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Pulsed laser micro ablation of polycrystalline cubic boron nitride

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Abstract

Polycrystalline cubic boron nitride (PcBN) is the second hardest material after diamond. Because of its unique properties, PcBN is extensively used as a cutting tool material for the machining of hardened steels. Pulsed laser ablation (PLA) offers the possibility to generate tailored microgeometries on PcBN tools and can thereby increase tool performance. However, the thermal response of PcBN materials to the laser ablation and the laser efficiency in laser machining is not known in dependency of certain PcBN grade characteristics. In this paper the influence of different laser sources in the short and ultrashort pulse duration regime is investigated for a wide number of PcBN grades. Thermally induced surface alterations are examined in detail and connected with the functional performance of the material. It could be shown that a careful parameter definition is crucial for enhancing the performance of laser prepared PcBN cutting tools.

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1. Introduction

Polycrystalline cubic boron nitride (PcBN) is widely used in the cutting tool industry due to its unique physical properties regarding hardness, chemical resistance and high temperature strength. In the geometric processing of PcBN tools typically mechanical processes such as grinding or brushing and blasting are conducted, to generate the desired tool shape [1,2]. Laser ablation is an alternative method for wear-free processing of PcBN tools. However, the tool surface integrity and thereby its functional performance is likely to be influenced by the thermal energy induced by the laser beam. Several authors investigated the influence of different laser sources and laser energies on the thermal response of PcBN substrates and the obtained laser ablation efficiency [3-7]. Thereby, laser induced phase transformations from the cubic allotrope cBN to the hexagonal form were obtained [4] which could also be linked to the resulting tool hardness [6]. First results regarding the achieved ablation performance in terms of ablation depth and efficiency are presented in [5] for picosecond laser processing of a high

PcBN content grade. However, a detailed investigation of different PcBN grades and properties in combination with different laser sources which prevents the design of productive laser processes in the industry has not been conducted yet. Furthermore, only very little research was conducted regarding the influence of laser processing on the functional performance of cutting tools [8]. Therefore, two aims for the presented research are derived. First, a detailed investigation of the influences of different PcBN compositions and laser sources on the ablation behavior is conducted, in order to derive industry relevant knowledge for the laser process design with regards to this influencing factors. Secondly, the influence of different laser processes on the functional tool performance in the most relevant industrial application hard turning is investigated.

2. Experimental Setup

To investigate the influence of PLA on surface integrity of PcBN materials, hardness and microstructure analyses are conducted. To investigate the effects on microstructure a

scanning electron microscope Zeiss EVO 60 VP is used. Vickers hardness measurements are conducted on a Struers Duramin 5 hardness tester. Each hardness measurement was repeated four times. The measurement of the ablation depth was carried out with the available tactile measurement devices within each laser machine tool.

Within this study, three different laser machine tools were used to cover a wide range of industrially relevant laser parameters. An overview about the specific properties of each machine is given in Table 1.

Table 1. Applied laser machine tools and characteristics

Parameter	LT50 Femto	LT45 Pico	LT40 Nano	LT45 Shape
Pulse duration τ	300 fs	10 ps	70 ns	400 ns
Wavelength λ	1,030 nm	1,064 nm	1,064 nm	1.064 nm
Max. mean power P_m	18 W	50 W	12 W	100 W
Max. repetition rate f	400 kHz	800 kHz	100 kHz	100 kHz
Focus diameter d_f	35 μm	35 μm	35 μm	35 μm
Max. pulse energy E_p	45 μJ	125 μJ	200 μJ	100 μJ
Max. pulse power P_p	150 MW	12,5 MW	2,9 kW	250 W

To cover a wide range of material properties six different PcBN grades were investigated. Their specific composition with regards to PcBN content, binder type and grain size is given in Table 2.

Table 2. PcBN grades properties

PcBN substrate	PcBN content in Vol%	Grain size in μm	Binder type
N1	40	1-3	TiC
N2	50	2-3	TiC
N3	60	3-4	TiCN
N4	65	5-6	TiCN
H1	85	2-3	Co-WC-Al
H2	90	1-2	AlN-Co

Cutting experiments were conducted in cutting hardened bearing steel 100Cr6 (60 HRC) on a Hembrug Mikroturn 100 lathe. The workpieces were supplied as cylindrical parts ($D = 165 \text{ mm}$) with center hole ($D_i = 90 \text{ mm}$).

3. Laser ablation characterization

The ablation threshold $F_{p,th}$ represents the energetic limit below which no material removal occurs. To determine the influence of the PcBN composition on laser processing the value of $F_{p,th}$ is analyzed under consideration of PcBN substrates and laser sources (Fig. 1). As a procedure for determining the ablation threshold the single pulse fluence F_p was increased gradually in orthogonal ablation of a pocket ($500 \times 500 \mu\text{m}$) with a constant pulse and track distance of $5 \mu\text{m}$ with 20 ablation layers for each laser source and PcBN substrate. Afterwards the ablation depth was measured, divided by the number of layers and plotted against the single pulse fluence. Linear extrapolation against an ablation depth of zero leads to the ablation threshold values.

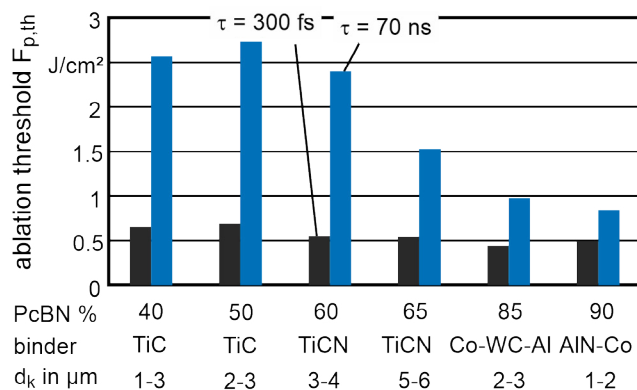


Fig. 1. Ablation threshold $F_{p,th}$ for different PcBN grades

The value determined in this way represents the removal threshold for a number of pulses N , since the process control results in the superimposition of several pulses. Compared to the ablation threshold for a single pulse due to incubation effects [9], the value is expected to be lower. Taking the pulse and track distance and the number of ablation levels into account, an average pulse overlap of $N = 380$ can be determined. The incubation factor for the investigated materials is not known, but in a wide range of metallic and ceramic materials it is $S = 0.85$ [9]. In the following, this value is therefore assumed to be valid for the sake of simplicity. The respective ablation thresholds for individual pulses can thus be calculated based on the formula given in [9] and displayed in Fig. 1.

First, it becomes clear that the ablation thresholds achieved for the femtosecond laser are significantly lower than those for the nanosecond laser. The reason is likely to be the stronger interaction of the laser radiation with the resulting material plasma when processing with a nanosecond laser. This reduces the proportion of energy coupled into the material. With regard to the differences between different PcBN substrates, similar trends can be seen for both laser pulse durations. The decrease in the PcBN content leads to an increase in the ablation threshold. This is due to the high melting and sublimation point of the titanium-based ceramics TiC and TiCN in the binder. The increase in the ablation threshold is particularly pronounced for the nanosecond laser.

The removal thresholds determined in this way are to be used in the further course of this study for the modeling of the removal behavior. In order to allow an estimation of the ablation threshold even for unknown substrates, in the following the extent to which a simple correlation can be established between available material parameters and the removal thresholds is investigated. The following properties of the individual substrates are used:

- Thermal conductivity of the substrate λ_{therm}
- Specific heat capacity of the substrate c_p
- Evaporation temperature T_v

With regard to the ablation behavior of the individual substrates, it can be expected that a high evaporation temperature will increase the removal threshold. The same applies to a high specific heat capacity c_p , since this increases the amount of heat required to reach the evaporation temperature. Moreover, thermal conductivity should result in better propagation of the introduced heat, even though heat

conduction plays a minor role in ultrashort pulsed laser processing. In order to obtain a user-friendly, compact design model, the empirical material index K_{th} is introduced below:

$$K_{th} = \frac{c_p \cdot T_v \cdot \rho}{\lambda_{therm}} \quad (1)$$

The values for each composed PcBN substrate were obtained by using chemical pure substance properties of the individual components, extracted from [10,11,12] and their superposition. The obtained results for the used PcBN substrates is given in Table 3.

Table 3. Value of ablation parameter K_{th} in $cm^3 \cdot s \cdot K \cdot m^{-3}$

PcBN N1	PcBN N2	PcBN N3	PcBN N4	PcBN H1	PcBN H2
34.5	27.0	22.7	21.3	16.1	14.7

The correlation between the ablation parameter K_{th} introduced and the ablation thresholds derived is shown in Fig. 2. To extend the results, laser sources with the pulse duration $\tau = 10$ ps and $\tau = 400$ ns were used in addition to the results shown in Fig. 1 for selected substrates. This shows that the ablation threshold $F_{p,th}$ has an approximately logarithmic relationship with the introduced ablation parameter. Thus, the ablation parameter K_{th} can be used to evaluate and model the removal threshold.

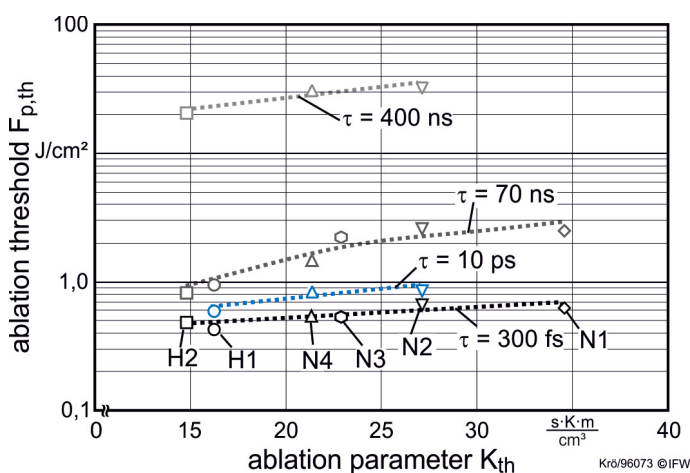


Fig. 2. Ablation threshold as a function of material specific ablation parameter K_{th} and pulse duration τ

The characteristic value can be determined from a simple superposition of material characteristic values available in the literature. With regard to the influence of different pulse durations, it can be seen that in particular with a high pulse duration of $\tau = 400$ ns, the ablation threshold increases drastically. This is due to a correspondingly stronger interaction of material plasma with the acting laser pulse. As expected, the ablation thresholds for the picosecond laser lie between those of nanosecond and femtosecond lasers. As the results so far show, the various PcBN substrates show different phenomena in terms of ablation behavior, which in turn influence the achievable productivity of laser ablation. For industrial process design and evaluation of the achievable productivity, it is necessary to be able to forecast the removal

rate for a wide range of PcBN substrates depending on the laser sources and parameters used. Furthermore, geometrical removal models need to be parameterized with the removal depth in order to achieve the specified geometric target values. In practice, this results in a strong iterative effort to determine the removal depth depending on different laser parameters and substrates. For this reason, an empirical model of the removal depths Δ achieved for five different PcBN substrates was developed (PcBN N1, N2, N4, H1, H2). A simple analytical target function as given in (2) and introduced in [13] was used and parameterized by using the obtained experimental data.

$$\Delta = C1 \cdot F_A \cdot \ln \left(\frac{F_p}{F_{p,th(1)} \cdot \left(\frac{F_A}{F_p} \right)^{S-1}} \right) \quad (2)$$

With the areal fluence F_A calculated by the mean laser power P_m , the pulse repetition rate f_p and the pulse (PD) and track distance (TD):

$$F_A = \frac{P_m}{f_p \cdot PD \cdot TD} \quad (3)$$

Incubation is considered using an incubation factor of $S = 0.85$. The modelling result for three different pulse durations is displayed on Fig. 3. Model validation was executed using the results for PcBN N3 and a set of differing laser ablation parameters for each substrate.

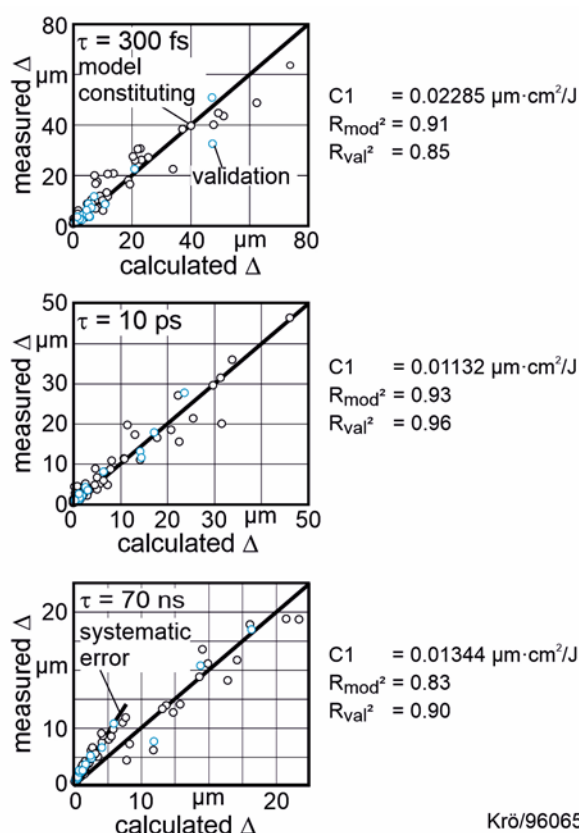


Fig. 3. Prediction model for ablation depth in dependency of ablation threshold and pulse duration

With $R_{\text{mod}}^2 > 0.8$ all regressions achieve a high model accuracy. The relatively large model deviation in the area of low removal values for the nanosecond laser is however indicating a systematic model error. The ablation depth achieved is underestimated by the regression model, so that an alternative linear relationship is evident in the diagram shown. The process results from combinations of process variables that lead to efficient material removal without strong melt recrystallization effects (compare [6]). These are characterized by a high single pulse fluence with moderate areal fluence, whereby the effect is particularly pronounced with the low PcBN-containing substrates with a ceramic binder. The chosen model approach is not able to take such non-linearities in the removal behavior into account. A high level of model accuracy is only possible with sufficiently constant removal mechanisms in the parameter space. This applies to the femto and picosecond laser, which is why no systematic model deviations can be observed here.

In [6] it could be demonstrated that laser processing leads to transformations of the cutting material structure. The determined conversions of the cubic into the hexagonal boron nitride crystal structure as well as the oxidation to B_2O_3 generally indicate a reduction in hardness. An analysis of the influences on the hardness of the cutting material was carried out in the following in order to be able to take this into account in the design of the laser processes (Fig. 4). Using the pulse duration $\tau = 70$ ns, PcBN H1 converts from cBN to hBN with increasing laser energy. This results in a moderate decrease in surface hardness up to approx. 2,700 HV1. In a range of low to moderate single pulse and areal fluence, there is only a very slight decrease in the cutting material hardness compared to the initial state.

With the low PcBN-containing substrate PcBN N2 and $\tau = 70$ ns, there is considerable binder recrystallization on the cutting material surface if the laser energy applied is too low. The structures produced in this way are soft compared to the PcBN basic structure, so that there is a considerable decrease in hardness. A hardness that is unchanged from the initial state is only achieved for the parameter range with high single pulse fluence and low areal fluence. Using the ps laser, the hardness of the PcBN H1 substrate is comparable to that achieved by the nanosecond laser. Only in the area of very high areal fluence and accordingly also high removal rates a noticeable impairment of the cutting material hardness occurs. Under these energetic conditions, the entire surface is covered with B_2O_3 (see also [6]). With regard to the PcBN N2 substrate, a significantly smaller influence is observed during processing compared to processing with an ns laser. The reason for this is that, compared to processing using ns lasers, there are almost no defects from melting and recrystallization, and a reduction in hardness is thus avoided. Using the femtosecond laser, the influence on hardness is the least for both PcBN substrates considered. Only with very high single and areal pulse fluence conversions occur that negatively affect the hardness of the cutting material after laser ablation

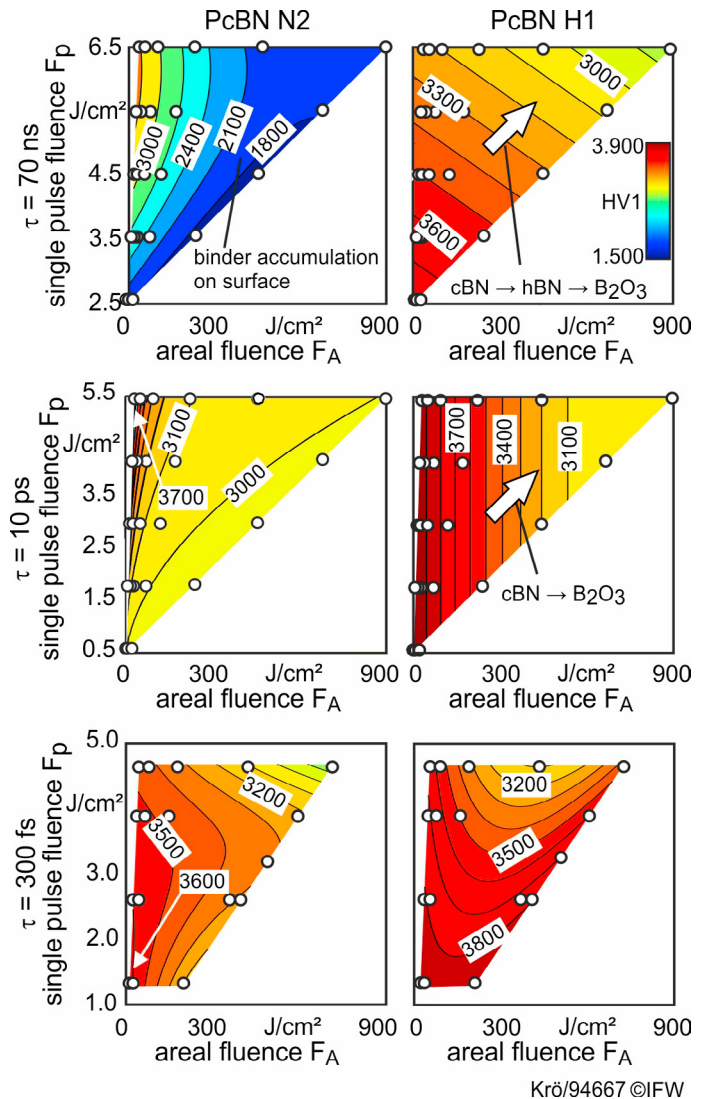


Fig. 4. Influence of single pulse, areal fluence and pulse duration on the hardness of PcBN N2 (low PcBN content) and PcBN H1 (high PcBN content)

4. Hard turning with laser ablated tools

For hard turning in continuous cutting, indexable inserts made of the PcBN N2 substrate with titanium-based, ceramic binder (CNGA120408 geometry) are used. The laser ablation of the cutting edge microgeometry was executed perpendicular to the rake face. The laser tracks were oriented parallel to the edge contour along the corner radius of the cutting tool. The cutting edge micro geometry was based on an industrial reference geometry of $S_\alpha = 22 \mu\text{m}$ and $S_\gamma = 30 \mu\text{m}$. The chamfer angle was $\gamma_f = 20^\circ$ and a chamfer length $b_\gamma = 170 \mu\text{m}$. Two cutting edges were prepared using the respective laser parameters depicted in Table 4 and Table 5. The target values for the cutting edge sections S_α and S_γ were achieved with a maximum deviation of $5 \mu\text{m}$. The chamfer angle γ_f also showed only slight deviations from the target value for all manufactured tools. Only the chamfer width of the tools manufactured using the nanosecond laser deviates from the target value by up to $12 \mu\text{m}$. In the later application tests, however, a maximum chip thickness of $h_{\text{max}} = 0.031 \text{ mm}$ (taking into account κ_{eff}) was used, so that the entire chamfer width is effective for all tools. Accordingly, no significant

influence on tool wear due to the slight deviation of the chamfer width can be expected.

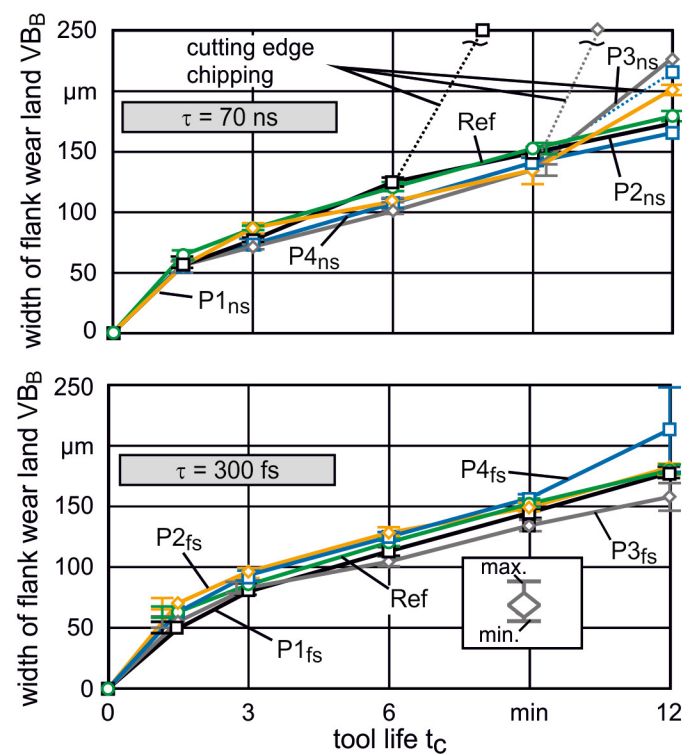
Table 4. Ablation parameters for femtosecond laser ($\tau = 300$ fs)

Femtosecond laser	P1 _{fs}	P2 _{fs}	P3 _{fs}	P4 _{fs}
F _p in J/cm ²	2.6	3.9	2.6	3.9
F _A in J/cm ²	25	37.5	100	150

Table 5. Ablation parameters for nanosecond laser ($\tau = 70$ ns)

Nanosecond laser	P1 _{ns}	P2 _{ns}	P3 _{ns}	P4 _{ns}
F _p in J/cm ²	6.4	10.2	6.4	10.2
F _A in J/cm ²	51	81	142	227

As a reference, tools were prepared conventionally using circumferential grinding with vitrified bond diamond grinding tools and a subsequent abrasive brushing with a diamond brushing tools. The results of the hard turning experiments are shown in Fig. 5.



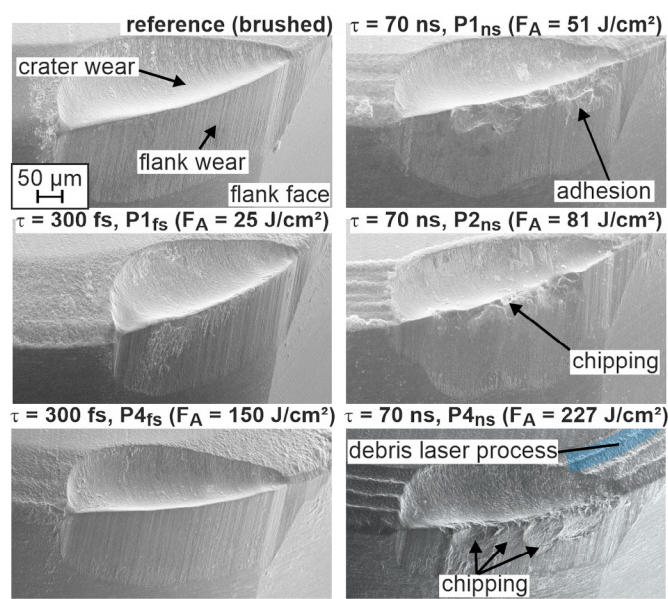
tool N2, CNGA120408 process:
 CBN-content: 50 % external turning, continous
 binder: TiC feed: f = 0.1 mm
laser: cutting velocity: v_c = 200 m/min
 var. depth of cut: a_p = 0.15 mm
 pulse duration: var. workpiece: 100Cr6 (60±2 HRC)
 Krö/98354 ©IFW

Fig. 5. Tool wear progression of laser prepared tools in comparison to conventionally prepared tools (top: nanosecond laser, bottom: femtosecond laser)

The test tools prepared by means of a femtosecond laser show a wear behavior that is very similar to that of the reference tools. The least wear is achieved for the tool manufactured with process parameter combination P3_{fs}. Only the parameter

combination with the highest laser energy P4_{fs} introduced shows a slight increase in the flank wear land width towards the end of the operating time.

In the case of the PcBN tools prepared by means of the nanosecond laser, only the tools prepared with a low single pulse fluence and low areal fluence (P1_{ns}) have a wear behavior comparable to that of the reference tools, with an approximately 25 % increase in flank wear land for the laser-prepared tools at the end of the operating time. Cutting edge chipping occurs for the other tools, which limits the tool life of each of the tools. Thus, a slight increase in laser energy and the conversion mechanisms that take place regarding hardness prove to be critical for tools prepared using ns lasers. To further characterize the forms of wear, SEM investigations of the turning tools used were carried out, Fig. 6.



tool N2, CNGA120408 process:
 CBN-content: 50 % external turning, continous
 binder: TiC feed: f = 0.1 mm
laser: cutting velocity: v_c = 200 m/min
 var. depth of cut: a_p = 0.15 mm
 pulse duration: var. workpiece: 100Cr6 (60±2 HRC)
 Krö/96053 ©IFW

Fig. 6. Tool wear forms of laser prepared tools in comparison to conventionally prepared tools obtained by SEM images

The characteristic wear form for all tools is crater wear and uniform flank wear along the active cutting edge length. A tool that was prepared with the highest areal fluence F_A = 150 J/cm² and a tool prepared with the lowest areal fluence F_A = 25 J/cm² are representative for the femtosecond laser. Both tools have a very similar wear form compared to the reference tool. For the tools prepared with the nanosecond laser, chipping and micro-chipping near the cutting edge occurs from an areal fluence of F_A = 81 J/cm² on, which in some cases propagate towards the flank face. The increasing weakening of the cutting wedge due to the crater wear in combination with a reduced load capacity of the cutting material due to the laser process can be identified as a reason for the cutting edge chipping. Due to the increasing crater wear, the rake angle of the worn tools becomes

increasingly positive and the wedge angle decreases. If the cutting material is already pre-damaged as indicated in Fig. 4 cutting edge failure is triggered.

The obtained results show that laser-processed tools have a tool performance comparable to conventional preparation methods. However, there is a need for further research to make the accuracy and repeatability of laser ablation industrially usable for the production of cutting edge geometries.

5. Conclusions

Based on the obtained results the following conclusions can be drawn:

- The ablation threshold is decreased for decreasing pulse duration τ and increasing PcBN content.
- The achieved ablation depth in laser processing of PcBN can be modelled with high accuracy applying a logarithmical ablation model.
- Tool hardness is deteriorated significantly by nanosecond laser ablation. Applying ultrashort laser pulses leads to minor influences in tool surface integrity.
- The deteriorated surface integrity after laser ablation results in increased wear phenomena in cutting application for the nanosecond laser prepared tools.
- The use of femtosecond laser processing allows for efficient laser processing of various PcBN substrates without affecting their functional performance.

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