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Ultra-short pulsed laser machining of ultra-hard cutting tool materials

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Abstract

Ultra-short pulsed (USP) laser technology has been successfully used in recent years for post-processing or even the complete fabrication of micro cutting tools from ultra-hard cutting tool materials. In this paper, polycrystalline diamond (PCD) and cemented carbide (WC-Co) are machined using an USP laser. Pockets are generated with different process parameters. The influence of the pulse duration on the ablation behavior is examined in the range between 0.3 ps and 10 ps. The energy-specific ablation volume is calculated out of the measured ablation volume. Finally, the experimental results are compared to an analytical model, showing the influence of the pulse duration on the threshold fluence and penetration depth. The findings can be used for productivity calculations and comparisons to other manufacturing technologies. Furthermore, the analytical model can serve for extrapolations and should help to choose the optimal laser system for the manufacturing of cutting tools.

Keywords: ultra-short pulsed laser machining; cemented carbide; polycristalline diamond; pulse duration; threshold fluence; penetration depth; Neuenschwander model; tangential laser processing; parallel laser processing

1. Introduction

Tools that are made of hard cutting materials are usually ground. This conventional manufacturing technology has several drawbacks. The main ones are friction and wear, caused by forces occuring during the mechanical process of material removal. This can cause predamage to the cutting tool while being produced. Furthermore, the continuing wear of the grinding wheel can reduce precision. In the case of PCD cutting tools, the blanks are machined by diamond plated grinding wheels. Due to the fact, that diamond is the hardest known material, there is no alternative to machine PCD mechanically. This limitation results in a fast wear of the grinding wheels and therefore high costs for the production of such cutting tools.

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Nomenclature

A_{eff}	absorptance as a function of the pulse duration
$C_{e,0}$	proportionality factor between the heat capacity and the temperature of the electrons
D	diffusivity
Δ_{Abl}	volume-specific threshold energy for ablation
E_P	pulse energy
$E_{P,opt}$	optimal pulse energy as a function of the focal laser spot radius
f_{Rep}	repetition rate
F_{abs}	absorbed fluence
F_{th}	theoretical threshold fluence
$F_{th,eff}$	effective threshold fluence
N_p	number of applied pulses
N_U	number of passes or slices in the 2.5D ablation process
K_e	electronic heat conductivity
$K_{e,0}$	proportionality factor between the heat conductivity of the electrons and T_e/T_l
λ	wavelength
l	theoretical thermal penetration depth
l_{eff}	effective penetration depth
$L_{th,\delta}$	thermal diffusion length of a delta pulse in time
$L_{th,T_{max}}$	thermal diffusion length of a Gaussian pulse, at which $T_S = T_{max}$
L_C	critical electronic diffusion length
s_L	line distance between scanning paths
T_S	surface Temperature during a Gaussian laser pulse
T_e	temperature of the electrons
T_l	temperature of the lattice
T_{max}	maximum surface temperature during a Gaussian laser pulse
τ_P	(FWHM) laser pulse duration
τ_R	relaxation time of the electronic system
τ_0	constant in the fitting function of l_{eff}
V_E	energy-specific ablation volume
$V_{E,eff}$	effective energy-specific ablation volume
v_{e-e}	electron-electron collision frequency
ω_0	laser beam waist radius
ζ	quotient from the threshold fluence and the penetration depth
ζ_0	constant used in the fitting function for ζ

1.1. USP Laser processing of ultra-hard materials

An alternative to the conventional grinding process is the ultra-short pulsed laser machining. Due to the short pulse duration and high intensity, also transparent materials, such as the monocrystalline diamond (MCD) can be processed in a gently way. In contrast to mechanical processes, the hardness of the workpiece material is irrelevant. A further advantage is that the laser process is free of forces and wear.

In recent years, it has been shown that even complex milling or drilling tool geometries made of PCD or cemented carbide can be completely manufactured from a blank using an USP laser in combination with optical and mechanical axes. The fabrication of PCD drilling tools was demonstrated by Warhanek et al., 2016. A single sided micro cutter with a diameter of 0.2 mm was produced out of cemented carbide by Pfaff et al., 2017. The production of a complex micro cutter with 0.1 mm in diameter on an 8-axis machine using a focal spot diameter of about 30 microns was shown by Hajri et al., 2018. The industrial production of drilling tools was presented by Eberle et al., 2018.

In these processes, a special laser machining strategy was used, the so-called tangential or parallel laser processing. This technique allows to precisely generate complex free-form surfaces due to its self-limiting property. To understand how the USP laser ablation takes place under different angles of incidence fundamental investigations has been carried out by Hajri et al., 2018. The obtained results can be used as a basis for developing a CAM for the production of micro cutters made of tungsten carbide.

The choice of the optimal laser system for this application is crucial for the industrial implementation of this process technology. The price of the laser source mainly depends on two basic parameters. First, the wavelength that can be provided with relatively little effort by a retrofit of the laser source. Second, the pulse duration which has the greatest impact on the price. Thus, this study investigates only the influence of the pulse duration.

1.2. Influence of the pulse duration on the ablation behavior

The influence of pulse duration has been intensively studied by Jaeggi et al., 2011 and Neuenschwander et al., 2012, 2013. The removal of macroscopic pockets by 2.5D laser ablation is an efficient method to determine the ablation threshold fluence and penetration depth for different pulse durations, as demonstrated by Neuenschwander et al., 2013. The pockets are evaluated by measuring the total ablated volume and calculating a pseudo efficiency. This pseudo efficiency is an energy-specific ablation volume with a typical curve shape ("Neuenschwander-Curve"). This curve has a maximum at the optimal fluence or optimal pulse energy $E_{P,opt}(\omega_0)$. Fitting this curve allows to determine an effective threshold fluence and penetration depth. Analogous to Jaeggi et al., 2011, the specific ablation volume V_E can be described as a function of the pulse energy:

$$V_E = \frac{\pi}{4 \cdot E_P} \cdot \omega_0^2 \cdot l \cdot \ln^2\left(\frac{2E_\mathrm{P}}{\pi\omega_0^2 \cdot F_\mathrm{th}}\right) \tag{1}$$

Macroscopic laser processes uses hundred thousand or even millions of pulses for material removal. The number of pulses is considered by multiplication of $\mathrm{N_P}$ to Equation (1):

$$V_{E,N,eff} = N_P \cdot \frac{\pi}{4 \cdot E_P} \cdot \omega_0^2 \cdot l_{eff} \cdot \ln^2\left(\frac{2E_\mathrm{P}}{\pi\omega_0^2 \cdot F_\mathrm{th,eff}}\right) \tag{2}$$

This effective specific ablation volume depends on many process parameters such as the repetition rate and the pulse overlap. For this reason, the penetration depth and the threshold fluence are called effective to avoid mixing them up with microscopic physical constants or functions.

The knowledge of these effective parameters are useful to predict the ablation rate and ablation efficiency for industrial processes.

Therefore, equation (2) is used to determine the effective threshold fluence F_{th} and effective penetration depth l_{eff} for a given parameter set. Consequently, the study on pulse duration helps to separate the penetration depth and reflectivity through the following equation:

$$F_{th}(\tau_P) = \frac{\Delta_{Abl}}{A(\tau_P)} \cdot l_{eff}(\tau_P) \quad (3)$$

Where Δ_{Abl} is the volume-specific threshold energy needed for ablation, $A(\tau_P)$ the absorptivity as a function of the pulse duration and l_{eff} the effective penetration depth as a function of the pulse duration.

In general, the exact functions of l_{eff} (τ_P) and the absorptivity $A(\tau_P)$ are unknown. These functions can be measured indirectly by using Equation (2) and (3). So applying the method of Neuenschwander allows us to measure the pulse duration dependent penetration depth and pulse duration dependent effective absorptivity.

There are several observations in literature showing that the threshold fluence is not constant but also increasing in the sub-pico and picosecond regime of the pulse duration, as for example shown in Jaeggi et al., 2011. This increase of the threshold fluence might seem to be plausible at first, because the thermal diffusion length should be increasing with pulse duration. However, it can also be observed that the penetration depth decreases for increasing pulse durations. Therefore, the increase of the threshold fluence has to be a consequence of the decreasing absorption. The exact mechanisms are still unclear and subject of numerous investigations.

The following assumptions and calculations introduce a simple model for linear absorption and should help to explain the experimental results.

The thermal diffusion induced by irradiation with short laser pulses in the case of thermal equilibrium of the electron gas and the ions can be described well by the 1D heat equation. According to Wellershof et al., 1999, the solution of the heat equation with a delta pulse in time for an area source is given by:

$$\Delta T_\delta(z,t) = \frac{F_{abs}}{C\sqrt{\pi D t}} e^{-\frac{z^2}{4Dt}} \quad (4)$$

Where the thermal penetration depth is defined as:

$$L_{th,\delta} = \sqrt{\pi D t} \quad (5)$$

By calculating the convolution integral, the thermal penetration depth for a temporal Gaussian pulse can be determined for the time, at which the surface temperature reaches its maximum $T_S = T_{\max}$. This gives the following relation by Wellershof et al., 1999:

$$L_{th,Tmax} = \sqrt{2D\tau_P} \tag{6}$$

This is the cause for the well-known dependence on the threshold fluence on the square root of the pulse duration for longer pulse durations in the range of nano-seconds, also shown in Byskov-Nielsen, 2011. According to Wellershof et al., 1999, a similar approach with the use of a temperature-dependent electronic heat capacity $C_e = C_{e,0} \cdot T_e$ and a temperature-dependent electronic conductivity of $K_e = K_{0,e} \cdot T_e/T_l$ results for the heat equation:

$$C_{e,0}\frac{\partial}{\partial t}(T_e) = \frac{K_{e,0}}{T_l}\frac{\partial^2}{\partial z^2}(T_e^2) + 2S(z,t) \tag{7}$$

Its solution is analogous to equation (4)

$$T_e^2(z,t) = \frac{2F_{abs}}{C_{e,0}}\sqrt{\frac{C_{e,0}T_l}{\pi K_{e,0}\,t}} \cdot e^{\frac{-C_{e,0}T_l z^2}{4K_{e,0}t}} \tag{8}$$

As done by Wellershof et al., 1999, one can define the critical diffusion length for the electrons by:

$$L_C = \sqrt{\frac{2K_{e,0}\tau_R}{C_{e,0}T_l}} \tag{9}$$

Where $\tau_R = C_{e,0} \cdot \frac{T_e(z=0,\tau_R)}{g}$ is the relaxation time of the electrons.

The critical diffusion length is assumed equal to the penetration depth, since at $t = \tau_R$ the major energy of the electron-system is transferred to the lattice and the ablation process starts. L_c is constant, if τ_R is also constant and therefore independent of the pulse duration. This fact is the basis of the proposed independency of the threshold fluence on the pulse duration in the sub-pico-second regime.

In contrast, a proportionality of the relaxation time to the maximum surface temperature of the electrons during the laser pulse is proposed here:

$$\tau_R \propto T_{e,max} \tag{10}$$

This means, that the relaxation time is longer for higher electron temperatures.

Analogous to equation (6), the maximum electron temperature has to be reciprocal to the pulse duration $T_{e,max} \propto \frac{1}{\sqrt{\tau_P}}$. This leads to the following dependency of L_C:

$$L_C \propto \tau_P^{-\frac{1}{4}} \tag{11}$$

Thus, the penetration depth should be reciprocal to the fourth root of the pulse duration for linear absorption. Assuming a constant absorption, the threshold fluence should decrease with increasing pulse duration, due to Equation (3). But the opposite has been observed in experiments, as discussed above.

The absorptance is inversely proportional to the threshold fluence according to equation (3):

$$A_{eff}(\tau_P) \propto \frac{l_{eff}}{F_{th,eff}} \tag{12}$$

A higher absorption of the laser light is related to a lower threshold fluence. According to the relation of Hagen-Rubens, a decrease in the reflectivity can be traced back to an increase in the electron-electron collision frequency. This collision frequency is proportional to the square of the electron temperature, as shown by Wang et al., 1994. Starting from the frequency for electron-electron-collisions

$$\nu_{e-e} \propto T_e^2 \tag{13}$$

It can be concluded that

$$A(\tau_P) \propto \sqrt{v_{e-e}} \propto T_{e,\max} \propto \frac{1}{\sqrt{\tau_P}} \tag{14}$$

The applicability of these assumptions is examined in the following sections for cemented carbide and PCD.

2. Experiment & Measurement

2.1. Experimental Setup & Procedure

A commercial USP laser source, a Coherent Monaco, was used at a green wavelength of λ = 515 nm to examine the influence of the pulse duration. The pulse duration is changed via the graphical user interface.

Table 1. Process parameters used for the laser ablation of pockets.

Process parameters	Value	Unit
Pulse duration τ_P	0.3 - 10	ps
Pulse energy E_P	0.5 - 38	µJ
Frequency f_{Rep}	500	kHz
Spot radius ω_0	17.65	µm
Wavelength λ	515	nm
Scanning speed v_{scan}	841	mm/s
Number of passes N_U	15	
Line distance s_L	4	µm
Number of Pulses N_P	552’854	

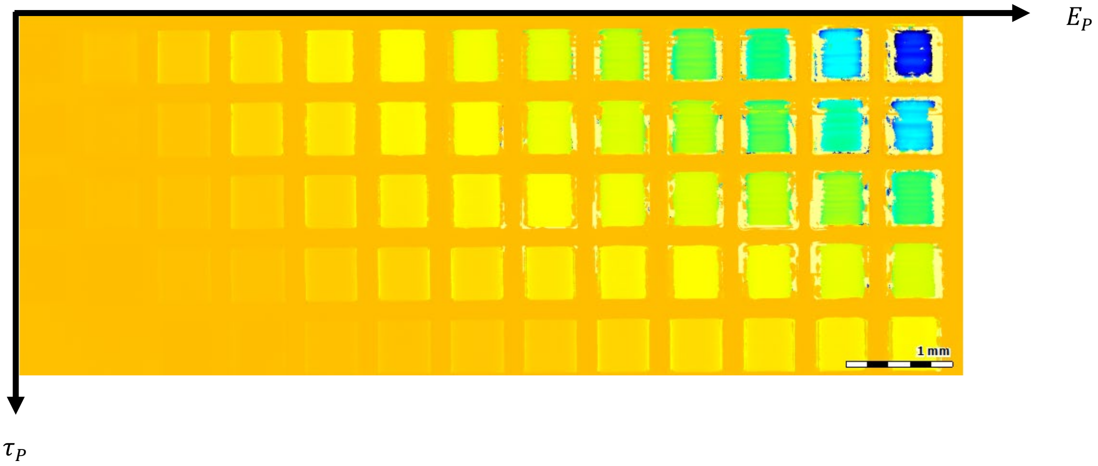

Fig. 1. Topography of the ablated pockets in cemented carbide obtained by a confocal measurement. The variation of the pulse energy and the pulse duration result in a matrix of pockets

To investigate the influence of pulse duration on the threshold fluence and the penetration depth, the aforementioned method of Neuenschwander was used. Pockets with an edge length of 0.49 x 0.49 mm were ablated at various pulse energies according to a logarithmic distribution. This experiment was conducted for five different pulse durations ranging from 0.3 to 10 ps at different pulse energies. The experiments have been carried out for a flat piece of cemented carbide and PCD. The circularly polarized laser beam has been deflected by a galvo scanner and focused on the workpiece surface by a f-theta lens, reaching a focal diameter of about 36 microns. The applied process parameters are summarized in table 1.

2.2. Measurements

We measured the ablated pockets using a confocal microscope. The topography of the carbide pockets is shown in figure 1. The pockets are arranged in a matrix, where the pulse energy is varied within the rows, whereas the pulse duration is varied from row to row. The ablated volumes were measured by extracting a profile of the cross section of a row und determining the depth of each pocket. Multiplying the obtained depth with the side lengths gives the ablation volume. By following this procedure, boundary effects such as elevations of the depth due to reflection or laser delays can be handled.

Results & Discussion

The measured specific ablation volumina were fitted to the following formula according to equation (2):

$$V_{E,N,eff}(\tau_P) = N_P \cdot \frac{\pi}{4 \cdot E_P} \cdot \omega_0^2 \cdot l_{eff}(\tau_P) \cdot \ln^2\left(\frac{2E_\mathrm{P}}{\pi\omega_0^2 \cdot F_{\mathrm{th,eff}}(\tau_P)}\right) \tag{15}$$

Charts along with the experimental data and the corresponding fits for the specific ablation volume of cemented carbide and PCD are exemplary shown in in figure 2 at a pulse duration of $\tau_\mathrm{P} = 1.7$ ps. The threshold fluences and penetration depths of cemented carbide and PCD determined, by fitting the energy-specific ablation volumes for different pulse durations, are shown in Figures 3 and 4.

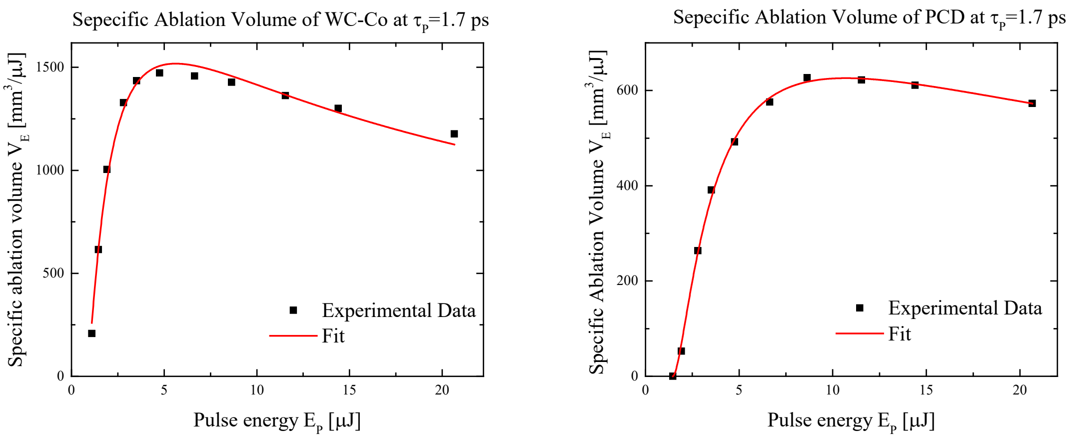

Fig. 2. The specific ablation volume of cemented carbide and polycrystalline diamond as a function of the pulse energy at a pulse duration of $\tau_P = 1.7$ ps. The experimental data was fitted by using the method of Neuenschwander.

As a total result, higher threshold fluences can be observed for PCD at approx. $0.3\ \mathrm{J/cm^2}$ whereas the threshold fluences of cemented carbide range between 0.15 and $0.2\ \mathrm{J/cm^2}$.

For cemented carbide an increase of the threshold fluence can be observed for longer pulse durations. Simultanously, the penetration depth decreases from 18 to 13 nm, whereas the penetration depth of PCD seems to be nearly constant at about 12 nm.

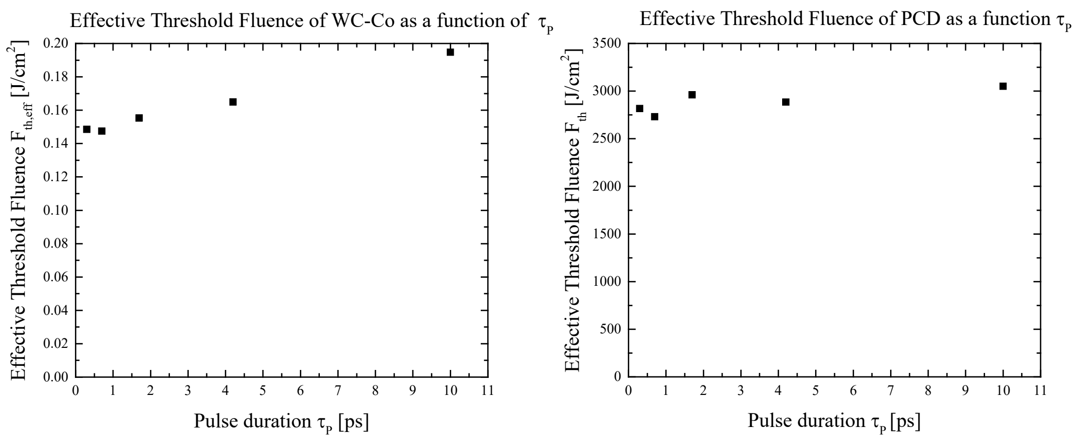

Fig. 3. The effective threshold fluences of cemented carbide and polycrystalline diamond as a function of the pulse duration. An increase of the threshold fluence with the pulse duration can be observed for cemented carbide.

On the basis of equation (11) the penetration depth for cemented carbide was fitted with the function

$$l(\tau_P) = l_0 \cdot (\tau_P - \tau_0)^{-\frac{1}{4}} \tag{16}$$

A good agreement with the experimental data is obtained for $l_0 = 23.2$ nm and $\tau_0 = -2.8$ ps as values for the fitting parameters. The absorptance is reciprocal to $\zeta = \frac{F_{th,eff}}{l_{eff}}$. The corresponding chart with ζ as a function of τ_P is shown in figure 5 for cemented carbide. This function increases with increasing pulse duration. This is equal to a dropping absorptance for longer pulse duration. The experimental data was fitted by following function:

$$\frac{F_{th,eff}}{l_{eff}} = \zeta(\tau_P) = \zeta_0 \cdot \sqrt{\tau_P - \tau_0} \tag{17}$$

A good agreement is obtained for $\zeta_0 = 0.041$ pJ and $\tau_0 = -3.9$ ps.

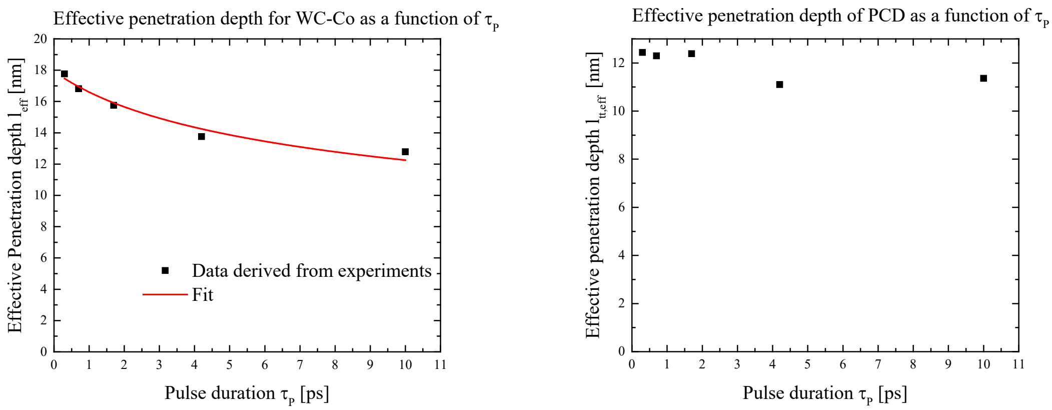

Fig. 4. The effective penetration depth of cemented carbide and polycrystalline diamond as a function of the pulse duration. The penetration depth of cemented carbide is clearly decreasing with the pulse duration. The experimental data was fitted by the function introduced in equation (16).

Cemented carbide has a rather metallic optical behaviour due to the existence of free electrons. This can be assumed because of its shiny and reflective surface. In contrast, the ablation behavior of PCD is strongly influenced by its actually transparent diamond grains. Non-linear absorption is necessary for laser ablation of transparent materials. Nevertheless, the cobalt binder should improve the absorptance due to linear absorption. The threshold fluence and penetration depth of PCD is independent of the pulse duration in the examined regime. This observation can be explained by the different excitation behavior of PCD.

For cemented carbide, the energy-specific ablation volume and also the ablation rate show an increase by a factor of about 2 by reducing the pulse duration from 10 ps to 0.3 ps. Compared to the results in Hajri et al, 2018, ($\tau_P < 12$ ps) the ablation rate at λ=1064 nm is similar to the ablation rate at $\tau_P = 10$ ps and λ=515 nm. As a result, the use of a sub-pico second laser system with a green or infrared wavelength would lead to a significant higher productivity in the ablation of cemented carbide.

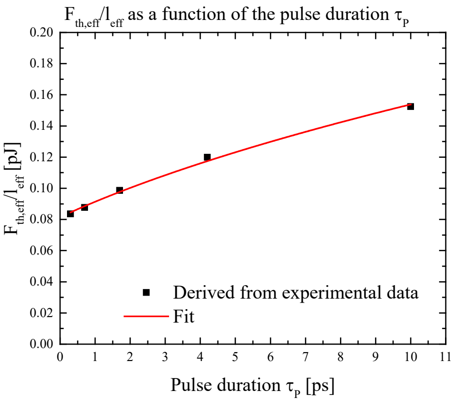

Fig. 5. The quotient from the threshold fluence and the penetration depth as a function of the pulse duration. This function is reciprocal to the absorptance. The experimental data was fitted by the function introduced in equation (17).

3. Conclusion

Pockets were ablated in flat workpieces of cemented carbide and PCD at different pulse energies. The measured ablation volumes were used to calculate the energy-specific ablation volumes according to the method of Neuenschwander.

The results show, that PCD has a higher threshold fluence of nearly constant ($F_{th}(\tau_P) \approx 0.3\ J/cm^2$ in the examined regime of pulse duration) compared to cemented carbide ($F_{th}(\tau_P) \approx 0.15 - 0.2\ J/cm^2$). The penetration depth of PCD also seems to be nearly independent of the pulse duration. For cemented carbide, a significant dependency on the pulse duration could be observed, which results in a higher ablation rate for $\tau_P = 0.3$ ps compared to $\tau_P = 10$ ps.

The introduced analytical model is able to explain the observed effects. Fitting functions for the penetration depth and threshold fluence of cemented carbide derived from the expected proportionalities, showed good agreement with the experimental data.

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