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Laser drilling of micro-holes in cutting tools

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Abstract

The cutting tool is a key element in the milling process; it determines the process performance and the quality of the machined pieces. For best performance, cutting fluids are applied as close as possible to the area between the tool and the work piece. Its primary functions are chip evacuation, cooling of the tool and piece as well as lubrication. Recent developments allow the injection of the fluid through the spindle, the tool holder and finally through a central hole in the cutting tool. For tools with large diameters (> 6mm) one or several central straight channels are used. For tools with small diameter (< 1 mm) no technology exists so far to lubricate the individual cutting edges, at best the internal channels end at the cone of the shank, well before the active cutting part. Due to the limited available space and not to weaken the tool stiffness, lateral holes of a diameter of about 0.1-0.3 mm are required. The position, diameter, shape and angle of these holes have been optimized by means of complex CFD fluid simulations.
A 10 pico-second laser was used for drilling the holes in order to avoid thermal impact in the tungsten cobalt (Wc-Co) – hard metal that would occur using other methods like EDM-drilling. For the milling tool of Ø 1.0 mm, the lateral holes have a diameter of 0.12 mm and, for the milling tool of Ø 2.5 mm, the lateral holes are Ø 0.3 mm. The diameter of the central blind hole is identical for both tools, i.e. Ø 0.3 mm. The paper focuses on the hole trepanning technology, i.e. the parametrization of both the laser and the scanner.
The tools developed were tested by processing stainless steel with injection of a water based emulsion as cutting fluid with 20 bars through the tiny channels. A significant increase in the tool lifetime as well as an improved surface quality have been observed.

Keywords: Laser machining ; cutting tools; micro-holes

1. Introduction

There is a continuous demand in the manufacturing industry to improve cutting performance, to decrease costs as well as to reduce environmental impact. This requires the development of cutting tools with increased lifetime and performance as well as the optimization of process strategies. During the cutting process special cutting liquids are injected to cool down the cutting tool and the machined work pieces, to remove the cutting chips and to reduce friction between the tool and the machined surface, and also to avoid adhesion of material on the cutting tool, thus increasing tool lifetime and cutting performance and reduce energy consumption [1].

So far, for small tools (< Ø 3mm), massive flushing technique with external nozzles close to the machining area are used [2]. To get the most benefit, the liquid should be injected exactly at the machining point, i.e. the cutting edge. This is achieved by using internal channels inside the cutter, ending as close as possible to the cutting edge. With such a configuration, one can get a low cutting fluid consumption as well as an

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efficient cooling power in the milling process. The cutting fluids are a mixture of oil and water and are harmful for environment. Small quantities of the cutting liquid injected through the internal tool channels will evaporate at the heat source, i.e. cutting zone. Evaporation will absorb much more heat energy than a heat exchange process of liquids, i.e. a massive flushing of the tool. In the later case, powerful chillers are normally used to cool down the liquid to ambient temperature (to guaranty machine precision), and the energy consumption can reach levels similar to those of the cutting operation [3], [4]. The liquid should be injected as close as possible to each cutting edge [5] (typically 3 cutting edges for small tools), the exact position is optimized by fluid analysis. This analysis takes into account the geometry of the tools as well as the machining speed (typically 10-20'000 rpm.) Unfortunately, the hard base material of the tool, as Wc-Co, requires advanced machining technologies to obtain tiny and very precise holes in the cutting tool. Conventional drilling is not possible due to the small size and the hardness of the tool. Electro-discharge machining (EDM) could be used, but it will create a heat affected zone, thus weakening bulk material. In [6] it has been shown that short pulse laser machining is able to remove the EDM created HAZ-zone without generation of micro cracks. The lifetime of textured cutting tool using ps-LASER even increased [7].

This paper describes a method based on laser trepanning using a 10 ps laser to drill a lateral hole at the tool tips. For small milling tools (Ø 1.0 mm) the holes have Ø 0.12 mm, and for larger ones (Ø 2.5 mm) the holes have Ø 0.3 mm at a milling tool. These lateral holes are blind holes joining a central blind hole of Ø 0.3 mm (same for small and large tools). FEM-fluid analysis determines the exact position of the holes and the drilling angles. The central blind hole ends close to the tool tip. Cooling liquid is injected at 20 bars through this central hole and flows through the lateral holes. Due to the improved cooling the thermal diffusion between the cutting edge and the material is drastically reduced, leading to an up to 4 times improved tool lifetime for stainless steel milling.

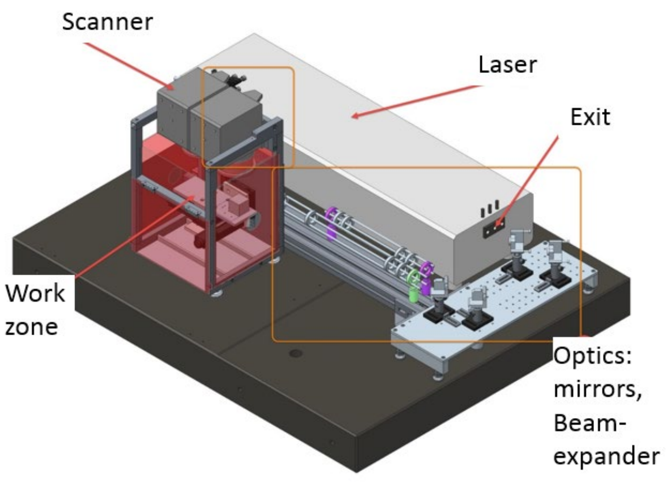

Fig. 1. Set-up laser system.

2. Experimental work

2.1. Equipment

A commercially available laser, Ekspla Atlantic series, emitting 1064 nm, frequency doubled, i.e. 532 nm radiation, is used in experiments. The laser generates 10 ps long pulses at repetition rates of 100 kHz. The maximum output power goes up to 8 W at 532 nm, M2 =1.5.

The laser beam is expanded to a diameter (D) of 10 mm and directed to the galvoscanner intelliScan 14 (ScanLab). Laser radiation is focused on the sample by a telecentric lens with focal length (f) of 100 mm. The measured spot size ($d= 2\omega_0= M^2 *4 *f*\lambda/D$) is approximatively 12 µm. According to the theory, d should be about 10 µm and the depth of focus (DoF) about 200 µm ($DoF= M^2*8*f^2*\lambda/D^2$). The scanner is controlled using SAM Light software (Scaps). All elements i.e., laser; optical elements and scanner are installed on a granite table (Fig. 1).

Laser power is measured at the machining table after the f-theta-lenses of the scanner, (as well as directly at the laser exit using an Ophir PA12 power meter, having a power range from 2 mW up to 12 W and an accuracy of +/- 3 %.

A special work table was designed, able to position a rod-shaped tool at variable angle, typically 45° and to rotate the tool 360° around its axis Fig. 2(a)). The desired angle is manually adjusted using a rotation table (Standa). The tool- rod is fixed on a exchangeable interface (to adjust for tool diameter) which is mounted on a motorized rotation stage (Standa motorized Rotations Stage 8Mr174-11-20 combined with Mini Rotation Stage 7R7E) giving an angular resolution of 0.9 arcmin (0.015°)). This installation is placed on a motorized ball screw translation stage (Altechna 8MT167) having a repeatability of 1.5 µm. Thus the working distance in the vertical z direction and the rotation movement can be modified via computer control. A digital camera microscope (Dinolite) is used to align the milling tools (Fig. 2(b)).

A computer tomography (RX) allows the control of the geometrical intersection of the drilled channels for the 1.0 mm tools of Wc-Co as well as for rods of different material and larger diameters. In fact, due to the high Z-value of tungsten, the X-rays get absorbed very strongly for diameters > 1 mm, limiting a 3D reconstruction.

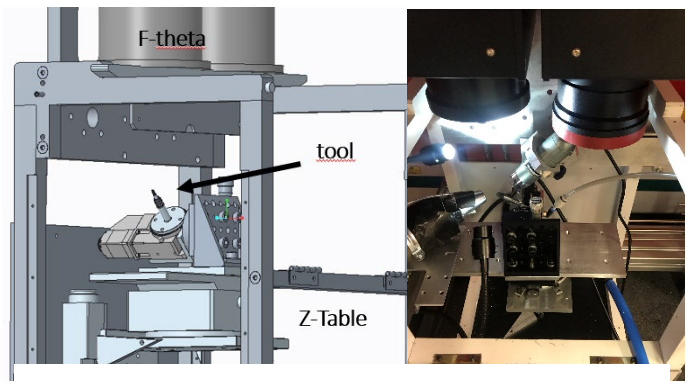

Fig. 2. Work table of laser system (a) design; (b) with camera.

2.2 Geometry of holes and fluid calculations

We selected two sizes of standard small milling cutting tools from the Swiss manufacturer Eskenazi, both made of tungsten carbide (typical grain size 0.8 µm and 89% Wc, 10 % Co binder). The tools have diameter 1.0 mm and 2.5 mm (shank diameter 3.0 mm for both) and both have three cutting edges arranged symmetrically at 120°. Both tools have a central blind hole of diameter 0.3 mm made before the processing of the final tool by patented sintering process [patent] in the rod bar.

These tools are scanned (using a CT-scanner) to obtain a CAD model used for Fluid-dynamic simulations using ANSYS Fluent (Release 17.2). The details of these simulations will be the object of a separate publication. A similar topic is studied in [8]. The results of this study are presented here after:

For the Ø 2.5 mm tool, the three lateral holes of Ø 0.3 mm have to be drilled at an angle of 45° starting at the vicinity of the cutting edges and joining the central blind hole of Ø 0.3 mm. For this configuration, a debit of about 40 ml/min and a pressure drop of about 5 bars (at typical spindle speeds of 10-15'000 rpm) are applied.

For the Ø 1.0 mm tool, the three lateral holes have Ø 0.12 mm, and joining the central blind hole of Ø 0.3 mm at an angle of 45. Here a debit of 4.5 to 6.4 ml/min was achieved for rotation speeds between 25-35'000 rpm and pressure drop of 0.2 to 0.8 bars. These values have also been verified by measurements.

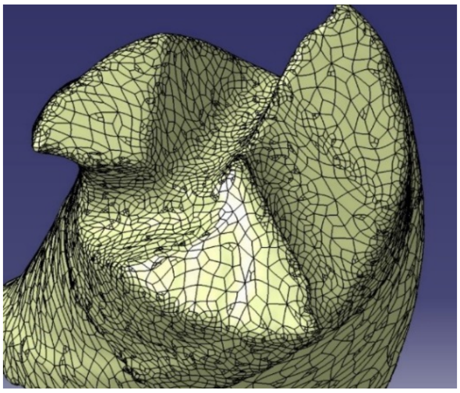

Fig. 3 CAD Model of milling cutter based on CT-Scan

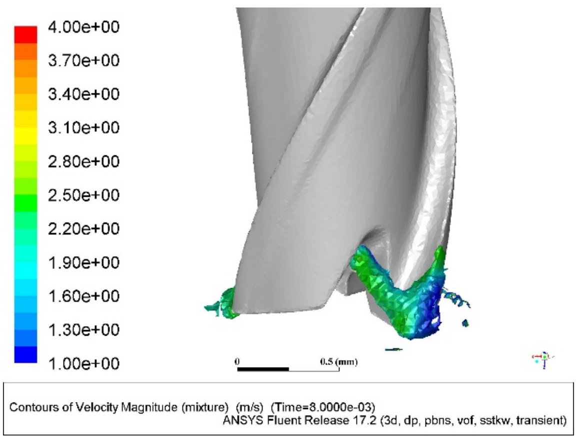

Fig. 4. FEM simulation with a flow rate of 4.5-6.4 ml/min at 25'000 rpm for tool of Ø 1 mm with three lateral holes of Ø 0.12 mm.

2.3 Pre-test and material

To optimize the laser machining parameters, samples of section 1x1 mm were manufactured by WEDM, made of WC, EMT210 grade from the Swiss manufacturer Extramet (https://www.extramet.ch/). This grade has an average grain size of 0.8 µm, 10% cobalt, 89% WC and 1% are other carbides. This composition is identical with the one of the final milling tools. Through-holes of Ø 0.3 mm and Ø 0.2 mm are drilled (Fig. 5). The CT-X-ray figure picture a taper effect, i.e. the correct and measured entry diameter (0.3 mm / 0.2mm) was reduced by about 20% at the exit of hole when applying standard laser machining strategies. The limited depth of focus and shadowing causes this. In the following a strategy is described, which reduces these effects.

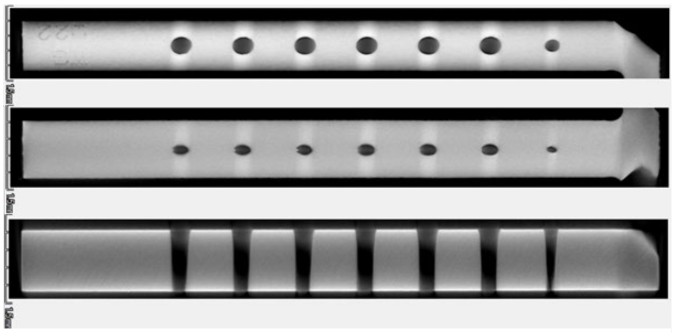

Fig. 5. CT scan of Ø 0.3mm holes drilled in 1 mm thick plats: (top) entry holes, (middle) exit holes, (bottom) cross section, (right) hole of Ø 0.2 mm.

2.4. Calibration of focus

On contrary to laser machining of flat samples, the adjustment of distance for inclined, cylindrical rods is more complex. The intersection of the laser beam (with a spot size of about 12 um) with an inclined (angle of 45°) and round piece is an ellipse which does not some focal distance all over. This ellipse represents the entry surface of the hole to be drilled. The ground flute and the high reflecting surface of the tool make the focal alignment even more difficult. Thus, pins of similar length as the milling tool are used. They are marked with a cross (horizontal lines are much shorter). The center of the cross represents the (0;0) coordinates of the system, i.e. position of the center of the lateral holes. In a second step, the pin is turned by 15° and vertical height changed by 0.1 mm (table moved in z-direction). The whole steps are repeated 21 times to cover a range of 2 mm.

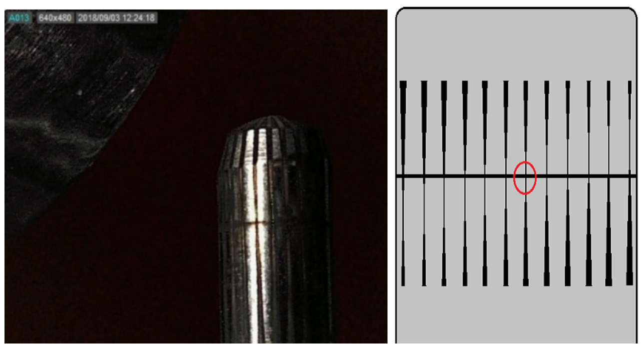

Fig. 6. Calibration of focal distance on inclined pin.

By looking on theses thickness of the longitudinal lines, at the intersection with the horizontal line, the ideal focal distance, e.g. table height z could be found. The line with smallest thickness at the intersection with horizontal line corresponds to the best focal distance value. Using trigonometry and the geometry of the milling tool (CAD model) this ideal position could be projected to milling tool and thus the center of starting point of the Laser trepanning operation fixed.

2.5. Laser drilling

With the help of a scanner, the laser beam can be directed to perform trepanning hole drilling. In our case the depth of focus (DoF) is about 200 µm which is about 2-3 times smaller than the depth of the holes to be drilled (i.e. about 0.4 for the Ø 1.0 mm and 1.0 for the Ø 2.5 mm tool). Thus, it is necessary to adjust the focal distance several times during the drilling operation in order to achieve best performance. In the case of the 2.5 mm tool, the table is vertically raised by 690 µm in 23 steps of 30 µm, such as to reach the central channel. At each level, concentric circles (Fig. 7(a)) are scanned from the inside to the outside, with radius increasing by 10 µm, up to a maximum diameter of 300 µm. The second last outer circle is repeated once and the outer circle twice. This sequence of concentric circles was repeated 5 times before raising the table by 30 µm. Before drilling the next hole, the table is moved again to its initial position and the tool is turned by 120° to drill the next hole. The entire machining process per tool (2.5 mm) takes about 5 minutes 20 seconds. The following table summarizes the parameters of the process.

Table 1: Operation parameters.

Parameters	Values
Scanning speed	50 mm/s
Laser pulse frequency	100 kHz
# paths (cummulated)	115 (23*5)
# compensation in z , 30 µm each	23 (total 690 µm)
Laser power at working area	3.2 W
Diameter of hole	300 um
Machining time	5 min 20 sec
Attack angle	45°

As for the Ø 1.0 mm milling tools, a similar technology is applied, but the hole diameter is limited to 0.12 mm (instead of 0.3). The number of focal distance compensations is reduced to 2 compensations of 30 µm, i.e. a total of 60 µm. Machining time for the 3 holes is about 90 seconds.

2.6. Optimized geometry

The central position of the pre-manufactured central hole Ø 0.3 mm was not guaranteed due to manufacturing process issues. Although the entry of the hole at the shaft is perfectly centered, it can be slightly off–center at the opposite end. Thus when drilling the Ø 0.12 mm holes (for the 1.0 mm tool) it can happen that one or more channels do not well connect the central hole or do completely miss it. To reduce this risk the holes are drilled with a small lateral offset (50 µm) thus resulting in three virtual intersection points (green) covering a bigger area instead of only one (red) (Fig. 7(b)).

3. Analysis of drilled hole

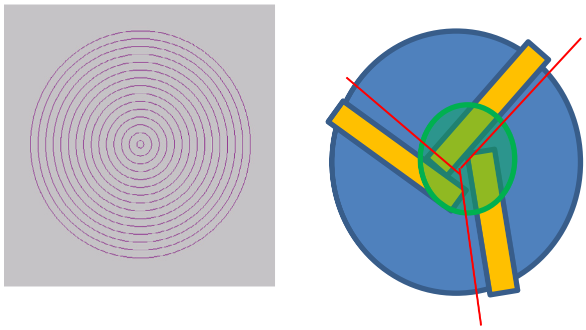

Fig 7. (a) Trepanning pattern. (b) Intersection of holes.

3.1. CT-Scan of drilled holes

The explained strategy of laser trepanning by repeated drilling operations of concentric circles and adaptation of the z-position is done to compensate the change of focal distance and to achieve lowest possible taper (i.e. same diameter of hole independent of depth). After reaching the desired depth and joining the central channel, laser machining should stop to avoid waste of machining time and drilling further in the tool. Two methods are used to control the geometry of the drilled holes and the intersection point.

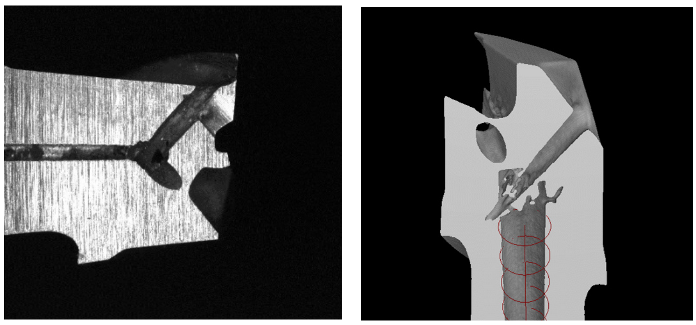

Fig. 8. (a) (right) Section of Ø2.5 mm tool, ground to 1 mm thickness; (b) (left) CT-scan of Ø1.0 mm tool.

For the Ø 2.5 mm tool, the machine tool is ground until about half of its thickness (approx. 1 mm), thus only one of the three lateral holes can be seen in the plane. This lateral hole has a constant diameter of 0.3 mm and intersects the central channel at its top end. The beginning of a second lateral channel is also visible at the bottom. The diameter of the central channel appears to be smaller than the ones of the lateral channels. A more detailed analysis using CT-scan, shows that this is due to the fact that more than half of the tool radius is removed (final thickness now is 0.5 mm instead of 1.25 mm) and that the central channel is not exactly at the center of the tool and is therefore truncated. For the Ø 1.0 mm tool, we can use a CT-scanner, i.e. a non-destructive method.

The use of the CT-scanner allows detecting the presence of particles and burr like structures at the intersection of the channel. These particles can block one or several lateral exit channels preventing liquid flow. Luckily they can be removed either mechanically or by inverse flushing, i.e. injection of liquid through the three lateral channels.

We presume that this is due to redeposit of vaporized material, previously removed by laser ablation during hole drilling. By a combined injection of air through the central channel and suction of air/vapor close to the laser-machining zone this redepositing phenomenon could be eliminated.

3.2. Bending tests and FEM Simulation

During the milling operation, cutting forces act on the tool tip. As can be seen from the CT-scan of the Ø 1.0 mm tool, a significant amount of material is removed from the tool (the central channel of Ø 0.3 mm and the three lateral channels of Ø 0.12 mm each). This may result in a reduction of bending stiffness. In addition, in case of thermal impact of laser machining, micro-cracks might occur, thus reducing tool stiffness even more. Comparison of two FEM simulations of tools with and without holes did not show any significant decrease of stiffness due to the holes (< 1 %). Bending tests applied up to 400 N (until breakage) at the tool tip and confirmed these simulations.

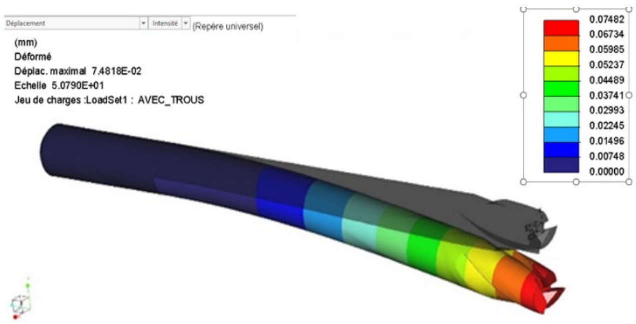

Fig. 9. FEM – bending simulation: 31 N applied at tool tip.

Fig. 10. Bending tests.

3.3. Milling tests

The milling tests are performed comparing standard milling tools with tools having drilled holes. Both tools had the same geometry but for the standard tool external lubrication was used, and for the tool with drilled holes intrinsic lubrication. For lubrication, an oil-water emulsion (Blaser SwissLub) is injected at a pressure of 20 bars. The milling machine DMU-80 (manufacturer DMG) is equipped with a spindle with maximum 18'000 rpm and a Siemens's CNC which allows monitoring of the motor currents of the feeding axis, in order to compare the cutting forces.

Milling machining parameters have to be adapted to perform real machining tests. The cutting machining parameters are reported in Table 2. Parallel groves of 10 cm length, with an interval of 1.5 mm and grove width depending on the diameter of the tool are machined.

Table 2: Milling parameters.

Tool Ø (mm)	Material	Ap (mm)	ae (mm)	n (rpm)	Vc (m/min)	Vf (mm/min)
2.5	brass w/o lead	2.5	2.5	14642	115	659
1	brass w/o lead	1	1	14642	46	220
1	stainless steel	0.5	1	12740	40	66

The maximum cutting length in stainless steel with standard tools was 6.6 m. This distance has been increased up to 16.3 m using tools with intrinsic lubrication. Also the cumulated paths of all tests show a similar improvement, i.e. a 2.4 times longer cutting length (134 paths with external flushing against 316 paths with intrinsic flushing).

Table 3: Cutting length of Ø 1.0 mm tools before rupture.

Tool #	Intrinsic holes	# Paths	cutting length (mm)
1	no	41	3800
2	no	66	**6250**
3	no	27	2400
4	yes	163	**16000**
5	yes	102	9800
6	yes	51	5100

As mentioned before the Siemens CNC of the milling machines allows to record motor current during machining. This current is a good indication of the applied cutting forces. Fig. 11 shows a significant decrease in applied current i.e. reduced cutting forces when using intrinsic lubrication. In addition, surface quality of the machined part was same or better.

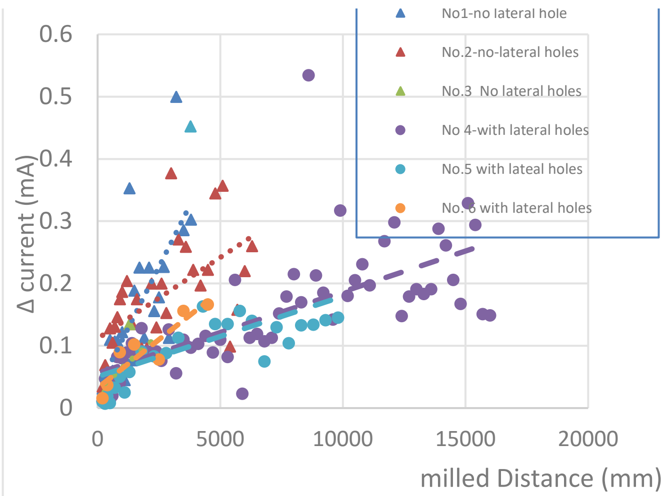

Fig. 11. Registered motor current during milling operations using standard and intrinsic lubricated tools.

4. Conclusion

Lubrication is a key element for the performance and lifetime of cutting tools. Chip removal and cooling of the cutting edge improves significantly when the lubricant is injected as close as possible to the cutting zone. Although such solutions using internal cooling channels exist for bigger milling tools (diameter > 6 mm), they could not be applied to small monobloc milling tools of diameter < 3 mm made of tungsten carbide.

In the present study we developed a technology to drill lateral holes of 0.12 (or 0.3) mm diameter at 45° in tool of diameter 1.0 (or 2.5) mm joining a central channel of diameter 0.3 mm. A ps-laser with a scanner allows to drill these holes (in trepanning mode) without thermal impact; the manufactured tools did not have any significant change in stiffness. A special tool holder table has been built allowing tool rotation and keeping the tool at laser focus with growing hole depth. Thus, achieving holes without taper, verified by CT-tomography. The exit position of the holes close to the cutting edge has been optimized using Fluid-dynamics simulations.

Comparative cutting tests using standard tools with external flushing and tools with intrinsic lubrication channels show a significant increase of tool lifetime by a factor of more than 2.5 as well as an improved machined surface quality. An EU-patent application was filed for this technology [9]. This technology is not limited to carbide milling tools of Ø 1.0 mm and 2.5 mm with three cutting edges, but can be easily adapted to other small sized tools, and/or more cutting edges as well as to other materials like ceramics which are hard to machine.

Acknowledgements

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