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Increased performance in high speed turning of Inconel 718 by laser structuring of PcBN tools

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Abstract

In order to improve the cutting performance of PcBN tools, the cutting edge is prepared e.g. by grinding or brushing. Since PcBN is the second hardest material besides diamond, mechanical preparation of PcBN tools is associated with high wear and low productivity, which leads to high process costs. The laser preparation provides a high potential in preparing PcBN tools because of its wear free technology and its short process times. Additionally, several authors have shown that laser preparation can also lead to beneficial effects such as hardness increase or increased compressive residual stresses. Although these effects are known, they have not been linked to cutting performance of PcBN tools. This paper investigates the influence of nanosecond pulsed laser preparation of the cutting edge and the resulting surface topography on the cutting performance. Therefore, PcBN cutting tools were prepared with different laser velocities at the cutting edge and applied in high speed turning of Inconel 718. Surface integrity of the prepared tools was investigated regarding hardness, surface roughness and edge quality. Afterwards, the prepared tools are used in turning experiments, showing a decreasing flank wear of 40 % compared to reference tools. Tool life increase is linked to beneficial frictional behavior and less adhesive wear of the laser machined specimens compared to conventional tools.

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Keywords: Cubic boron nitride, laser micro machining, turning, cutting edge

1. Introduction

Tool life and cutting performance are strongly influenced by the cutting edge geometry [1-3]. The underlying physical mechanism is the reduction of local stress concentration along the cutting edge [1]. To provide an adequate cutting edge rounding, several mechanical preparation methods such as grinding, abrasive jet machining, drag finishing or brushing are used in industry [1]. In the preparation of superhard cutting materials such as polycrystalline diamond (PCD) or polycrystalline cubic boron nitride (PcBN) these mechanical preparation methods are limited due to high tool wear and low resulting process reliability. Therefore, in these use cases pulsed laser ablation (PLA) is gaining more importance due to its wear free technology and short processing times [4-8]. In contrast to mechanical preparation methods, PLA is characterized by high specific energy input to the machined

substrate, which is necessary to ablate the material. Due to this thermal impact, the surface and subsurface properties of the machined substrate can be altered. Pacella and Pacella et al. show that the chemical composition at the tool surface after PLA exhibits higher binder content compared to bulk material resulting from melting and recrystallization processes [5,6]. Furthermore, a transformation from cBN to hBN is detected for high laser fluence. Suzuki et al. analyze the impact of PLA on PcBN tool surface properties and the effect on the surface quality in hard turning [7]. It is shown that the hardness of PcBN tools can be increased up to 20 % by PLA because of the formation of hard TiB_2 within the binder matrix. As a result, the surface roughness in hard turning could be decreased for PLA processed tools due to a higher resistance against abrasive tool wear. Similar results were achieved by Breidenstein et al. in hard machining of steel using laser prepared PcBN tools [8]. A tool life increase in

hard turning was also linked to the formation of TiB_2 , which lead to the formation of compressive residual stresses in the PcBN substrate. Besides cutting edge preparation, PLA can be used to create microstructures on the tool surface. Various studies have shown enhancements in tool life due to microstructured surfaces [9-11]. Those results are related to reduced contact areas between tool and workpiece. Thereby, adhesion of the workpiece material and friction forces are decreased [9]. Although the above-mentioned researchers have shown a possible tool life increase in hard turning with laser prepared PcBN tools, the knowledge has not been transferred to other applications with different thermomechanical tool load and cutting material properties. Especially the machining of Ni-based super alloys such as Inconel 718 is of increasing importance in industry and characterized by extensive mechanical and adhesive wear [12]. Therefore, it is the aim of this paper to investigate the tool wear behavior of PcBN tools prepared by PLA in high speed turning of Inconel 718.

2. Experimental Setup

In this investigation round PcBN tools (SECO RNGN 090300E25) with a specified cBN-Content of $c_{cBN} = 65$ wt%, TiCN as binder material and a mean grain size of $d_{grain} = 3 \mu m$ were used. The exact chemical composition as measured by EDX on the tool surface is given in Table 1. The material texture before laser preparation is shown in Fig. 1.

Table 1: Chemical composition of unprepared PcBN tools

Element	B	N	Al	Si	Ti	W	C	O
wt%	36.9	25.8	7.0	1.9	19.3	2.2	3.3	3.5

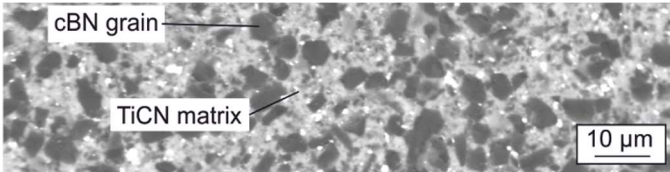


Fig. 1: SEM image of ground tool before laser preparation

Laser preparation is performed using a DMG Sauer Lasertec 40 machine tool. This machine tool is equipped with a Nd:YVO₄-Nanosecond laser with a wavelength $\lambda = 1,064$ nm and a focus diameter of $40 \mu m$. The experiments were conducted with constant repetition rate $f_r = 60$ kHz, mean power $P_m = 4.1$ W and pulse width $\tau_p = 85$ ns, while the laser velocity was varied in four steps between $v_1 = 200$ mm/s and $v_1 = 800$ mm/s. The track distance TD was chosen according to the pulse distance PD to ensure an evenly structured surface. The pulse distance PD can be calculated as quotient of laser velocity v_1 and repetition rate f_r . As hatch style, crosswise orientation of the subsequent ablation planes was chosen. The overall ablation depth was $30 \mu m$ for all specimens. For the cutting experiments, the PcBN inserts were prepared on the cutting edge and the surrounding areas on rake and flank face within $500 \mu m$ from the cutting edge. The cutting edge preparation was performed in two steps. First, the cutting edge rounding was prepared with the laser beam orientated perpendicular to the flank face. Second, the preparation of the cutting edge is finished by a preparation

perpendicular to the rake face for all specimens.

Detailed analytic investigations regarding the surface properties were conducted. Therefore, the roughness was characterized by a confocal microscope nanofocus $\mu surf$. Each measurement was repeated twice. Surface topography, texture and adhesion on the surface of laser prepared and worn tools were analyzed using a scanning electron microscope Zeiss EVO 60 VP. The cutting edge geometry was examined on an Alicona InfiniteFocus G5 focus variation microscope. The cutting experiments were performed on a CNC lathe Gildemeister CTX 520 linear. Inconel 718 (hardness 36 HRC) was chosen as workpiece material for the application of external turning with coolant. The cutting speed, depth of cut and feed were set at $v_c = 300$ m/min, $a_p = 0.2$ mm and $f = 0.2$ mm, respectively. The tool wear was analyzed on a digital microscope Keyence VHX600. Cutting forces were measured with a Kistler dynamometer type 5015.

3. Results and discussion

3.1. Surface properties

Fig. 2 presents the surface roughness of the PcBN tools after PLA, measured on the rake face. The laser prepared tools show an increasing surface roughness with increasing heat input. The main reason for the increasing roughness values is the inhomogeneous ablation depth within the laser focus spot due to a Gaussian intensity profile. With increasing heat input the groove depth increases leading to higher mean and maximum roughness.

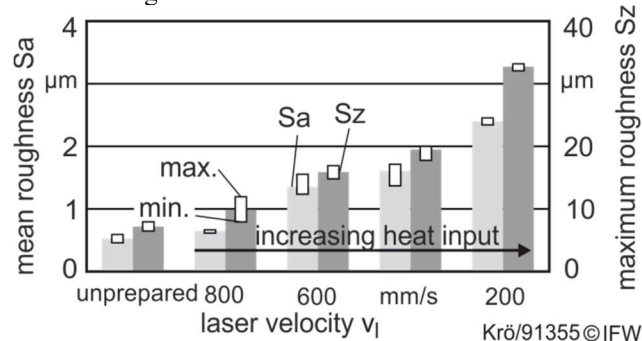


Fig. 2: Surface roughness of laser prepared specimens

Detailed results of the achieved topography along the cutting edge are displayed in Fig. 3. The specimen prepared with $v_1 = 800$ mm/s exhibits a fine and isotropic microstructure with small spherical grooves. Reduction of the laser velocity to 400 mm/s results in a linear, anisotropic groove structure. Further heat input increase for $v_1 = 200$ mm/s causes a drastic change of the ablation mechanism. Especially the tool flank face shows coarse structures whereas the tool rake face is comparatively even. As a reason for the different results on flank and rake face the differing hatch sequence is suspected. When processing the flank face, a curved ablation model is applied (necessary for round tools). Therefore, each section of the final cutting edge is brought into laser focus once, achieving maximum ablation depth. The surrounding section is then prepared in a differing focal position, whereby a flattening of the surface due to a track overlap is hindered. When processing the tool perpendicular to the rake face, neighbouring segments of the cutting edge are ablated in the

same focal position, so that the effective overlap and surface flattening is bigger.

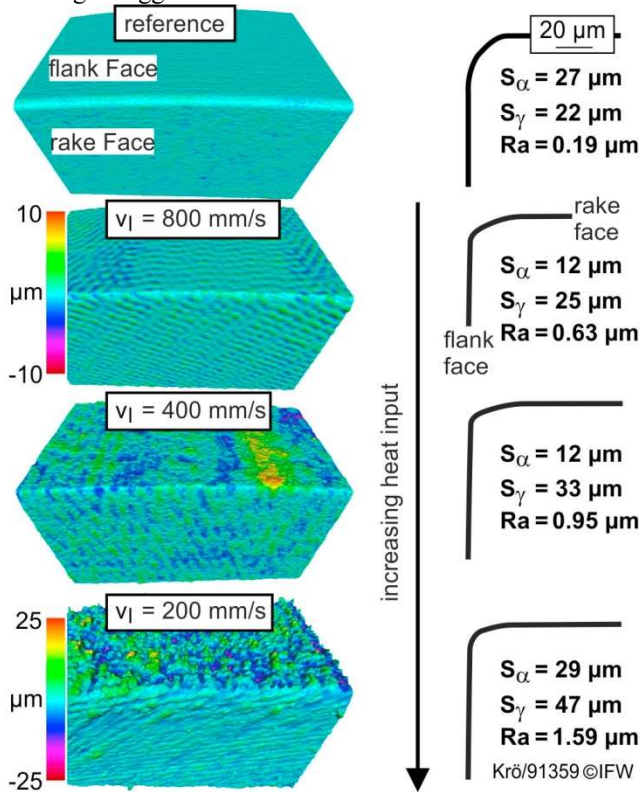


Fig. 3: Topography Cutting edge geometry of PcBN tools

Furthermore, the resulting cutting edge microgeometry is evaluated using Alicona EdgeMaster Software. As shown in Fig. 3, the cutting edge rounding is shifted to the rake face by applying PLA. The reason for this is the final processing perpendicular to the rake face, leading to a flat progression of the rounding to the rake face due to the size of the laser focus diameter. Similar to the surface roughness, the cutting edge roughness is increased for increasing heat input. The increasing roughness can also be displayed by analysing the texture using SEM. As depicted in Fig. 4, an increasing heat input results in coarsening of the material texture due to melt and recrystallization processes. For the highest heat input, a fissured surface with deep grooves between recrystallized binder material is obtained.

Furthermore, the hardness (HV2) was measured for the laser prepared and the reference specimens, respectively. The average hardness of ten measurements and the standard derivation σ are presented in Table 2. The measurements show that no significant differences between unprepared and laser prepared tools exist.

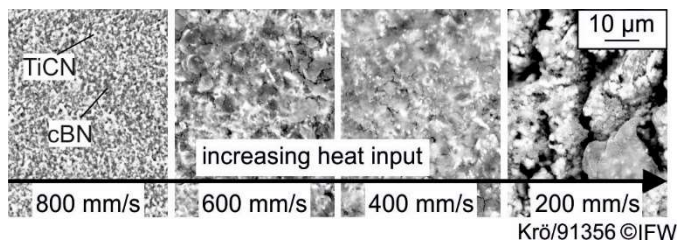


Fig. 4: SEM images of laser prepared cutting edges

Table 2: Hardness of the cutting tools

v_1 in mm/s	reference	200	400	600	800
Hardness in N/mm ²	3302	3229	3262	3181	3342
σ in N/mm ²	133	181	180	138	234

3.2. Cutting Experiments

The cutting experiments were conducted with an unprepared reference tool and three different laser prepared tools ($v_1 = 200$ mm/s; 400 mm/s; 800 mm/s). To validate the results, the experiments were repeated for the unprepared reference tool and one laser prepared tool ($v_1 = 800$ mm/s).

During the cutting experiments, the wear was measured continuously. Flank wear could be identified as main wear mechanism. On three out of four laser prepared tools, a significant wear reduction was observed compared to the reference tool. Only the tool prepared with the highest heat input ($v_1 = 200$ mm/s) lead to a deteriorated performance and cutting edge chipping after a cutting time of $t_c = 120$ s. By applying the tool prepared with a laser velocity $v_1 = 800$ mm/s, a flank wear decrease of approximately 40 % was achieved.

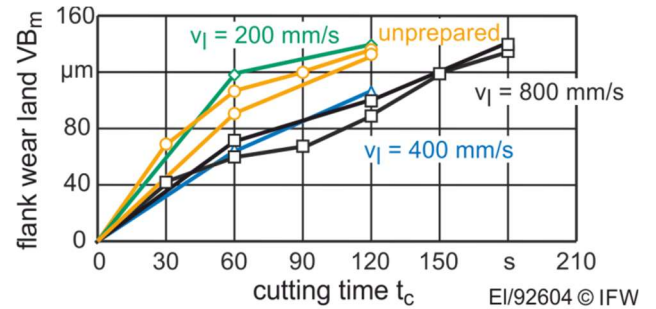


Fig. 5: Progression of flank wear land VB_m for laser prepared specimens

Tool wear progression for the reference tool and the PLA processed tool with $v_1 = 800$ mm/s is compared in Fig. 6. The reference tool exhibits homogenous wear formation along the cutting edge. In contrast, the laser prepared tool is characterized by saw-tooth like wear propagation but significantly lower mean flank wear land VB_m . The wear propagation is closely linked to the tool topography. It is likely to assume that the elevated areas of the topography get into frictional contact with workpiece material before these areas are abraded and tool wear is propagated. To analyze this mechanism in more detail, SEM images of the worn cutting edges are prepared (Fig. 7).

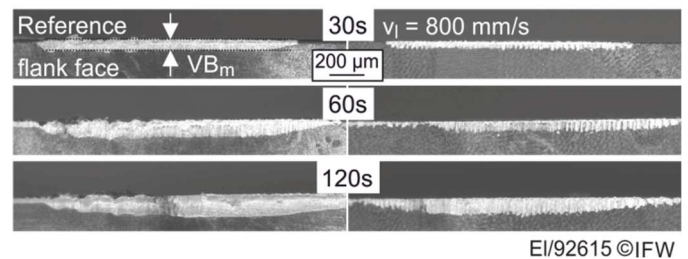


Fig. 6: Comparison of flank wear land progression for reference tool and laser prepared tool with $v_1 = 800$ mm/s

It can be seen that workpiece material adhesions are present on all cutting tools. Furthermore, the adhesion is lower for the laser prepared tools with $v_1 = 400$ mm/s and $v_1 = 800$ mm/s

compared to the reference tool. The resulting surface topography from PLA obviously reduces the frictional contact length on the flank face. In so far, this effect results in less adhesive wear compared to the smooth surface of the reference tool. Moreover, the effect of differing cutting edge geometries as shown in Fig. 3 might enhance the reduction of flank wear progression for laser prepared tools, because the contact length of the cutting edge rounding to the flank face is reduced [13].

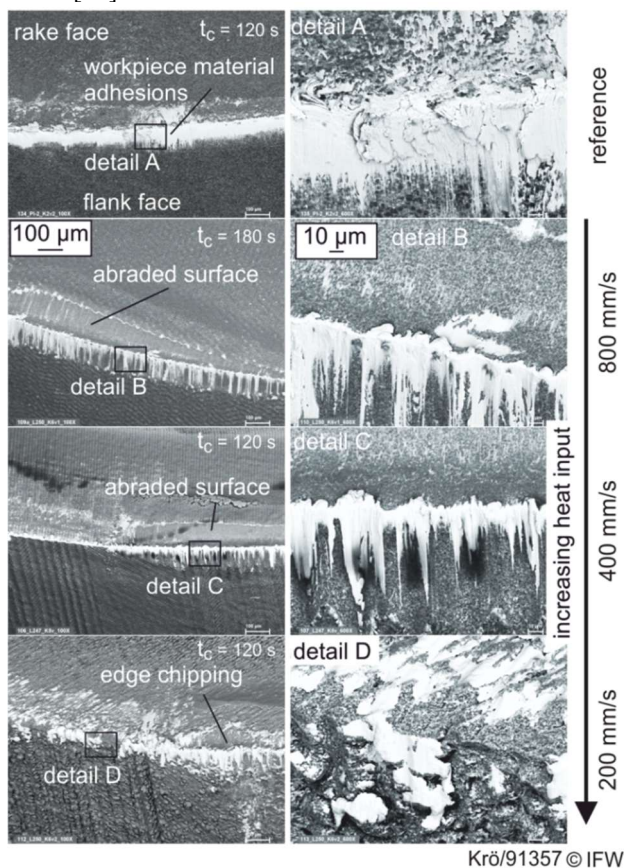


Fig. 7: SEM images of worn cutting edges

The results suggest that the microstructure of the prepared specimens on tool surface is the main reason for the wear decrease. In order to examine this assumption, force measurements were conducted with an unprepared tool and a laser prepared tool ($v_1 = 800$ mm/s). Figure 8 shows the average forces out of two measurements with new tools. It can be seen that all three force components decreased using the structured tool. This effect can be attributed to a decreased contact between tool and workpiece leading to reduced friction.

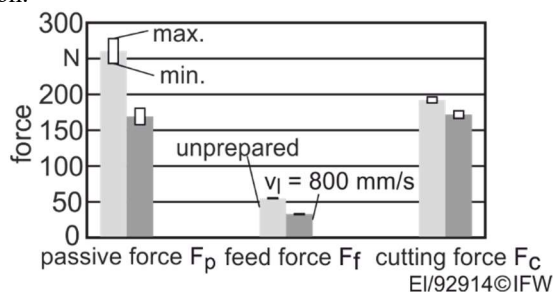


Fig. 8: Forces for reference tool and laser prepared tool with $v_1 = 800$ mm/s

4. Conclusions

Based on the presented results, the following conclusions can be drawn for PLA of PcBN tools:

- PLA of the cutting edge leads to increased surface roughness due to microstructure formation
- No changes in hardness due to PLA could be observed
- Cutting forces can be reduced due to microstructure formation
- Adhesive tool wear can effectively be reduced by the resulting surface microstructure
- PLA strategies with extensive heat input results in low surface quality and edge chipping in cutting experiments
- Further research needs to be conducted in order to separate microstructure from edge microgeometry effects

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