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Multi-axis positioning approach for precise sharpening of monolithic cutting tools by USP laser processing

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Abstract

Laser processing of monolithic cutting tools is widely discussed in many research papers, where complete monolithic cutting tool (from stock material to final cutting tool) were processed. This kind of complete tool manufacturing is suitable only for microtools due to big processing durations.
Therefore, a new multi-axis positioning approach using a tangential laser processing was designed. This approach consists of algorithms for detecting of flute parameters for multi-axis trajectory and laser processing. Superstructure of multi-axis positioning approach lies in its automation, where a recognition interface is used. This extended property of flute detection, using features of analytical geometry, makes implementation of USP laser processing into production chain more convenient. This multi-axis positioning approach is suitable for precise sharpening of cutting edges of ground monolithic tools made of cemented carbides, where cutting edge radiuses are limited by grain size of substrate. It is also applicable on preparation of thin coated layers (e.g. CVD-D). Cemented carbide as a cutting material, CVD-D layer as a thin coating and different approaches of laser beam to the cutting edges were considered. A lot of variables of tangential laser processing were examined in experiments. After optimal setting of laser parameters prepared cutting edge radius r_β could be reached under 2µm and roughness of new facet is smaller than $R_a < 0.2$µm.

Keywords: axes synchronization, precise microgeometry, cutting edge preparation, USP Laser

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1. Introduction

Precision of macrogeometry and microgeometry manufacturing of cutting tools is an essential for their final behavior in cutting process. These macrogeometry and microgeometry preparations, especially of indexable cutting inserts, are described in many research papers [1-5]. On the other hand, a few papers [6-9] are representing a complete manufacturing by combination of radial and tangential laser micromachining. Last mentioned way of manufacturing of cutting microtools requires a high level of kinematics and laser optics synchronization. However due to big durations of manufacturing [8], where drilling microtool with cutting length of 5mm and diameter of 2mm was manufactured in 4 hours, this technology is affordable only for monolithic cutting microtools.

On basis of previous paragraph, where a laser micromachining of already ground monolithic cutting tools was missing, a new method of multi-axis positioning approach for laser micromachining of conventional ground monolithic cutting tool was designed by authors.

If the monolithic cutting tools are manufactured by conventional grinding, created shape deviations of ground general surfaces are bigger than geometrical entities made by laser micromachining. These shape deviations of created general surfaces cannot provide the constant relative position between laser beam and monolithic cutting tool, which is unconditional for technology of laser micromachining and achieving of constant geometrical preparations in whole cutting length of monolithic cutting tool. Therefore a method of multi-axis positioning approach was developed. According to this designed method, the constant relative position between laser beam and general surface of monolithic cutting tool is kept.

Another motivation for design of new multi-axis positioning approach is to get a better implementation of laser micromachining into production chain of monolithic cutting tools with higher efficiency, fast and accurate investigation of flutes geometry, new kinds of cutting tool preparations and synchronization up to 4 mechanical and 2 optical axes, which can open up new application ways.

2. State of the art

2.1. Initial state of multi-axis positioning approach

First design of multi-axis positioning approach, where a trajectory of one flute solved by manual measurement and investigation, was very time consuming. In first step, algorithms with basic calculations of trajectory were programmed by authors, where obtained values were logged into text files. This information was taken into next steps, where served for next calculations creating a trajectory. Sequence of these steps and their process of analysis are shown below:

1. Tool axis investigation
2. Pitch of helix investigation
3. Investigation of tool contraction
4. Calculation of initial point in front of tool
5. Algorithms for micromachining process

First four steps are used for investigation of kinematic parameters of trajectory, which specified precise helix trajectory of one cutting edge. Fifth step contained a basic core of micromachining process. The data from all previous steps were being processed in it. Final result of initial state did not contain algorithms, which were able to automatize this analysis procedure. Positioning data in these steps were set and corrected manually, therefore an achieving of precise parameters of cutting edge trajectory was very time consuming.

2.2. Automation of multi-axis positioning approach

Another development direction of these state, in this realization called sub-programs, was their extension. The aim of trajectory analysis was an automation of algorithms, where recognition interface is used. This expanded property of multi-axis positioning approach made a monolithic cutting tool preparations more effective, improved repeatability and mainly reduced analysis times, where more than 90% of time was reduced against manual investigation.

This time reduction greatly simplified an implementation of (macro/micro) geometrical preparations on monolithic cutting tools. Advanced analysis of trajectory contained a group of sub-programs, where data from recognition interface (RI) were processed and evaluated by designed algorithms. Data accuracy are influenced by correct setting of boundary conditions of RI, which were consisting of correct defining of searched elements (lines, radiuses) including their exposure conditions for getting of appropriate contrast (e.g. edge/flute). Complete advanced analysis is created by 5 sub-programs. All 5 sub-programs are merged together into one program, where input data are entered only from drawings. Input data needed for programs are:

- Diameter of shank part
- Diameter of cutting part
- Count of flutes and their regular/ irregular spacing
- Angle of helix
- Length of cutting edge

2.3. Final state of multi-axis positioning approach

Last state of multi-axis positioning approach is getting a better efficiency of geometry analysis, where algorithms were extended by random number of flute, depending on geometry of monolithic cutting tool. Trajectories of all flutes of monolithic cutting tools are analyzed and assessed by this final solution. In this case, design of all sub-programs is generalized, which offers a choice between regular and irregular flute spacing. Data recording among individual sub-programs is made into matrix structures. This data recording can be solved by available ways e.g. recording in text files or random access memory (RAM). In next paragraphs, the final state of multi-axis positioning approach is characterized.

3. Principle of multi-axis positioning approach

3.1. Defining points for multi-axis positioning approach

This methodical approach consists of designed points. According to these points, which are investigated by sub-programs, precise values of trajectory for each flute are obtained. These designed points are depicted in figure 1. Basic sequence of monolithic cutting tool analysis is shown. At first, a tool axis in shank part is investigated. In next step, position of points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$ are solved in tool axis, then points $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$ on tool diameter. Finally trajectories of flutes are extended by distance K_y according to laser micromachining purposes. For each designed point (from $\boldsymbol{A^0}$ to $\boldsymbol{E}$) data about absolute coordination of rotation axis are recorded. This is needed for trajectory investigation of current flute.

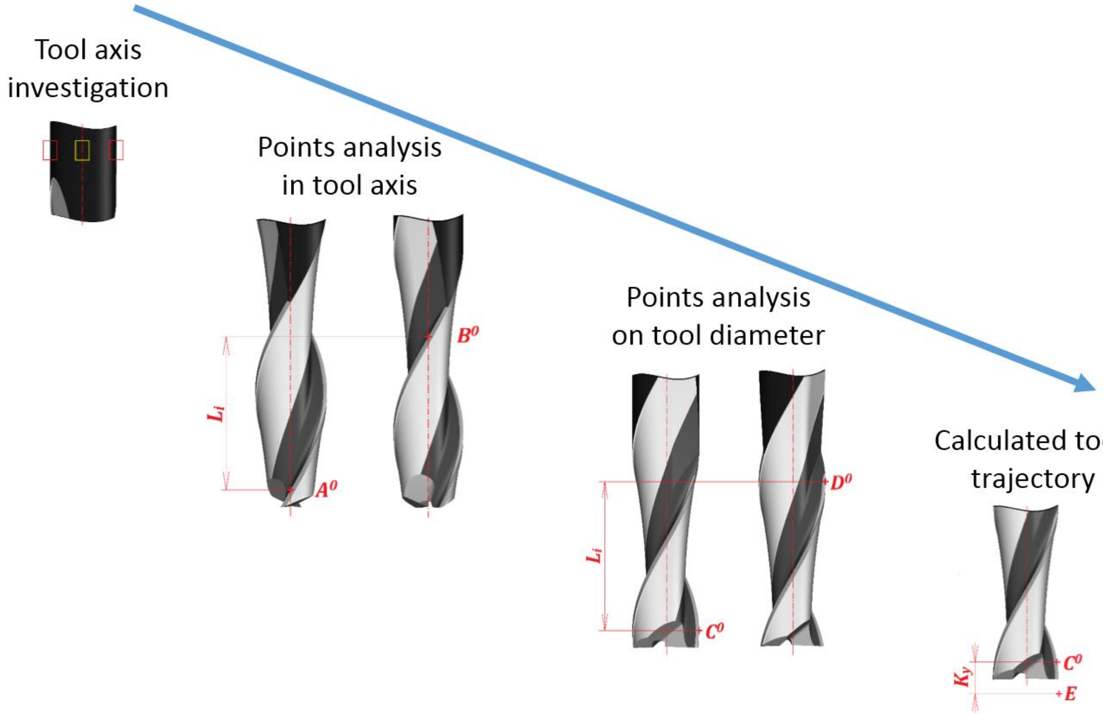

Fig. 1. Defined points for trajectory investigations for all flutes of monolithic cutting tools

3.2. Investigation of real pitch for all flutes

Real pitch for each flute is calculated from points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$, which lie on tool axis. Before pitch calculation, it is unconditional to investigate these points. Points are marked by upper index. Index 0 means intersection, which is calculated from recognized data of lines (index 1 – white line in figure 2) and specified data of lines (index 2 - yellow line in figure 2).

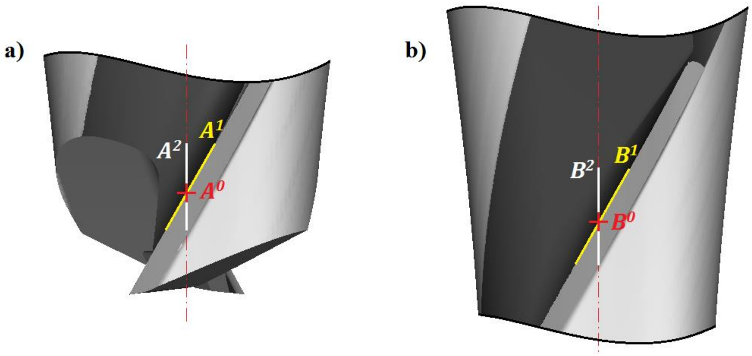

Fig. 2. Calculated intersection points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$ for real pitch calculation

According to these points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$, data about real cutting length for each flute L_i, rotation between these points for each flute $Rot_{rel,i}$ and real pitch for each flute p_i is investigated. In next characterization, abbreviation n is used for count of analyzed flutes.

$$L_i = \begin{pmatrix} L_1 \\ \vdots \\ L_n \end{pmatrix}, \text{ where } i = 1 \dots n. \tag{1}$$

$$Rot_{rel,i} = Rot_{abs,i}{}^{B} - Rot_{abs,i}{}^{A} \tag{2}$$

$$p_i = L_i \cdot (360/Rot_{rel,i}), \text{ where } i = 1 \dots n. \tag{3}$$

3.3. Investigation of tool contraction

In next phase, next points are investigated on tool diameter, especially points $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$. After their investigation a tool contraction for each flute is calculated. Figure 3 shows, that points $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$ are calculated from two kinds of lines again, as previously in points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$.

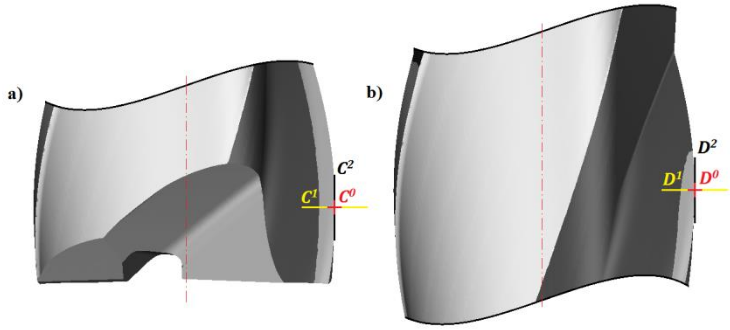

Fig. 3. Calculated intersection points $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$ for tool contraction

According to these investigated points $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$, tool contraction for each flute ζ_i is investigated. Final calculated data are shown below.

$$\zeta_i = \begin{pmatrix} \zeta_1 \\ \vdots \\ \zeta_n \end{pmatrix}, \text{ where } i = 1 \ldots n. \tag{4}$$

3.4. Defining of initial point of trajectories

After trajectory investigations of each flute between points $\boldsymbol{A^0}$ and $\boldsymbol{B^0}$, respectively $\boldsymbol{C^0}$ and $\boldsymbol{D^0}$, a calculation of initial point ***E*** (figure 1) can be performed. Final position of point ***E*** is situated according to laser micromachining purposes. If a chip breaker preparation is processed according to this trajectory, point ***E*** must be defined on monolithic cutting tool. If a precise sharpening preparation is processed according to this trajectory, point ***E*** must be defined in front of monolithic cutting tool as a technological approach of laser beam. After defining of K_y value, parameters of calculated trajectory are investigated

$$\zeta_{cal,i} = K_y \cdot tg\left(\frac{\zeta_i}{L_i}\right) \text{ where } i = 1 \ldots n, \tag{5}$$

$$Rot_{cal,i} = \frac{K_y}{p_i} \cdot 360, \text{ where } i = 1 \ldots n. \tag{6}$$

After that, an initial point ***E*** (7) with absolute value of tool rotation $Rot_{abs,i}{}^{E}$ (8) and trajectory data for each flute ***T*** (9), distance between points ***E*** and $\boldsymbol{D^0}$, are calculated.

$$E = \begin{pmatrix} X_1{}^{C0} - \zeta_{cal,1} & Y_1{}^{C0} - K_y \\ \vdots & \vdots \\ X_n{}^{C0} - \zeta_{cal,n} & Y_n{}^{C0} - K_y \end{pmatrix}, \tag{7}$$

$$Rot_{abs,i}{}^{E} = \begin{pmatrix} Rot_{abs,1}{}^{A} + \frac{\pi}{2} + Rot_{cal,1} \\ \vdots \\ Rot_{abs,n}{}^{A} + \frac{\pi}{2} + Rot_{cal,n} \end{pmatrix}, \tag{8}$$

$$T = \begin{pmatrix} \zeta_{celk,1} & L_{celk,1} & Rot_{celk,1} \\ \vdots & \vdots & \vdots \\ \zeta_{celk,n} & L_{celk,n} & Rot_{celk,n} \end{pmatrix}. \tag{9}$$

4. Precise sharpening of monolithic cutting tools according to multi-axis positioning approach

After analyzing of all flutes according to multi-axis positioning, nonstandard geometrical preparations in field of monolithic cutting tools can be performed by tangential laser micromachining. After achieving of a constant relative position of laser beam and general surfaces, precisely sharped cutting edge with constant facet width can be manufactured. In this case, tangential laser micromachining has many benefits. Some of them include the fact that finalized sharpened cutting edges have lower values of cutting edge radiuses r_β and have qualitatively better surfaces than origin ones. This is caused by principle of material removal by laser. If the cutting tool (e.g. made of cemented carbide) is prepared by abrasive way of material removal (e.g. soft grinding), the carbide grains are ripped out of cobalt binder [10]. From this reason, the value of cutting edge radius r_β is significantly influenced by grain size of substrate.

In case of cutting edge preparation by tangential laser micromachining it is possible to get better values of r_β, because laser beam does not affect the carbide grains by any forces. Therefore there is no effect of unwanted ripped grains from substrate. When selecting an appropriate processing parameters of the laser beam (e.g. laser fluence F and scanning strategy of laser beam), the carbide grains are cut without unwanted oxidation of the substrate.

4.1. Experimental setup

For experimental investigation of precise sharpening a 6 fluted monolithic cutting tool was examined. Substrate of this monolithic cutting tool is made of cemented carbide with 91% of WC and 9% of Co binder, where grain size is around 1μm. There are input parameters of monolithic cutting tool in table 1.

Table 1. Input parameters of monolithic cutting tool

Input parameters	Nominal values
Diameter of shank part	10mm
Diameter of cutting part	10mm
Count of flutes	6
Flute spacing	Regular
Angle of helix	45deg
Cutting length	22mm

Due to used substrate with fine grain size and combination of smooth grinding, the final cutting edge radiuses were $r_\beta = 3.5\ \mu m$ and profile roughness of flank faces $R_a = 0.4\ \mu m$ after grinding. A five-axis kinematics with precise positioning accuracy, a DPSS laser with ultrashort pulse length of 11ps were used. Another details of laser system configuration are shown in table 2.

Table 2. Details of laser micromachining system

DPSS laser system	Data
Wavelength	532nm
Maximum pulse energy	60µJ
Pulse repetition rate	0.2-1MHz
Beam quality	$M^2 \leq 1.3$
Laser radius at $1/e^2$ intensity	12.5µm
Focal length	160mm

4.2. Experiment results

A dynamic scanning strategy of laser beam was made by wobbling, where circular strategy with certain values of amplitude and frequency were set. At first, an influence of laser pulse energy E_p on oxidation of WC grains was investigated. An extent of $5\mu J < E_p < 50\mu J$ was chosen and results were assessed by EDX analysis. Results of cut grains are depicted in figure 4.

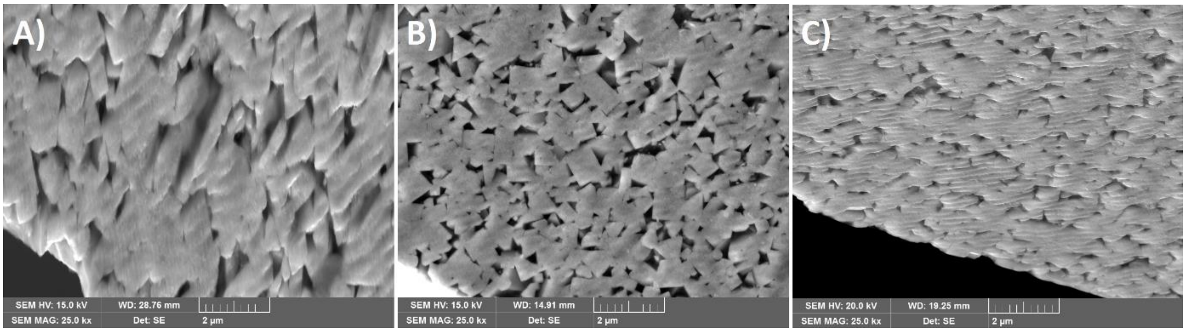

Fig. 4. Influence of laser pulse energy on quality of carbide grain cut: a) $E_p = 5\ \mu J$; b) $E_p = 25\ \mu J$; c) $E_p = 50\ \mu J$

According to fig. 4a, grains were not cut clearly due to low pulse energy – $E_p = 5\mu J$. In fig. 4b, where $E_p = 25\mu J$ was used, boundaries of grains are clearly visible. In both cases a minimal oxidation of grains against reference ground surface had occurred. In last example, depicted in fig 4c, the highest value of pulse energy $E_p = 50\mu J$ was used. The boundaries of carbide grains are smoothed due to high pulse energy. There is the biggest relative oxidation of WC with smallest amount of Co binder, which is inappropriate for further cutting process due to unwanted brittleness of cutting edges.

On basis of this EDX analysis, other process parameters, especially influence of polarization and wobble parameters, were investigated. Value extents of these parameters were chosen with respect to get sufficient cutting edge parameters with negligible material oxidation. These cutting edge parameters are: cutting edge radius r_β, K factor and profile roughness of flank facet R_z. Final results are depicted in fig. 5, where dependences of laser setting on influencing of cutting edge parameters were investigated.

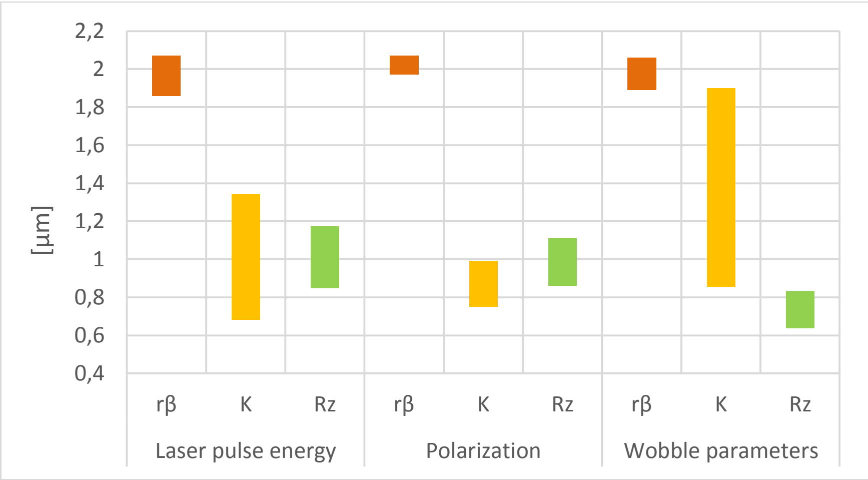

Fig. 5. Dependence of process parameters on cutting edge microgeometry

According to examined parameters of laser processing and cutting edge in fig. 5, a final experiment on 6 fluted milling cutter was performed. Input data of monolithic cutting tool are noted in Table 1. The final cutting edge radiuses, after grinding, were r_β = 3.5 µm and profile roughness of flank faces R_a = 0.4 µm. After precise sharpening, widths of facets 0.13 – 0.16 mm were obtained with using of multi-axis positioning approach. The final lasered cutting edge radiuses have values in extent of 1.85 – 2.05 µm and K factor 1.01 – 1.2. Created flank facets have profile roughness in extent of R_a = 0.08 – 0.12 µm. Both states, before and after laser micromachining, are depicted in fig. 6. Assessment of cutting edge parameters were performed by Alicona IFM G4.

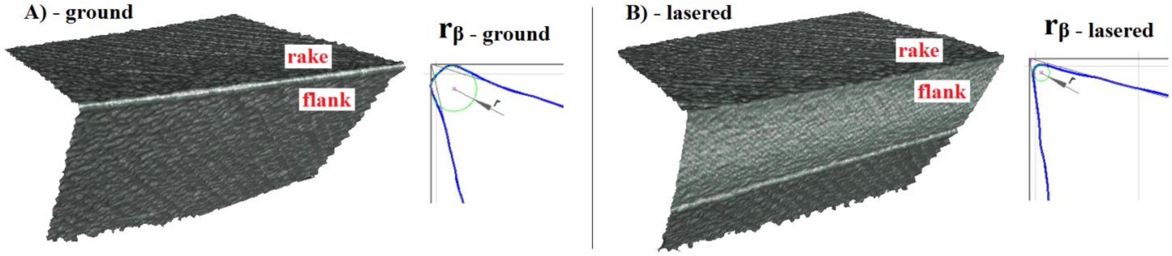

Fig. 6. Comparison between ground cutting edge (A) and lasered one (B): magnification 500x

5. Conclusion

The multi-axis positioning approach enables a higher application potential of laser micromachining in field of monolithic cutting tools. Time reduction of designed approach was achieved with sufficient repeatability of flutes analysis. As an example: 6 fluted milling cutter is analyzed by this designed approach in 2 minutes. Other characterized goals in the introduction of this paper were obtained, therefore a better implementation of laser micromachining into production chain of monolithic cutting tools is ensured. Precise sharpening technology by laser tangential micromachining is suitable for various types of cutting material.

Experiment of precise sharpening according to multi-axis positioning approach was performed on 6 fluted monolithic milling cutter made of cemented carbide, where better cutting edge parameters were observed. Cutting edge radiuses were under $r_\beta < 0.2$ µm and profile roughness of lasered facets is under $Ra < 0.12$ µm. Designed multi-axis approach can provide a synchronization up to 4 mechanical and 2 optical axes, therefore a next authors' goal is to apply the described approach into general multi-axis laser micromachining.

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