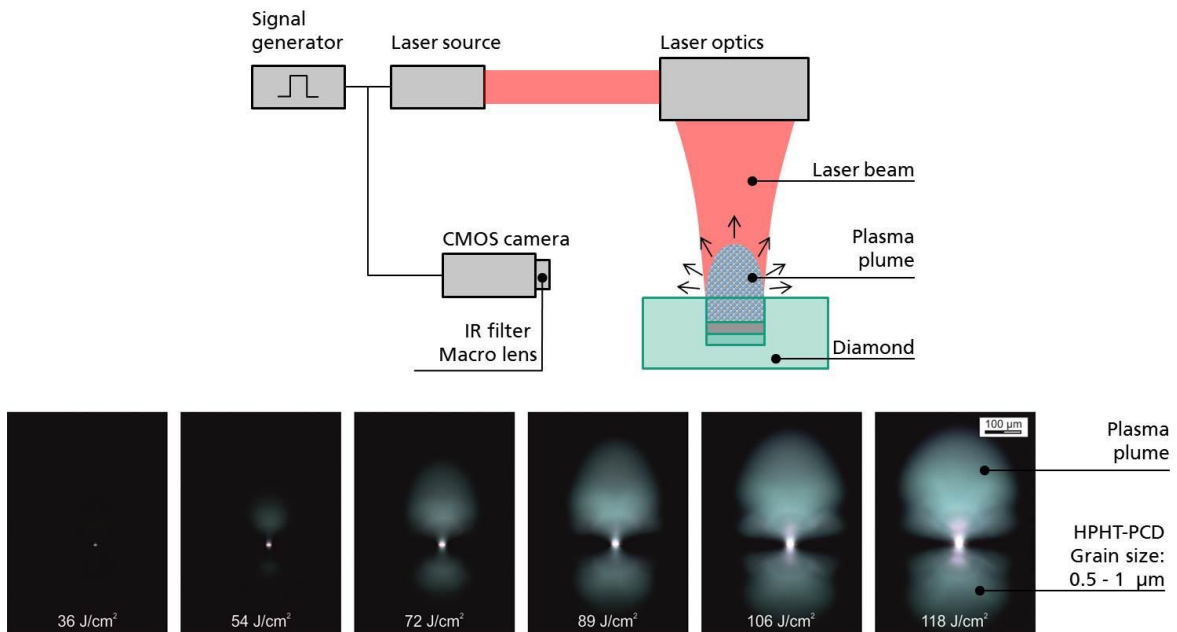


Fig. 7. Plasma Formation during Single Pulse Laser Ablation for Different Values of Fluence

In a second experiment a second laser source is used to measure the absorption in the plasma plume (figure 8). The second laser source is horizontally installed and the laser beam is focused into the plasma. On the other side of the plasma a high speed photo detector is installed to measure the laser power transmitted by the plasma plume.

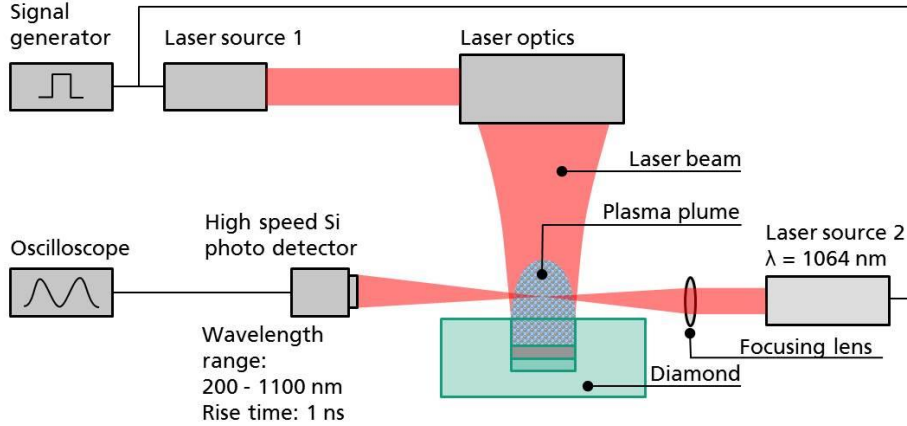


Fig. 8. Experimental Set-up for Plasma Absorbance Measurement

The absorption of laser radiation in the plasma is increasing with increasing values of fluence of laser source 1 (figure 9). For different diamond materials the absorption of laser radiation in the plume is insignificant.

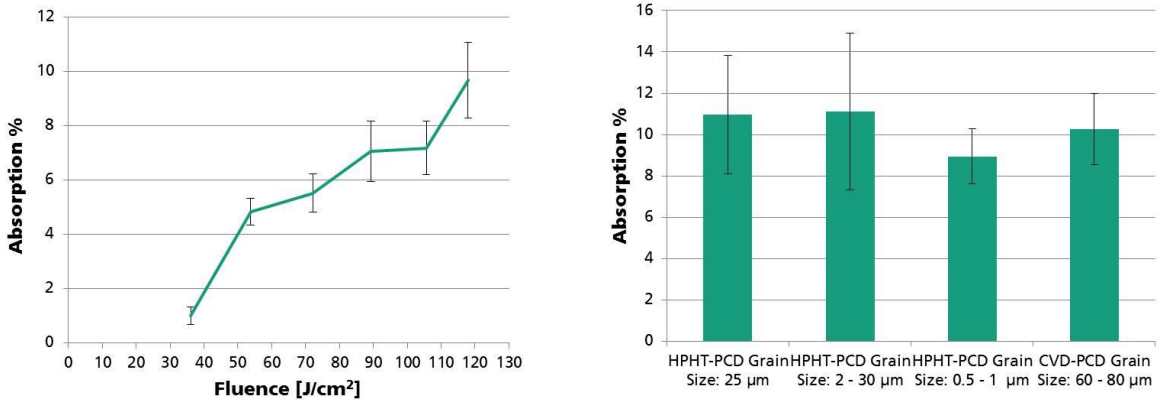


Fig. 9. Results for Plasma Absorbance Measurement

It can be further observed that the ablation depth is limited for higher values of fluence for all PCD materials. As shown in figure 4 laser radiation is absorbed in the plume after material has been evaporated. This effect is further analyzed by two experiments. First experiment (figure 7) shows the plasma formation during single pulse laser ablation for different values of fluence. For that purpose a CMOS camera is installed

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Summing up the short pulse laser ablation behavior of different PCD materials depends on the thermal properties of the diamond. Higher thermal conductivity leads to higher achievable ablation depth. The ablation depth is limited by plasma formation and absorption of laser radiation in the plasma plume. Absorbance of laser radiation in the plume has to be avoided to achieve high process efficiency.

4. Application

The Fraunhofer IPT uses optimized ablation strategies for a novel approach for diamond tool processing: laser roughing. In laser roughing operations, a laser beam minimizes the PCD material allowance required by the manufacturing process swiftly, without causing any tool wear. Only a few micrometers subsequently need to be finished by grinding in order to achieve the required surface qualities. The combined process reduces the finish machining effort by more than 50 percent and also lowers the consumption of high-cost diamond grinding disks. The quality of the tools matches that of the tools produced in conventional manufacturing processes.

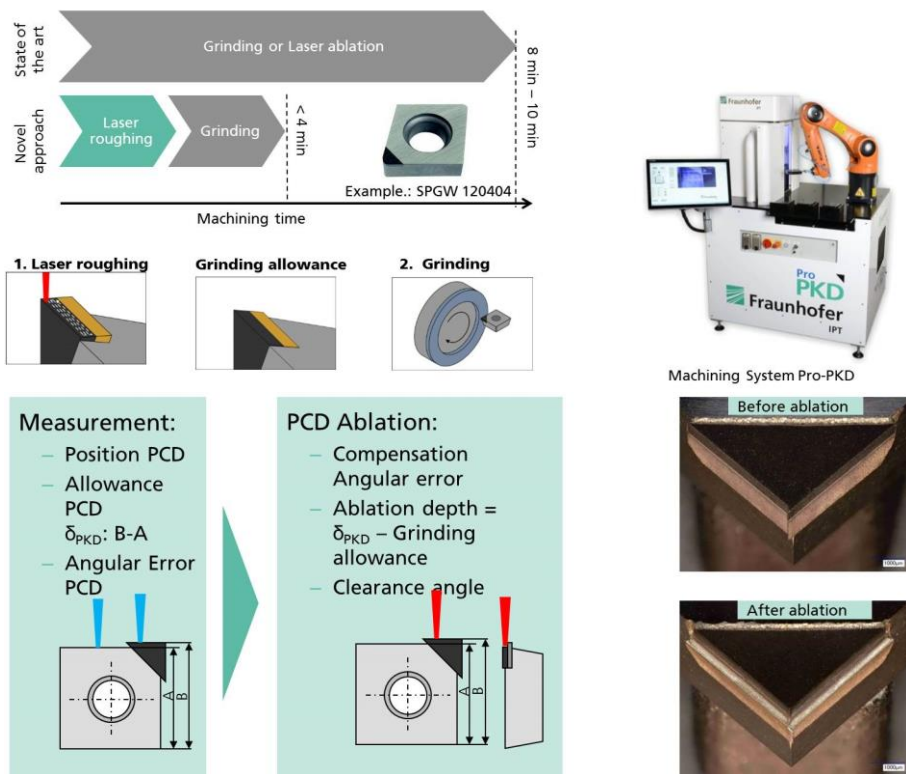


Fig. 10. Approach and Results for Laser Roughing of PCD Cutting Insert

The Fraunhofer IPT is developing ways of integrating laser roughing operations within the process of manufacturing PCD cutting tools. We have many years of experience in laser system engineering and in manufacturing special purpose machinery geared to facilitating optimum development of new production processes. The Fraunhofer IPT has pioneered a PCD roughing laser module which can be customized to meet the requirements of PCD cutting tool manufacturers: fully automated laser processing of PCD cutting tools, flexible adaptation to required cutting edge geometries, encapsulated system to ensure laser safety, low energy consumption, compact design and low acquisition cost.

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