SEGMENTAL LASER STRIPPING OF THIN COATINGS ON MONOLITHIC CUTTING TOOLS

ADAM CERMAK[1], PAVEL KOZMIN[1], SIMON SYROVATKA[1,2], PAVEL ZEMAN[3], TOMAS PRIMUS[3]

[1] Research & Development, HOFMEISTER s.r.o., Pilsen, Czech Republic

[2] Department of Machining Technology, Faculty of Mechanical Engineering, University of West Bohemia, Pilsen, Czech Republic

[3] Department of Production Machines and Equipment (RCMT), Faculty of Mechanical Engineering, Czech Technical University in Prague, Prague, Czech Republic

This study outlines the methodology of the new approach of laser stripping technique in functional surfaces of monolithic cutting tools. Starting from the initialization test of the coating thickness using a laser calotest including beam-material interaction test, through the introduction of the main geometrical elements necessary for the analysis of the tool, the study discusses segmental laser stripping including its evaluation, where the effects of different segment modifications (overlapping, resizing, rotation or reordering) were investigated. The influence of the presented technology on the microgeometry of the tool was beneficial from several points of view: the area around the cutting edge can be influenced by the polarization of the laser beam and the resulting radius values show no negative influence of the substrate by the laser.

KEYWORDS

laser stripping, cutting tools, multi-axis analysis, advanced positioning

1 INTRODUCTION

The continuous pressure to increase production efficiency in many industries branches creates enormous demands on cutting tool manufacturers. Ensuring or extending the lifetime of the tool for these products can be achieved by so-called tool recoating. An old damaged coating can be restored by this process, which enables to achieve the original behavior of the cutting tool in the machining process, i.e. providing a thermal barrier, reducing the friction associated with and reduction in cutting forces [Denkena 2014]. A proper recoating process of cutting tools is preceded by the removing (stripping) of the damaged thin coating so that the original cutting tool properties (macro and micro geometry, material composition) are retained [Marimuthu 2019].

Currently, a renewing of cutting tools can be mainly processed by two types of stripping: chemical (as a conventional method) and ultra-short pulsed (USP) lasering. The former technology is inefficient due to many factors such as time consuming (stripping rate from 168-294nm/h) [Bonacchi 2003], leaching of cobalt binders, unsuitable for some type of coatings, nonenvironmentally friendly [Marimuthu 2010], and uneven coating removal [Marimuthu 2019]. The biggest advantage of this type of stripping lies in applicability to general surfaces. Another advantage may be that the stripped surface may in some cases have better adhesions for recoating [Tobola 2013], but this finding should be verified and compared in further experiments.

The second mentioned variant is a very precise technology, where the accuracy of the stripped thin coating is in the order of tens of micrometers (±0,5μm) in the case of long pulses τ_p = 10μs by study from [Zivelonghi 2017]. When USP lasers are used (τ_p > 10ps), the stripped layer is more accurate and no damage to the substate is observable [Marimuthu 2018]. Laser stripping is also advantageous in other aspects: suitability for problematic Diamond-like-Carbon (DLC, CVD-D) based coatings (due to nonmachinability by standard stripping techniques), the possibility of removal only upper layers from multilayer coatings, low durations of processes and applicability only to functional surfaces of cutting tools [Marimuthu 2010].

The paper by [Marimuthu 2010] solved a laser stripping in nanosecond regime (τ_p = 16ns, λ = 248nm) where a micro tool made of tungsten carbide WC with TiN coating with 2μm thickness was removed. This experiment was performed by continuous rotation of micro tool around its axis. Due to the small size of the micro tool (∅ = 0,5mm), it allowed to use the whole focal depth of the laser beam. Many studies also experimentally dealt with laser stripping by USP using only samples with planar surfaces [Kononenko 2000; Ragusich 2013; Zhou 2001].

The current disadvantage of laser stripping is its applicability on planar surfaces due to the small focal depth of the laser beam.

This paper describes the application extension of laser stripping technology to the functional (freeform) surfaces of monolithic cutting tools, thus eliminating its main disadvantage described above. We focused on investigation of the effect of method parameters on how to perform USP laser stripping of free form surfaces on monolithic cutting tools with impact on quality. TiAlN coating was chosen in combination of tool shapes and dimension of 8mm in diameter (multiple times larger size of tool diameter than the focal depth of laser beam) were selected for this study.

This proposed approach is necessary to be done as a first step of research. The application of the methodology for the paper is based on the authors' patent. The paper is mainly solving an impact of laser stripping segmentation by entities and its influence on stripping quality with regard to the assessment of tool microgeometries.

2 EXPERIMENTAL PROCEDURE

For proper implementation of laser stripping it is necessary to determine the coating thickness by a procedure called laser calotest developed by authors. This procedure is beneficial in two ways: the coating thickness is precisely inspected by a certain scanning strategy and laser fluence F, which is set slightly above the ablation threshold F_{th} of thin coating (can be also expressed by ratio F/F_{th} > 1). These data from laser calotest are also applied in the developed laser stripping method.

Figure 1 represents a methodical approach of laser calotest which begins with the ablation of a rectangle with the longest side in the X direction. When the first layer is ablated the algorithm shortens the longest side of a rectangle about a certain length and fabricates another layer. This gradual shortening of rectangle per each layer constrained to the one side (to the right – in Figure 1) creates "stairs". If sufficient amount layers for ablation are applied, then the laser ablation gets through the coating to the substrate (cut-section in Figure 1). After finding an interface between the coating and substrate the thickness of the coating can be determined.
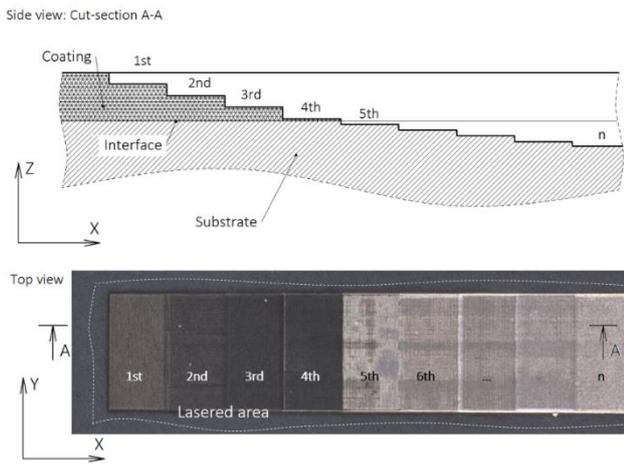
Figure 1. Schematic picture of laser calotest in 2D plane

For the purpose of laser stripping in free-form surfaces of monolithic cutting tools, the implementation of analysis for the circumferential part of tool geometry is conditional to the proper connection of stripped areas. Figure 2 represents functional surfaces (rake faces by dashed hatches, flank faces by cross hatches) of monolithic cutting tool on its circumferential and front areas, which have to be stripped.
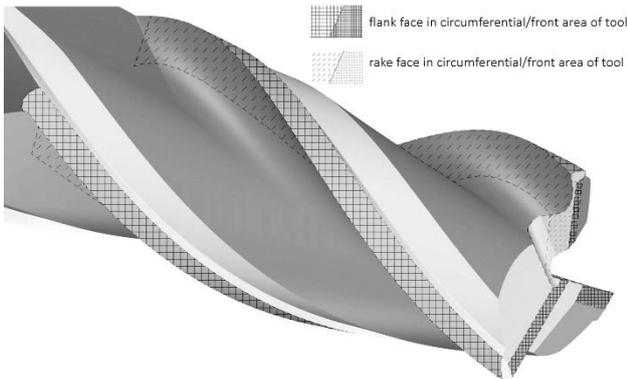

Figure 2. Schematic picture of functional areas in monolithic cutting tools

Mentioned analysis calculates a cutting-edge trajectory (Figure 3: dashed curve) for the multi-axis kinematics of the laser system, which enables to keep a relative position between the laser beam and functional surfaces, therefore the focal depth is kept in an appropriate range.

The analysis of the tool is carried out after clamping into the laser system. It takes place directly inside the laser workspace, the so-called in-machine measurement. During the analysis of the tool, the main geometric features such as diameters at the beginnings of flutes $\emptyset D_c$, diameters at the ends of flutes $\emptyset D_u$ and pitch ω are measured.
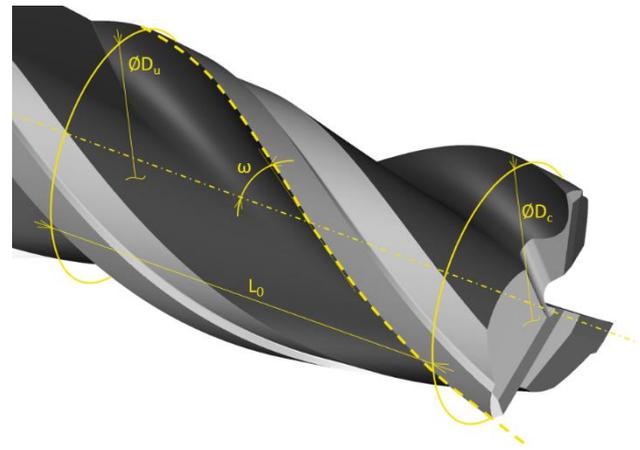

Figure 3. Definition of measured features for implementation of selective laser stripping

From these values a tool contraction ξ and technological approach in front of the tool are calculated. The firstly mentioned parameter can generally be expressed in length L_0 according to formula 1

$$\xi = \emptyset D_c - \emptyset D_u. \tag{1}$$

This analysis is applied to the circumferential part of the cutting tool, its flank faces (land widths) and the rake faces (bigger cross and dashed hatched areas in Figure 2).

3 EXPERIMENTAL SETUP

3.1 Laser system

A picosecond laser system was used for experimental investigation. Laser source (Atlantic, Ekspla) generates pulse length τ_p = 13ps with pulse repetition rate of 0,2-1MHz. The operating wavelength was used at 532nm with an output power of 12W. The optical path for the laser beam was equipped with rotators for circular/linear polarization, a beam expander and a power meter for precise setup of pulse energy. Laser beam guiding in quality of $M^2 \le 1,3$ was performed by a galvo-scanner with digital encoders (IntelliScan, ScanLab), further guided through F-theta telecentric lens with focal length of f = 160mm to the sample. The resulting laser beam spot size of the used setup was ~ 25µm. All data are presented in Table 1.

Table 1. Laser source and optical path characteristics

DPSS laser system	Data
Wavelength	532nm
Maximum pulse energy	60µJ
Pulse repetition rate	0,2-1MHz
Beam quality	$M^2 \le 1,3$
Polarization	circular/linear
Laser radius at 1/e² intensity	12,5µm
Focal length	160mm

The sample was clamped in a precise collet and positioned by multi-axis stages (Aerotech). Configuration of stages (axis X, Y, Z, A, C) with optical axes (U, V) of galvo-scanner corresponds to the Figure 4.
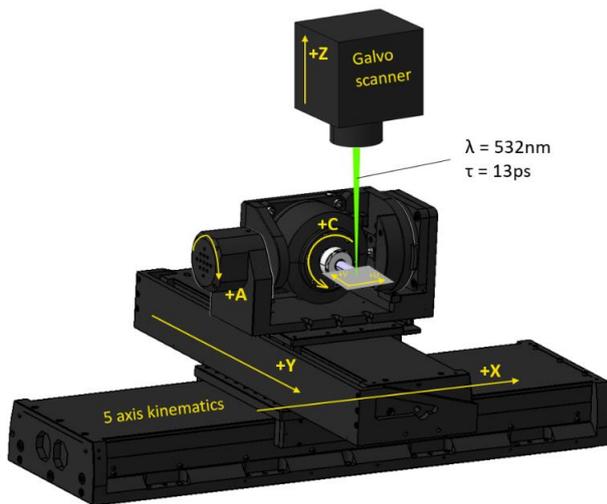
Figure 4. Scheme of laser kinematics

3.2 Cutting tool characterization

Selective laser stripping was applied to a cemented carbide (grade K20) milling cutter with 2 flutes about cutting diameter of 7,75mm and shank diameter of 8mm in tolerance h6. The angle of helix was fabricated at 25°. From view of microgeometry, an initial radius of the cutting edge (after deposition) r_β was 3,29µm. The milling cutter was equipped with TiAlN coating with the thickness of 2,45µm (measured by Alicona IFM G4, magnification of 1000x).

Table 2. Overview of cutting tool characteristic

Input parameters	Nominal values
Diameter of shank part (h6)	8mm
Diameter of cutting part (e8)	7,75mm
Count of flutes	2
Flute spacing	Regular
Angle of helix	25deg
Cutting length	19mm
Coating	TiAlN
Cutting edge radius	3,29µm

3.3 Principle of selective laser stripping of monolithic cutting tools

The principle of the presented methodology consists of the segmentation of the functional surfaces depicted in Figure 2 into stripped entities (full and doted rectangles in Figure 5), which must be appropriately set up for the final continuity of the result. With regard to the correct optimization of the segmentation, it is necessary to proceed from the analysis of the cutting tool after clamping in the working space of the laser system. The segmentation principle is shown in Figure 5a for the flank face and Figure 5b for the rake face. According to the analyzed cutting edge (bold dashed line), a stripped entity of size m_y x m_x is positioned on the cutting edge according to the reference point. After laser stripping of one entity, the cutting tool is shifted by multi-axis kinematics by the increment size d_t, which is a function of the detected parameters ω (helix pitch) and ξ (tool contraction) according to the geometry analysis. The start of the process is set in front of the cutting tool (parameter m_i, where $i = 1...n$), to the point where the bold dashed line begins. The resulting number of stripped entities is expressed as parameter m_n (where $i=n$), which depends on the size of the model in Y direction m_y, its rotation δ with respect to the X direction and increment d_t.

The main reason for changing the entity rotation by the δ angle is the assumption of increasing the step d_t in the Y direction, which may be preferred due to the limited focal depth of the laser beam. The stripping entities can overlap by the size of the d_Δ. This overlap setting is necessary to achieve continuity of stripped surfaces. However, the correct range of values is currently unknown and is therefore under investigation.

3.4 Devices for Experimental Evaluation

Two measurement devices were applied for experiment evaluation. An optical microscope (IFM G4, Alicona Imaging GmbH) was used for initial depth measurements of laser calotest and continuity assessment among segmented entities via profile measurement module. Edge Master measuring module (also IFM G4, Alicona Imaging GmbH) was used for edge radiuses evaluation. Measurements of deeper details, especially laser induced periodical surface structure (LIPSS) orientation, were performed by a 3D laser scanning microscope (OSL5000, Olympus).
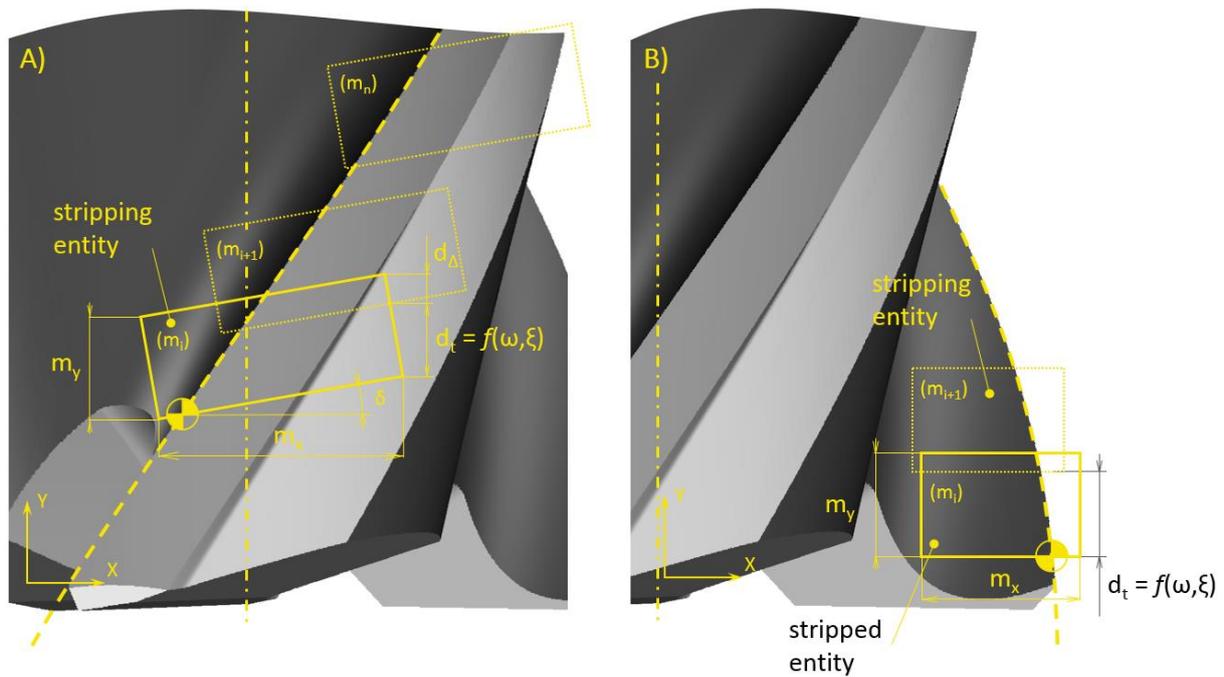
Figure 5. Principle of segmentation, when δ≠0° on flank face (a) and δ=0° on rake face(b)

4 RESULT AND DISCUSSION

4.1 Overlapping of Stripping Entity and its Impact on the Continuity

An effect of the difference in the m_y and d_t parameters on stripping continuity was experimentally investigated in this study. For certain overlap of stripping entities, a new parameter d_Δ (Figure 5) is used, which can be expressed as

$$d_\Delta = m_y - d_t. \quad (2)$$

Depending on the overlap size of the stripping entities, a uniform result can be achieved. If the value of the parameter $d_\Delta = 0$ (Figure 6a), a suitable connection can be achieved at the flank facet of the tool, but the minor flank face is stripped with visible errors (Figure 6a). If the value of d_Δ is too high (Figure 6c), then it also creates an undercut due to the big overlap of stripping entities. These undercuts can be expressed as z_{err} parameter, which is presented in Figure 7.
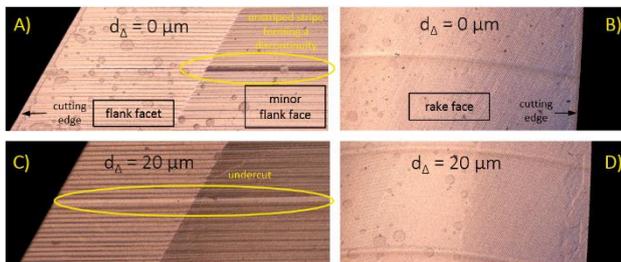

Figure 6. Effect of different parameter d_Δ for flank faces a) and c); for rake faces b) and c)

The detail of discontinuity on minor flank face (Figure 6a) is due to several aspects: the tool geometry at this point is a step change in the relative angle between the laser beam and the general surface of the tool, which is primarily aligned to the flank facet. The combination of this change and the applied laser fluence F, which is set slightly above the ablation threshold F_{th}

of the thin coating, results in a change in absorption at the edges of the stripping entities. By avoiding this discontinuity on the minor flank face, the parameter d_Δ is slightly increased so that the resulting undercut z_{err} (depicted in Figure 7) on the flank facet is negligible. In the case of rake faces, a similar approach is applied. If the fluent change of the relative angle is expected (regarding the tool macrogeometry), then parameter d_Δ can be closer to value of 0.
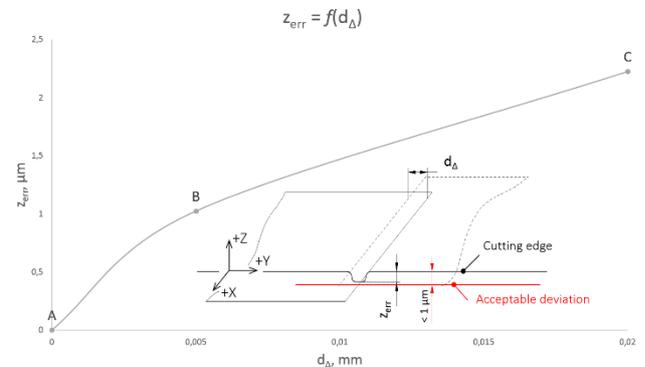

Figure 7. The dependence of the cutting edge discontinuity z_{err} on parameter d_Δ

The acceptable deviation in the cutting edge discontinuity z_{err} should be < 1 µm in the submicron region. Within this acceptable range, where points A and B are located (Figure 7), the cutting edge microgeometry of standard cutting tools is not affected.

4.2 Polarization Influnce on Micromeometry

When using a polarization during the USP laser processing in combination of applying gentle laser fluence F, the LIPSS is formed. The experiment verified the effect of polarization change on the cutting edge radius r_β. From the sample sets, three representatives were selected that contain circular polarization (CP) (Figure 8a) and two linear (LP) ones where the polarizations were oriented perpendicular (Figure 8b) and parallel (Figure 8c) to the cutting edge.
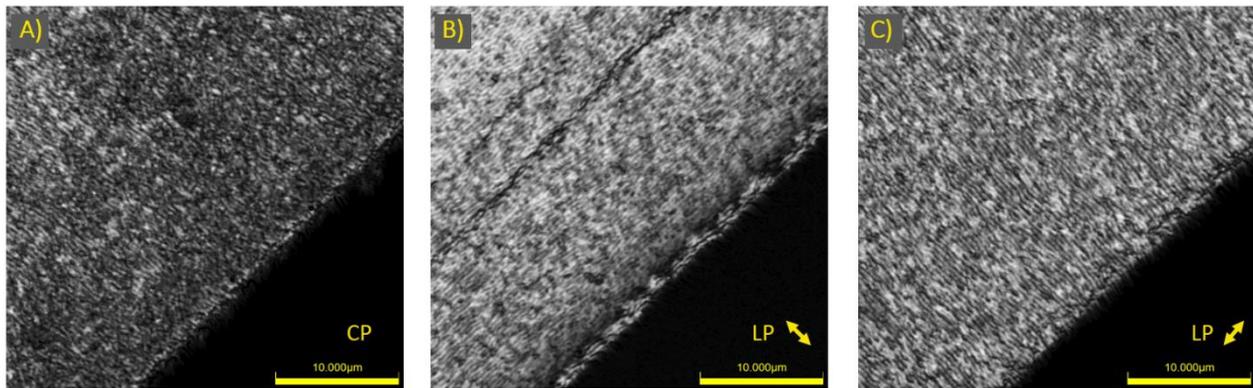
Figure 8. Details (magnification 9418x) of cutting edges (views of flank facets) and polarization directions

The formed LIPSS are nano-sized formations that do not affect the surface properties of the substrate and may have advantageous effects for further processing (coating) of the cutting tool. Verification of this hypothesis will be the subject of further experiments.

Main differences among tested sample and measured radiuses r_β are included in Figure 9, where two approaches of selective stripping were examined due to expected changes of radiuses r_β in stripping procedure. The flutes as A columns in Figure 9 were stripped from flank face at first and then from the rake faces. Flutes depicted as B columns show the opposite process strategy. Each assessed radius value is evaluated from 20 measurements by Edge Master with magnification of 500x (Alicona IFM G4).
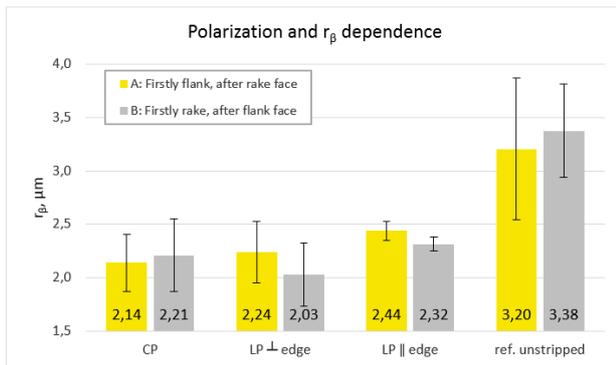

Figure 9. The dependence of stripped cutting edge radius rβ on used type of polarization on final value

Change of stripping process strategy did not show any significant effect on final cutting edge radiuses r_β. The displayed data show no correlation in favor of either process, but it would be useful to obtain data from a larger sample of tests for a closer assessment. The small difference between the stripped and unstripped radiuses r_β points to two possibilities: the coating was on the cutting edge of the tool with a significantly smaller thickness due to the physical vapor deposition (PVD) technology or the radius was affected (rounded) by the laser. These findings will be investigated and verified in future research.

4.3 The Effect of Stripped Entity Size

The necessity to increase model size m_y or rotate the stripping entity according to the δ angle (both characterized in Figure 5) arises from the requirements to reduce the duration of segmented laser stripping. For that case, three types of stripping entities (with constant areas) shown in Figure 10 were tested. The basic one with size m_{y1} (rectangle with full lines) had a halved dimension against the model with size m_{y2} (rectangle with dotted lines). The last tested model was m_{y3} (rectangle by

dashed lines), where rotation according to the helix angle ($\delta = \omega$) was applied. There is obvious a relative ratio among sizes in Figure 10, where $m_{y1} < m_{y2} < m_{y3}$ with the identical areas. The nominal sizes are summarized in Table 3.
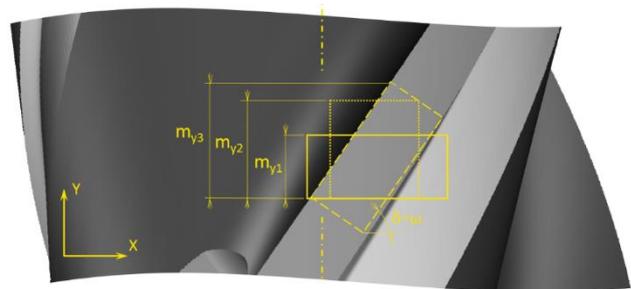

Figure 10. Types of the stripping entities

Table 3. The relationship between the entity size and relative time consumption

Input parameters	Nominal values	time consumption
m_{y1}	0,5mm	100 %
m_{y2}	1,0mm	69 %
m_{y3}	1,77µm	30 %

Increasing of model size brings a significant duration reduction needed for fabrication of whole cutting flute. The time consumption is summarized in Table 3.

Contrary to this finding, it is essential to keep the model size of the stripped entities in focal depth of applied optical setup relative to the general surfaces of the cutting tool. If curvature of general surfaces is out of focal depth, the laser fluence is rapidly decreasing and discontinuity of stripping entities occurs.

5 EVALUATION

Presented approach solves only the circumferential area of cutting tools, because the front area of the tool characterized in Figure 2 consists mainly of planar surfaces. Hence, there is no need to lead the laser beam along specific geometrical features, like flutes ground into the helixes. Due to the possibility to select only the functional surfaces (Figure 11a) the time for stripping can be dramatically shortened. A complete laser stripping can be also processed by the presented approach, which is shown in Figure 11b. In that case, the data obtained from tool geometry analysis is multiplied into a specific pattern copying the cutting edge trajectory.
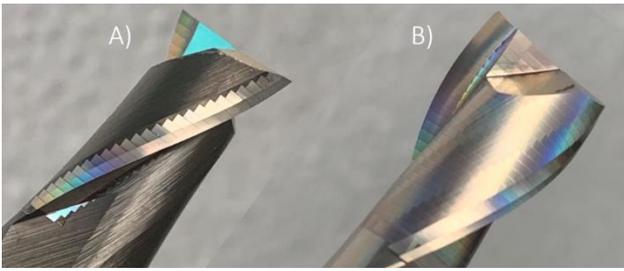
Figure 11. Example of stripped milling cutters, where only functional surfaces can be stripped (a) or whole cutting part of the tool (b)

6   CONCLUSION

This paper presents an ability to perform the laser stripping of TiAlN coating of general surfaces in monolithic cutting tools. Characterized method of segmental laser stripping by entities showed the way how to replace standard stripping techniques with a new one that offers many advantages (chemically free, low stripping durations, the possibility of precise positioning, option to strip any of thin coatings in case of multi-layer setup).

This study is focused on the intersection of certain limitations arising from optical setup of laser path and application of low laser beam fluences with complex macrogeometry of such cutting tools. The surrounding surface at the cutting edges and its microgeometry is essentially created and formed by LIPSS, which can be beneficially used in the next redeposition phase.

The ability to change the polarization and thus control the direction of LIPSS gives a new direction for further research and the potential to improve the adhesive-cohesive properties of recoated thin coatings in important areas on cutting tools. A further area of study would be to investigate the surface changes of the coatings in terms of chemical composition. This new method of laser striping has been in the patent process.

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CONTACTS

Ing. Adam Cermak, Ph.D.

Research & Development,

HOFMEISTER s.r.o.,

Daimlerova 9, 30100 Pilsen, Czech Republic,

cermak.adam7@seznam.cz, www.hofmeister-innovation.eu

Ing. Pavel Kozmin, Ph.D.

Research & Development,

HOFMEISTER s.r.o.,

Daimlerova 9, 30100 Pilsen, Czech Republic,

kozmin@hofmeister.cz, www.hofmeister-innovation.eu

Ing. Simon Syrovatka

Department of Machining Technology,

Faculty of Mechanical Engineering, University of West Bohemia,

Univerzitni 22; 301 00 Pilsen, Czech Republic

simonsyr@kto.zcu.cz, www.kto.zcu.cz

Ing. Pavel Zeman, Ph.D.
Department of Production Machines and Equipment (RCMT),
Faculty of Mechanical Engineering, Czech Technical University
Technicka 4, 166 07 Prague, Czech Republic
p.zeman@rcmt.cvut.cz, rcmt.cvut.cz

Ing. Tomas Primus
Department of Production Machines and Equipment (RCMT),
Faculty of Mechanical Engineering, Czech Technical University
Technicka 4, 166 07 Prague, Czech Republic
t.primus@rcmt.cvut.cz, rcmt.cvut.cz