Lasers in Manufacturing Conference 2019

Fabrication of cutting edge microgeometries on PcBN tools using pulsed laser ablation

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Abstract

Polycrystalline cubic boron nitride (PcBN) is widely used in industry as a cutting tool material for the machining of hardened steels, cast iron or nickel-based super alloys. For the generation of geometrical features on such cutting tools, laser ablation is a novel and promising technology, which offers wear-free processing and high geometrical flexibility. However, the influences of different laser parameters and pulse durations on the surface integrity of PcBN tools is not known in literature. Therefore, at first PcBN materials are laser processed with different laser sources ranging from nanosecond to femtosecond pulse durations. Laser induced phase transformations and residual stresses are characterized. Optimum laser parameters for each laser source are derived. Afterwards, a method for laser preparation of defined cutting edge microgeometries is presented. Lastly, the fabricated cutting tools are used in machining of hardened steel and the cutting performance is compared to conventionally machined reference tools.

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1. Introduction

The cutting edge microgeometry of a cutting tool describes the transition between the flank and the rake face, Denkena and Biermann, 2014. Due to the high stress concentration in the cutting zone during metal cutting, the size and shape of the cutting edge microgeometry have a strong influence on the resulting tool wear. Therefore, flexible manufacturing methods are necessary to enable an application-specific cutting edge design. Several mechanical methods such as grinding, brushing and abrasive jet machining have already been established in industry to provide adequately rounded cutting edges. However, those methods have limitations regarding the preparation of superhard cutting materials such as polycrystalline diamond (PCD) or polycrystalline cubic boron nitride (PcBN). In order to overcome those limitations, pulsed laser ablation (PLA) has recently been used to prepare cutting edges of PcBN tools. Suzuki et al., 2013, found that the hardness of PcBN tools is increased up to 20 % due to the formation of hard TiB_2 within the binder matrix induced by

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laser treatment with a ns-pulsed laser. The hardness increase of the PcBN tool could be linked to a decreasing roughness in the turning experiment. However, results are not compared to a conventionally prepared tool. In contrast to beneficial effects ranging from the formation of TiB_2, negative influences may arise from other transformation of PcBN material. It has been shown that laser preparation, especially in the ns-range, may lead to a transformation of the zinc-blend cBN structure to the softer hexagonal boron nitride (hBN) or even boron oxide (B_2O_3), Pacella, 2014, Pacella et al. 2015, Melaibari, 2015, Denkena et al. 2019. The presence of those transformations, induced by differing laser preparation, has not yet been linked to the cutting performance of PcBN tools. Furthermore, there are indications that laser ablation of PcBN results in significant residual stresses within the material caused by differing thermal expansion behavior of binder materials and cBN, Breidenstein et al., 2014. It is likely to assume that especially laser pulse duration has a significant impact on laser induced residual stresses. Therefore, it is the aim of this research to evaluate the impact of different laser ablation processes on the surface integrity of PcBN tools and to link those findings to the cutting tool performance. Based on that result, appropriate laser preparation strategies can be derived, which can be applied to fulfill the industrial demand of application specific cutting edge microgeometries on PcBN tools.

2. Experimental Setup

Within the investigations, two commercially available PcBN grades are applied (Table 1). The first grade is a low cBN-content grade with titanium based ceramic binder system. The grade is subsequently referred to as PcBN L. The main application of low cBN-content grades is the machining of hardened steel in continuous cutting. Moreover, a second, high cBN-content grade with a mostly metallic binder composition is used. This grade is subsequently named PcBN H. High cBN-content grades are mostly used in machining hardened steels in discontinuous cut. Both PcBN grades were supplied in the specified tool geometry CNGA120408. The cutting edge before laser preparation was sharp ($\bar{S} < 5\ \mu m$).

Table 1. Chemical composition PcBN grades

Grade properties	**Grade L**	**Grade H**
cBN content	50 vol.% (d_g = 2-3 µm)	90 vol.% (d_g = 2-3 µm)
Chemical composition binder (EDX analysis)	**Grade L**	**Grade H**
Al	12,2 wt.%	11,8 wt.%
Ti	80,0 wt.%	4,9 wt.%
W	7,3 wt.%	25,7 wt.%
Co	0 wt.%	39,2 wt.%
Ni	0 wt.%	18,4 wt.%
Chemical compounds in binder	TiC, AlN, WC	AlN, TiC, WC, Co, Ni, CoWB

Preparation processes were conducted with two different laser machine tools (Table 2). The main difference between those machine is the achieved pulse duration, ranging from ultrashort pulses (τ = 300 fs) to short pulses (τ = 70 ns). Both machine tools are equipped with three translatoric axis of the machine table and two translatoric axis of the laser galvo-system. For defining the workpiece position in the machine, the integrated camera measurement systems were used. Adequate positioning of the z-axis is achieved by the integrated tactile measurement system of each machine tool. Laser power was calibrated beforehand using a Coherent© FieldMax measurement device. The aimed tool microgeometries were designed using NX

Siemens© software and exported to an stl-file. Afterwards, the integrated software LaserSoft3D© of the laser machine tools was used to derive the laser beam paths and to transfer those to the machine control system.

Table 2. Laser machine tools

	Lasertec 50 femto	Lasertec 40 PT
Active laser medium	Yb:YAG	$Nd:YVO_4$
Wavelength λ	1.030 nm	1.064 nm
Pulse duration τ	300 fs	70 ns
Focus diameter d_f	40 µm	36 µm
Intensity distribution	Gaussian	Gaussian
Max. mean power P_m	18 W	12 W
Max. pulse energy E_p	45 µJ	200 µJ

Within the investigations of different laser preparation methods, a variation of the single pulse fluence F_p and the areal fluence F_A is conducted. The areal fluence F_A is calculated by dividing the accumulated energy of multiple pulses by the scanned surface, defined by the laser feed velocity and the track distance.

The given parameter combinations are later on named $P1_{ns}$-$P4_{ns}$ for the nanosecond laser machine tool and $P1_{fs}$-$P4_{fs}$ for the femtosecond laser source. It is to mention that the areal fluence, which is a measure for the introduced energy per surface area, is increasing for rising parameter combination number. All parameters are significantly above the ablation threshold of each PcBN material and in so far applicable for creating tool microgeometries.

Table 3. Applied laser parameters in cutting edge preparation

Nanosecond laser	Single pulse fluence F_p [J/cm²]	Areal fluence F_A [J/cm²]
Parameter setup 1 ($P1_{ns}$)	6.4	51
Parameter setup 2 ($P2_{ns}$)	10.2	81
Parameter setup 3 ($P3_{ns}$)	6.4	142
Parameter setup 4 ($P4_{ns}$)	10.2	227
Femtosecond laser		
Parameter setup 1 ($P1_{fs}$)	2.6	25
Parameter setup 2 ($P2_{fs}$)	3.9	37.5
Parameter setup 3 ($P3_{fs}$)	2.6	100
Parameter setup 4 ($P4_{fs}$)	3.9	150

Cutting edge microgeomtries are investigated using a focus variation microscope Alicona Infinite Focus G5. To investigate the effects of laser ablation on microstructure, a scanning electron microscope (SEM) Zeiss EVO 60 VP is used. The SEM is equipped with an energy dispersive X-ray detector to analyze chemical composition on the specimens' surface. For the analysis of the crystallographic structure of the laser processed PcBN, Raman measurements were conducted. Raman spectra were analyzed using a Bruker Senterra Raman spectrometer with an excitation wavelength of λ = 532 nm, a beam intensity of P = 10 mW and a focal spot size of d_{focus} = 5 µm. The position of the transversal PcBN phonon in the Raman spectra was additionally investigated to analyze the residual stress state of PcBN materials. The position of the peak was detected using Savatzky Golay filter methods and a peakfit algorithm. Afterwards, the peak position was compared to the stress-free position of $X = 1{,}054.7\ cm^{-1}$. The resultant residual stress was than calculated applying the given proportional coefficients of Sanjurjo et al., 1983. Cutting experiments were conducted in cutting hardened bearing steel 100Cr6 (58 HRC) on a Hembrug Mikroturn 100 lathe. The workpieces were supplied as cylindrical parts ($D_o = 165$ mm) with center whole ($D_i = 90$ mm) with and without cut interruptions. For the cut interruptions, six evenly spaced grooves were machined along the workpiece circumference.

3. Results and Discussion

Before applying laser ablation to machine cutting edge microgeometries, basic investigations of laser induced surface alterations of PcBN materials are conducted with ns-laser (Fig. 1) and fs-laser (Fig. 2) machine tools.

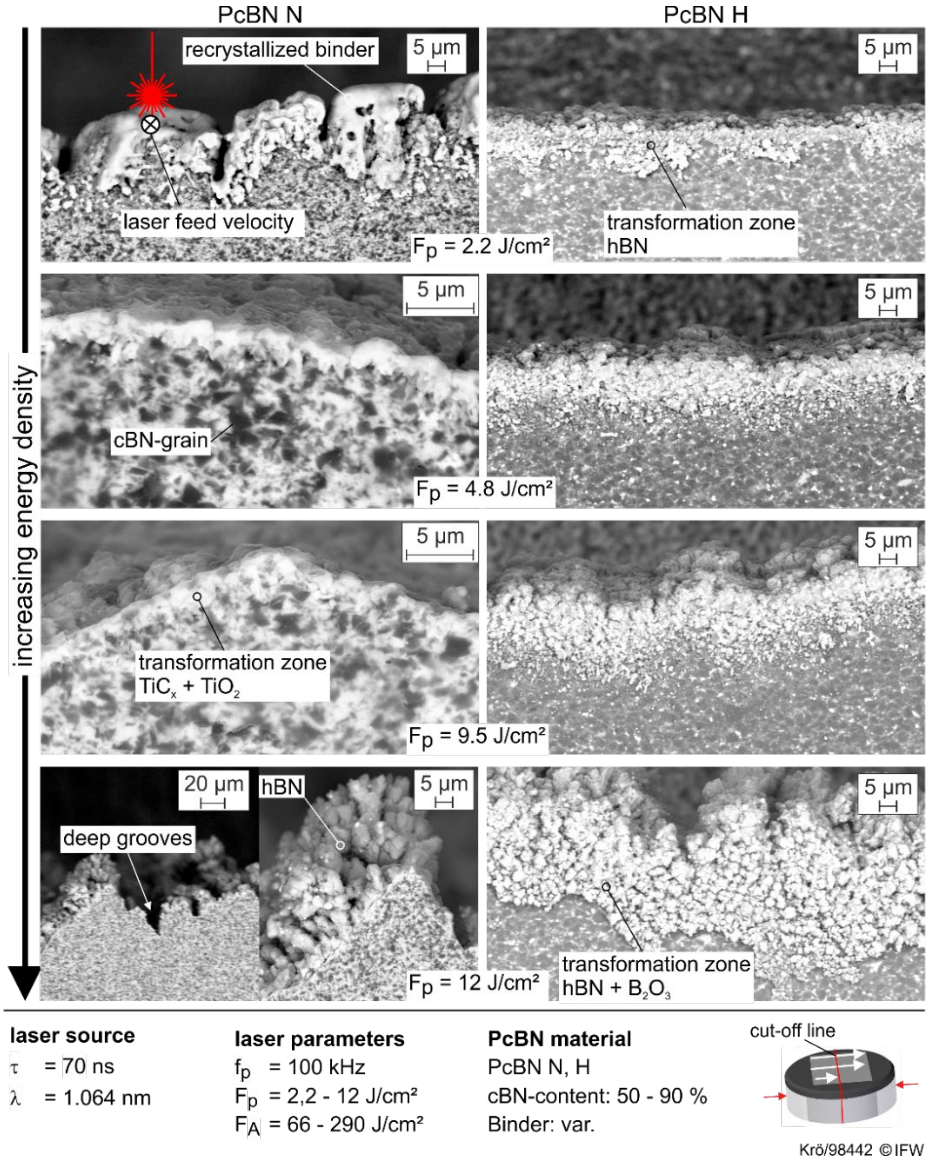

Fig. 1. SEM-images of laser induced surface modification in PcBN materials for ns-laser ablation

Therefore, an alternative method to focused ion beam technique was established to generate material cross sections after laser ablation. Specimens were disjoined before laser ablation using cut-off grinding. Afterwards, the resultant cross sections were polished by diamond polishing paste to achieve mirror like surface finish and remove a possible heat impact zone of the cut-off grinding. Thereafter, the specimen's cross sections were pressed together again applying mechanical pressure in a previously designed fixture. In the following, laser ablation was executed with the laser tracks running orthogonal to the cut-off line (see also Fig. 1). Finally, the specimens were disjoined again, to make the laser affected zone visible in the cross-sectional view. Within the investigations, both PcBN Grades were analyzed. Moreover, the single pulse fluence for each laser source was varied to expose the influence of laser pulse energy on the thermal response of PcBN materials. The results for ns-laser ablation are shown in Fig. 1.

For the low PcBN-content grade PcBN N, low single pulse fluence results in an accumulation of debris on the specimens' surface. This debris is characterized by a high titanium content. Therefore, the debris formation can be assigned to melting and recrystallization of the binder materials. The underlying mechanism is that the low introduced laser energy impedes the complete sublimation of the TiC binder matrix due to its high melting and evaporation point. If laser pulse fluence is increased to F_p = 4.8 J/cm², a homogenous surface structure with only small heat affected zone results. Applying very high laser pulse fluence of F_p = 12 J/cm² again leads to the formation of a significant transformation microstructure on the specimens surface. However, the resulting structure is not dense and smooth, like the heat affected zone for low pulse fluence, but porous and inhomogeneous. By the use of Raman spectroscopy, it could be derived that the microstructure consists of hBN and also a high titanium content. The connection to the unaffected surface is brittle and shows several fractures along the investigated cross sections. Therefore, it can be concluded that applying high laser energy results in a transformation of cBN to hBN.

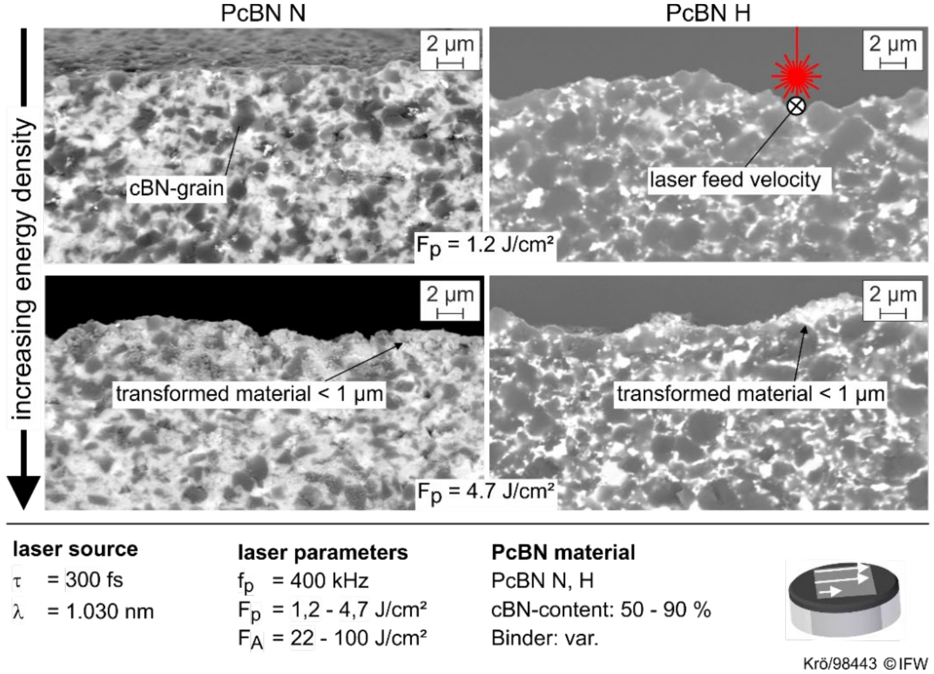

Fig. 2. SEM-images of laser induced surface modification in PcBN materials for fs-laser ablation

Furthermore, similar investigations are conducted for PcBN H with high cBN content. First, it is evident that no significant binder recrystallization takes place for low pulse fluence due to the reduced binder content and metallic binder composition with lower melting point compared to ceramic binders. Still, a heat affected zone consisting of hBN is found on the specimens surface. Thus, transformation of cBN to hBN is shifted to lower energy density for PcBN grade H compared to N. A possible reason based on the ablation behavior of ceramics like TiC could be a strong plasma formation (Teghil et al., 2006) for PcBN N, leading to a higher energy absorption of the induced laser plasma. This may result in higher energy introduced into cBN grains resulting in direct conversion to hBN for the high cBN content grade. Increasing the laser pulse energy results in a continuous growth of the heat affected zone and finally into conversion to B_2O_3. This oxidation reaction is enabled by the presence of hBN, which has significantly lower chemical stability compared to cBN.

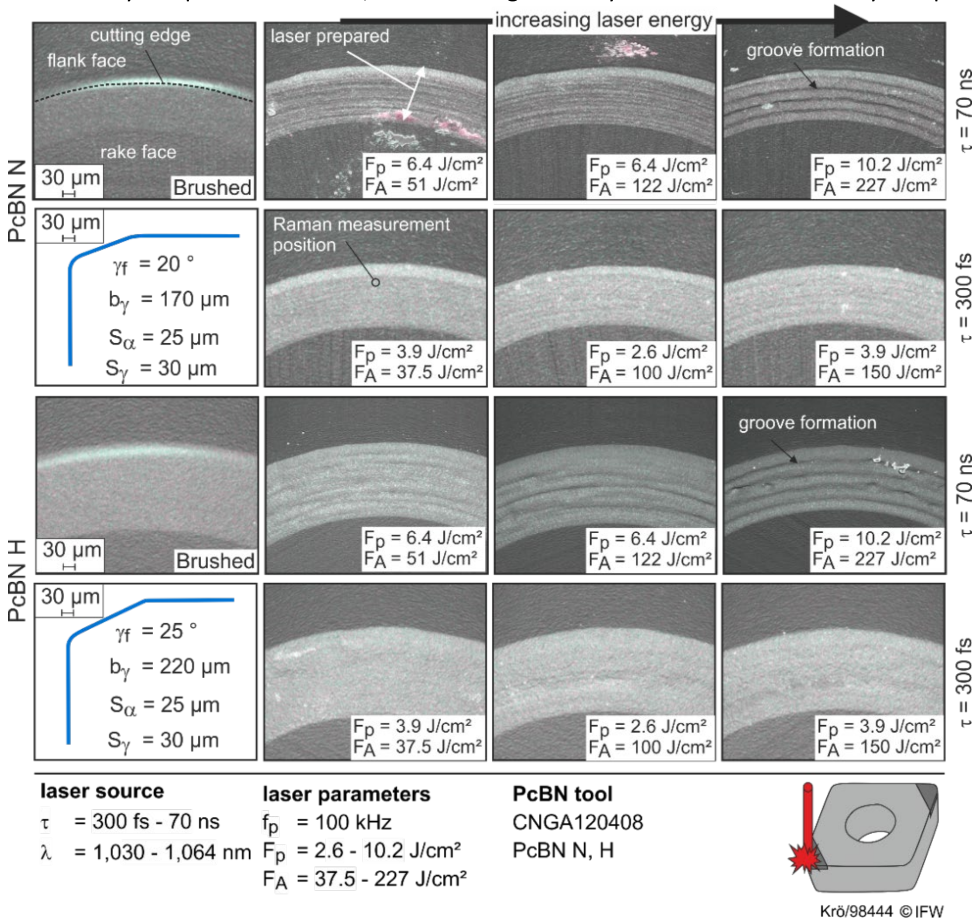

Fig. 3. Laser prepared cutting edges of PcBN N and PcBN H tools

It can be concluded that under ns-laser ablation, significant transformation zones occur on the surface of PcBN materials. Regarding low PcBN content grades, a medium single pulse fluence is beneficial, as binder recrystallization is prevented. However, after a value of approximately 9.5 J/cm² transformation to hBN occurs, which is expected to have negative influence on the materials hardness. Furthermore, for high PcBN grades, low single pulse fluence should be chosen, to reduce the size of the hBN transformation zone.

Additionally, the ablation behavior applying fs-laser sources is investigated (Fig. 2). The use of this ultrashort laser pulses results in minor alterations of the surface microstructure independent of the considered PcBN grade. In the presented SEM images, $F_p = 4.7$ J/cm² represents the highest possible pulse fluence for the laser machine tool. Therefore, fs-laser ablations prevents surface alterations significantly in laser ablation of PcBN.

Based on the given results, laser parameters for cutting edge preparation were chosen (Table 3). Especially regarding the ns-laser, process parameters with medium to high single pulse fluence are chosen, to investigate the influence of possible material damage on the cutting behavior. The resultant cutting edge geometries after laser ablation are presented in Fig. 3 compared to a conventional microgeometry, prepared by grinding and abrasive brushing. It can be seen for both PcBN grades, that increasing laser energy results in a tendency of groove formation for the applied ns-laser source. The reason for this behavior is a more steep ablation crater of the ns-laser. This is caused by the low energy density at the sides of the laser focus diameter, which results in low local ablation depth. The achieved results for the fs-laser enable a higher cutting edge quality in both PcBN materials with very low groove formation.

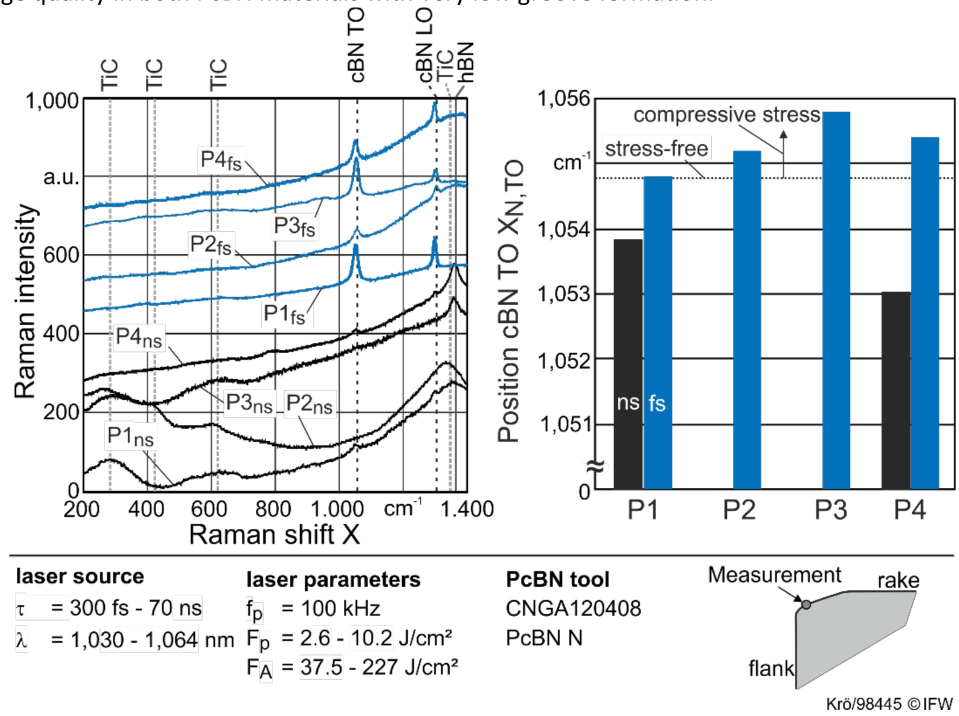

Fig. 4. Raman investigation of surface near composition and cutting edge residual stress state for PcBN N

To investigate the surface integrity at the cutting edge, raman spectra on the laser prepared rake faces close to the cutting edge are presented in Fig. 4 for PcBN N. Additionally the peak position of the transversal cBN phonon is shown, to consider the residual stress state after laser ablation. For the cutting edges prepared with ns-laser, low laser energy density for $P1_{ns}$ and $P2_{ns}$ results in dominance of TiC in the spectra, probably induced by a small zone of recrystallized binder on the surface. An increase in the laser energy for the setups $P3_{ns}$ and $P4_{ns}$ induces significant transformation of cBN to hBN microstructure. As expected from Fig. 2, cutting edges prepared with the fs-laser machine tool show no changes regarding the microstructure and only the dominant peaks of cBN. The residual stress state of the low PcBN content grade is tensile with a maximum residual stress of $\sigma_{tensile}$ = 500 MPa according to Sanjurjo et al, 1983. The cutting edges prepared with femtosecond laser are near wise stress free up to low compressive residual stresses. Therefore, it is concluded that the ablation behavior applying ns-laser not only results in bigger heat affected zone but also in an increased tensile residual stress, induced by differing thermal expansion coefficients of binder and cBN. Due to the direct sublimation, which is expected for the fs-laser, no relevant tensile stresses or compressive stresses occur. It is to mention that the peak position was not measurable for all specimens prepared with ns-laser due to the dominance of hBN or TiC in the Raman signal. For comparison the peak position for the conventionally prepared PcBN tool was measured to be at X = 1,061 cm^{-1}, indicating a stronger compressive residual stress induced by mechanical processing.

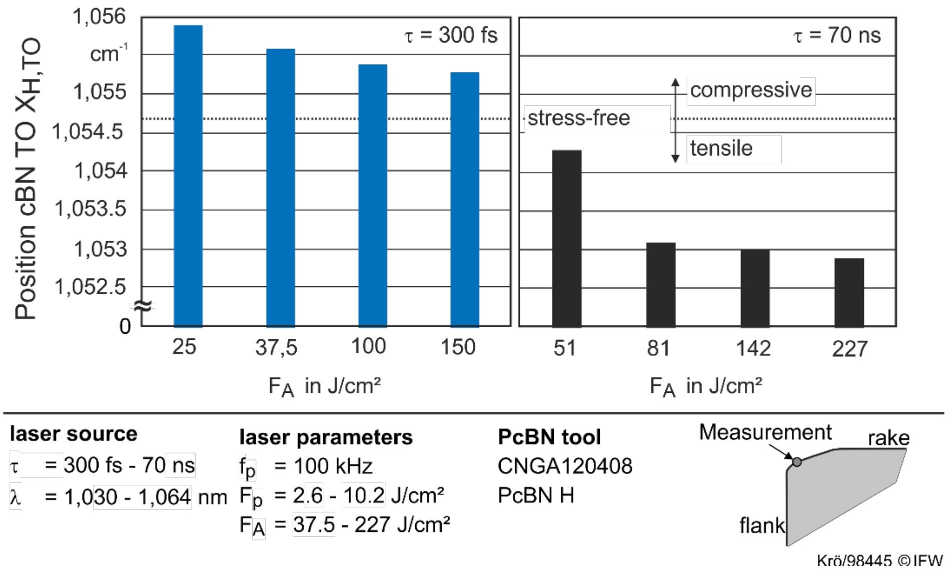

Fig. 5. Raman investigation cutting edge residual stress state for PcBN H

For PcBN H only the Raman peak position of the transversal cBN phonon is investigated in Fig. 5. The obtained Raman spectra contain hBN and cBN peaks for ns-laser ablation and only cBN peaks for fs-laser ablation. For both applied laser pulse durations a clear tendency for shifting the residual stress to lower compressive or even tensile state is evident. However, the achieved residual stresses for fs-laser ablation are all compressive whereas ns-laser ablation leads to tensile stresses in all parameter combinations. The resulting residual tensile stress for ns-laser ablation is comparable to PcBN grade N regarding maximum values.

As a conclusion ns-laser ablation of PcBN material clearly leads to tensile residual stresses, which are expected to have negative influence in cutting behavior e.g. crack propagation. Using ultrashort pulses avoids tensile stresses and even leads to compressive stresses in some cases. However, the compressive residual stresses induced by mechanical processing are higher compared to the stresses after laser ablation.

In the following, the cutting tools were applied in cutting experiments of hardened steel. The cutting tools of PcBN N were used to machine in continuous cut whereas PcBN H was applied in interrupted cut. In continuous cutting, only minor differences in the cutting performance of the applied tools were found.

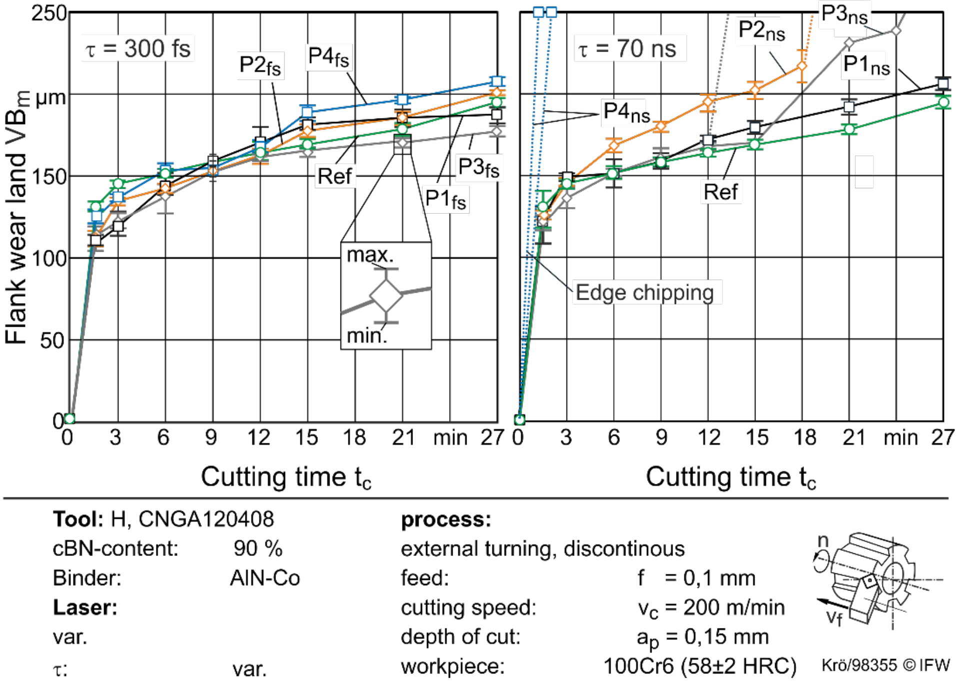

Fig. 6. Tool wear progression in discontinuous cutting of hardened steel

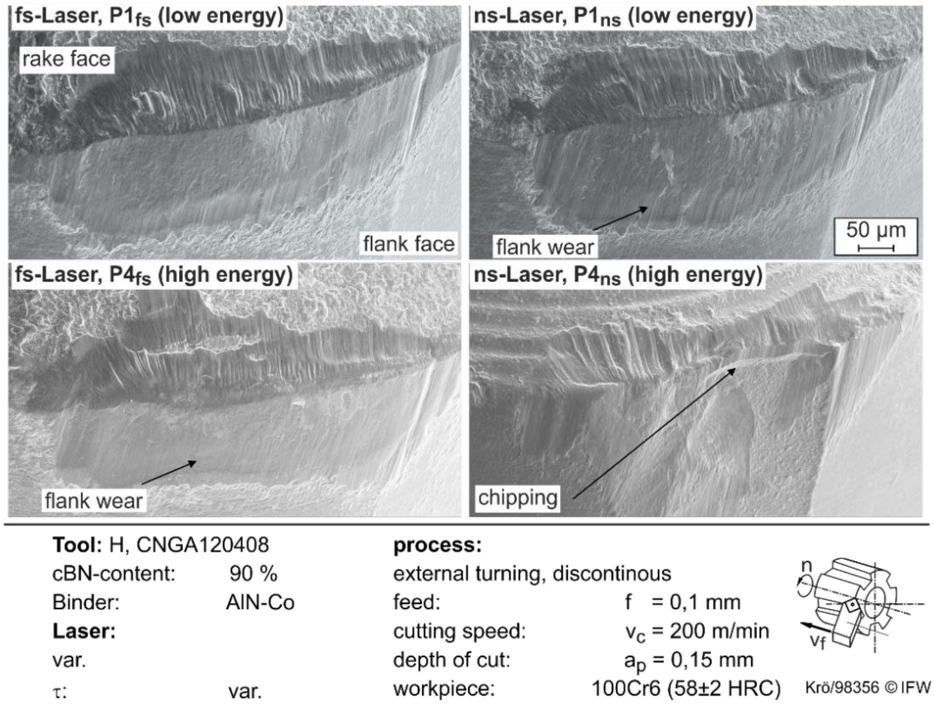

Fig. 7. Tool wear in discontinuous cutting of hardened steel after cutting time t_c = 27 min

The reason for this behavior is an intense crater wear on the rake face, which removes a possibly heat affected zone on the rake face during the initial wear progression. Therefore, only the results for the interrupted cut with PcBN H are discussed in the following. Resulting tool wear progression is displayed in Fig. 6, Fig. 7 presents SEM-images of the achieved wear characteristics. For the tools prepared with fs-laser, similar cutting performance to conventionally prepared cutting tools is achieved, independent from the introduced laser energy. This is in line with the results from Raman investigations, showing only minor differences and compressive residual stress and phase transformation. Applying ns-laser ablation results in significant edge chipping if laser energy is higher than the parameters of $P1_{ns}$. Therefore, the introduced surface damage of ns-laser ablation has a significant impact on the cutting performance of PcBN cutting tools in interrupted cutting.

4. Conclusion

Based on the results, it can be stated that the applied pulse duration significantly influences the surface integrity of PcBN tools. Alterations in the surface integrity, such as phase transformations (cBN to hBN) and tensile residual stresses, were measured using SEM and Raman spectroscopy and afterwards linked to the cutting performance. When the cutting edge is prepared with ns laser pulses, surface damage cannot be avoided, which is crucial in the machining of hardened steel with interrupted cut. If the pulse duration is in the fs regime, surface alterations are completely avoided, leading to a cutting performance equal to conventionally prepared tools. Therefore, it could be shown that laser ablation with ultrashort pulsed laser sources represents an innovative approach to create cutting edge microgeometries with high accuracy and geometrical flexibility.

Acknowledgements

The authors thank the German Research Foundation (DFG) for the financial support within the project "KO 4293/6-1". Moreover, the authors thank DMG MORI for supporting the experimental investigations.

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