Surface micro – texturing of tapping tools with complex geometry

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Abstract. Lubrication control and tribological aspects affect all the machining operations: minimizing the friction coefficient, reducing the heat generated during machining or decreasing stresses during cutting operations are just some sought goals during machining. A fundamental aspect is also related to the drop of the amount of cutting fluid required during manufacturing processes. In fact, this can respond to issues related to the process sustainability thus allowing machining under MQL (Minimum Quantity Lubrication) conditions. The aim of this work is to propose an effective methodological procedure to texture cutting tools with complex geometry. A picosecond laser system operating at infrared frequency was used to structure the whole cutting tool surface. Rectangular dimples were selected as texture pattern to ensure the evaluation of the dimensions achieved by the dimples. Textured surfaces topography will allow the evaluation of the effectiveness of the developed process.

Introduction

In recent few years, the development of new coatings, applied to cutting tools, has made it possible to reach significant technological results such as the achievement of high performance in terms of friction reduction, the mitigation of adhesion, or the decrease of forces and torques during machining [1]. Moreover, these aspects are also reflected to the sustainability of mechanical processes. In fact, some coated tools have contributed to minimum quantity lubrication (MQL) thus reducing environmental pollution related to the disposal of cutting fluids [1]–[3]. Despite that, the development of new coating materials is getting harder [1].

In view to meet these needs, a solution can be represented by the application of a combination of micro-textured surface and surface coating. Several studies have emphasized the benefits seen from this method [4], [5].

Dimensions and texture geometry of dimples have a lot of influence in determining the tribological characteristics of the machining process. Kawasegi et al. [5] performed turning of aluminum with textured tools by varying the parallel dimple width. They showed how dimple textures parallel to the cutting edge contribute better in terms of forces reduction in comparison to dimples perpendicular to the cutting edge and cross patterned textures. Similar results were presented by Sugihara and Enomoto [6] who applied micro texture and generated shallow dimples on a diamond-like carbon (DLC) coated cutting tool by femtosecond laser technology. They investigated aluminum alloy cutting performance and stated a decrease in adhesion in wet cutting using micro-textured cemented carbide tools. They also found improvement in the lubrication of the cutting tool surface. As a subsequent result, they studied [7] the influence of the texture dimension on the anti-adhesiveness by varying the parallel dimple width of the functionalized tools.

Obikawa et al. [1] investigated the effects of four different micro surface textures on the lubrication conditions at the tool rake in machining aluminum alloy A6061-T6. Their findings showed how parallel and square-dot type of micro-textures effectively improved the lubrication conditions by decreasing of coefficient of friction in orthogonal cutting of aluminum alloy A6061-T6. A similar study was recently made by Xing et al. [8] in which three different types of dimples (rectangular, circular and linear) were generated on the rake face of cemented carbide tools. During orthogonal dry cutting tests of A6061 aluminum alloy tubes, they studied the effects in terms of friction reduction, anti-adhesiveness, wear resistance and cutting force reduction of these textured geometries compared to the results achieved by a conventional tool.

Several studies, due to the positive effects of surface textures related to anti-adhesion properties [7], [9], [10], heat reduction [11], [12], anti-friction [6], have demonstrated a lot of fields of applications of these types of micro- and nano-machining, not only referred to the significant impact on tribological performance of cutting tool during machining [8] but also related to bearings [13], seal rings [14] and engine cylinder liners [15].

Textured tools surfaces can also lead to positive results in terms of processing sustainability via reaching minimum quantity lubrication as stated in [4], [16]. Nevertheless, if textures on cutting tools aren’t correctly used, they can deteriorate the mechanical strength of the tool or worsen the cutting conditions of metals [17].

Throughout this study, the thread of a commercial tapping tool has been textured. During machining, this kind of tool needs a large supply of lubricant, especially when high depth must be reached. Rectangular shape dimples were chosen to better allow the characterization of the entire geometric development of the generated dimples in terms of dimensions, depth and inclination evaluations. These dimples, during machining, could operate as lubricant retention zone to enhance lubrication. Preliminary tests were conducted on flat surfaces in order to optimize process and laser parameters with the aim to obtain the specified dimples. Then, these findings were extended to complex geometry represented by the thread of a tapping tool. To do this, an ad-hoc kinematic procedure has been implemented, also via system integration, to optimize the entire process. Picosecond laser processing with infrared (IR) beamline was used for structuring. Morphological analyses via optical (OM) and scanning electron microscopes (SEM) were also performed to confirm the effectiveness of the proposed procedure.

Materials and methods

Workpiece and material

The tools used for texturing are commercially supplied by Seco Tools under the MF-M10x1.50-ISO-6HX-XC-V055 codification. These are cold forming TiN coated tapping tools used for steels, hardened steels with <62 HRC and non-ferrous metals. Their peculiarity refers to the presence of a conical inlet aimed to facilitate the entry of the various threads into the pre-hole. This zone involves the first three threads and is characterized by an inclination with respect to the longitudinal development of the tool of $\beta = 7.5°$. Overtaken this area, the threat develops its behavior regularly conforming the DIN 2174 standard of M10x1.5. The inlet conical profile of several SECO M10x1.5 tapping tools was analyzed via an optical microscope (Mod. Nikon LV100ND). Subsequently, by using the image processing program “ImageJ”, the value of β angle as stated in the datasheet provided by SECO was confirmed with a tolerance of ± 0.5°. Fig. 1 shows the geometry of the considered tool.

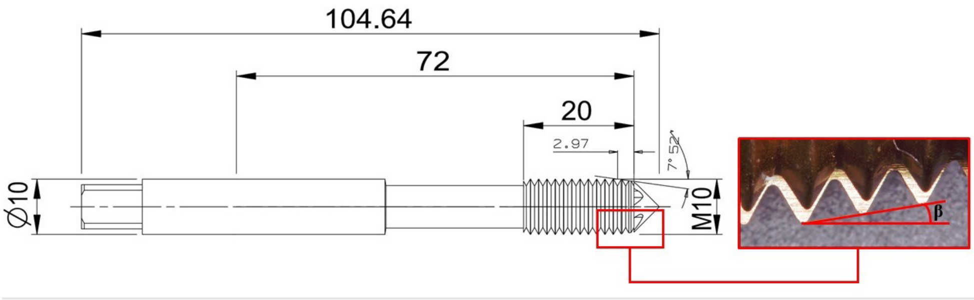

Fig. 1 SECO tapping tool used for the experiments (left); magnification in the conical inlet zone to measure and verify β angle (right). (All dimensions are in mm).

Laser texturing

Picosecond laser technology was adopted to perform textures on the thread. This technology is very promising compared to all other micro-surface structuring methods. Indeed, it operates with ultrashort pulses in picosecond duration which can produce, due to the high speed that can be reached, regular dimples on the workpiece. The necessity of post-processing is eliminated and no special tooling is required [4]. As the major advantage, pulsed laser systems, in the ultrashort regime, can structure surfaces of workpieces without limitation in terms of hardness of the material to be treated [4]. The laser amplifier EKSPLA Atlantic 50 operated at the IR wavelength of 1064 nm. The focused beam diameter was $Ø \sim 10$ μm evaluated at $1/e^2$ intensity. The same laser processing parameters, as summarized in Table 1, were used to texture both the flat surface and the entire tool.

***Table 1** Parameters used for texturing experiments.*

Wavelength λ [nm]	1064
Average output power P [W]	0.82
Pulse frequency f [kHz]	400
Pulse energy E [μJ]	4.1
Pulse duration τ [ps]	~ 10
Pulse fluence F [J/cm^2]	5.22
Line spacing s [μm]	5
Cumulated dose d [J/cm^2]	10.44
Marking speed v_s [m/s]	1
Number of passes on each dimple p	2

The Raylase Superscan IV galvanometric scanner coupled with an 80 mm F-theta lens assures a working area of 39 x 39 mm^2 through movements in X and Y of two mirrors mounted inside the scanner. The remaining displacements, outside the above scan area, are guaranteed by the translation of the Z axis, which allows positioning at different focal heights, and by the X- and Y-translation of the workpiece table. Rotation (both clockwise and counterclockwise) is permitted by a rotator, mounted on the automated X-Y table. Therefore, the entire system exhibits four global degrees of freedom.

Laser source, roto-translator system for workpiece and head manipulation, optical scanning system, beam shaping and sensors for process control are totally well integrated via C# libraries and LabVIEW to allow movement in the three translation directions and to permit rotation thus following the helical path of the thread. The setup used for laser texturing is illustrated in Fig. 2.

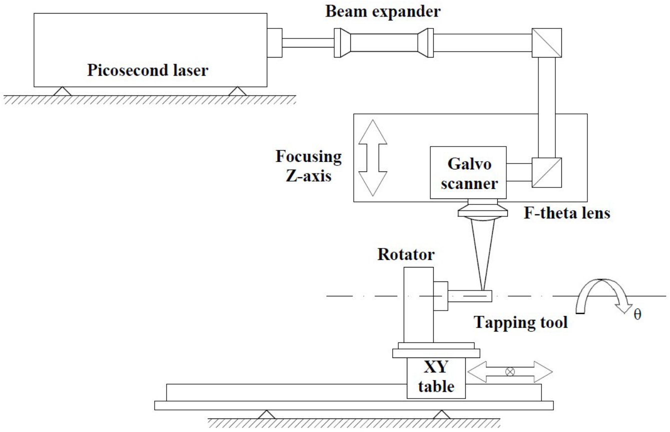

Fig. 2 Laser system used for the experiments.

Micro-texture fabrication

The entire textured area of the tapping tool had a width of 10 mm and a length of 20 mm.

The designed dimples were rectangular in shape with a maximum size of 30x60 µm and 10 µm as expected maximum depth. This geometry has remained unchanged for both flat and inclined machining. Dimples have been distributed along the entire circumferential and longitudinal development of the tapping tool with the aim of achieving a 15% coverage of the entire development of the thread surface. In both cases (flat and inclined surface) were performed three different dimples in terms of the trend of the depth variation of the dimples: flat bottom, positive- and negative-inclination with respect to the chip flow direction. These trends have been obtained by overlapping 7 rectangles with a constant height of 30 µm and gradually decreasing widths (60, 50, 40, 35, 30, 25, 20 µm). Every single rectangle was filled with an equally spaced horizontal hatch 5 µm in step to generate the desired maximum depth of the dimples of ~ 10 µm.

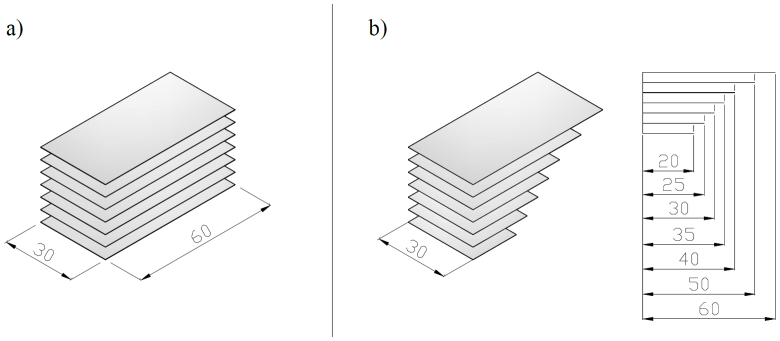

Fig. 3 Dimples generation criteria. a) flat bottom b) wedge dimples. Fillings of each rectangle are omitted to ease reading. Decreasing in width proceeds from top to bottom (All dimensions are in µm).

Planar samples were firstly textured to investigate the response of the material to infrared interaction with the aim to obtain a pulse overlap of 5 µm corresponding to a laser spot overlap of 50% of the whole surface. These tests were conducted by means of variation of the average output power, the number of passes on each dimple and the marking speed. The adopted optimized values settle as stated in Table 1 thus guaranteeing precise regular dimples formation, a gradual increase in depth up to 10 µm (as maximum) of the dimples preventing the formation of recast materials and a homogeneous distribution of energy on the treated area. During these tests, dimples with flat bottom, positive and negative inclination were generated, as mentioned above. To switch from planar to inclined surface an evaluation of the allowable depth of focus is required.

By considering a beam quality factor M^2 of 1.5, subsequent calculations made it possible to evaluate the diameter of the laser beam waist D_f which settles at 11.6 µm and the Rayleigh length z_f of about 100 µm. This evaluation indicates the possibility to be robust in obtaining the inclined thread flank results comparable to what was achieved on preliminary planar tests. Then, experiments on the thread of the tool, which can be treated as a strongly inclined surface, were performed. Considering these surfaces, the maximum size of the designed dimples of 30x60 µm must be treated as the maximum dimension with respect to the surface normal. This series of experiments, as well as the preliminary tests, has consisted of using the three different depth variations, as previously mentioned. Positive and negative inclination in the depth of the dimples is visible in the inset of Fig. 4.

The distribution of the dimples on the cutting tool was very crucial. The laser beam must follow the thread in its entirety. The implemented handling system allowed following the winding direction of the thread helix through the movement of the X and the Z axis and by rotation of the workpiece. This aspect was essential to operate at the correct focal height. As a direct subsequent of the adopted criteria, a simplified method was developed for the programming and the conduction of laser texturing part program of complex surfaces under study.

The automatic process of creating dimples on tapping tools consists of two stages. First, laser beam performs the progressive creation of the dimples by using a multi-quote Z approach for a fixed value of rotation. Thus, the laser initially focuses on the crest and creates textures on it. After completing this task, the system, through a movement of the Z axis, moves progressively to the next lower level until it reaches the thread root. This allows to calculate a single set of {X,Z} position of the laser vectors. The system can texture only one angular position in their entire height, from the crest to the root of the thread. The heights involved in the process were $z^* = 0, -0.06, -0.19, -0.38, -0.57, -0.76, -0.89, -0.99, -1.17$ mm with the origin for the z^* dimensions located at the outer radius of the tread. Then, by automatically rotating the tool with an angular step of 4.5° and shifting the X position to follow the helical path, the process restarts as mentioned above.

The parameters of the laser beam that can be calculated starting from the value of M^2 (e.g. D_f and z_f) allow for process optimization. In fact, it is possible to texturize in the same placement for a given value of z^*, three contiguous lines of dimples with an angular distance $d\theta$ of 1.5° as can be seen from the dotted rectangles in Fig. 4. The progressive rotations can thus be increased to $\theta = 4.5°$ (as mentioned above) resulting in a reduction of the number of mechanical placements to perform and in the reduction of the execution times thanks to the speed of the galvanometric optical scanner.

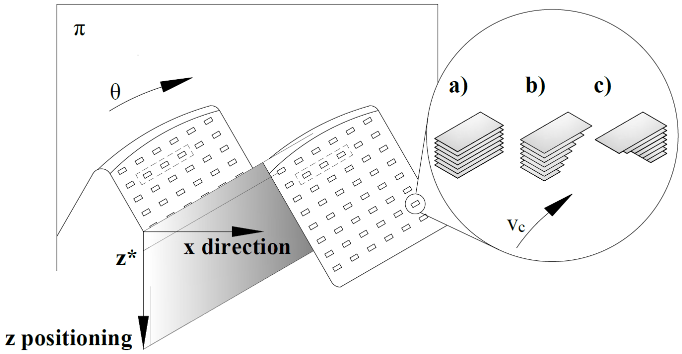

Fig. 4 Schematic diagram of textures on a circular sector of the tapped tool. In the enlarged figure are shown the projected views of: a) flat bottom dimples; b) - c) positively (and negatively) inclined dimples with respect to cutting speed v_c.

Characterization and measurements

The textured tools were cleaned in an ultrasonic bath. A Nikon LV100ND optical microscope was used to qualitatively measure the depth of the dimples by changing the depth of focus. Then, the textured surfaces were characterized via a Scanning Electron Microscope (Mod. Nova NanoSEM 450 - FEI) to measure the two dimensions of the dimples.

Results and discussions

The comparison of the images obtained via SEM analysis (Figs. 5-6) confirms the possibility to get regular dimples with specific dimensions on the thread of the tool. As first result, SEM images of the textured dimples on the planar surface confirmed the chosen laser parameters. In fact, dimples were unchanged in dimensions in the passage from the designed to the actually realized geometry. The maximum depth is evaluated to be about 10 µm.

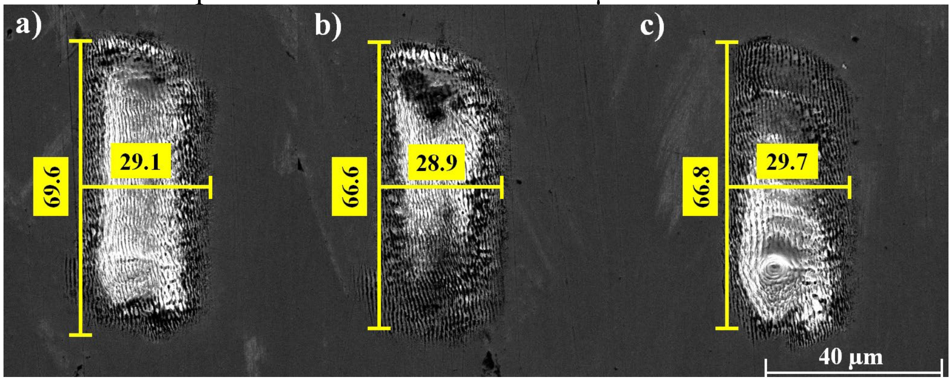

Fig. 5 SEM images of preliminary tests on planar surface: a) flat bottom; b) and c) shows the positive and negative increasing in depth.

Extending the study to the inclined surface similar results are achieved. The maximum depth reached by the dimples settles around 8 µm.

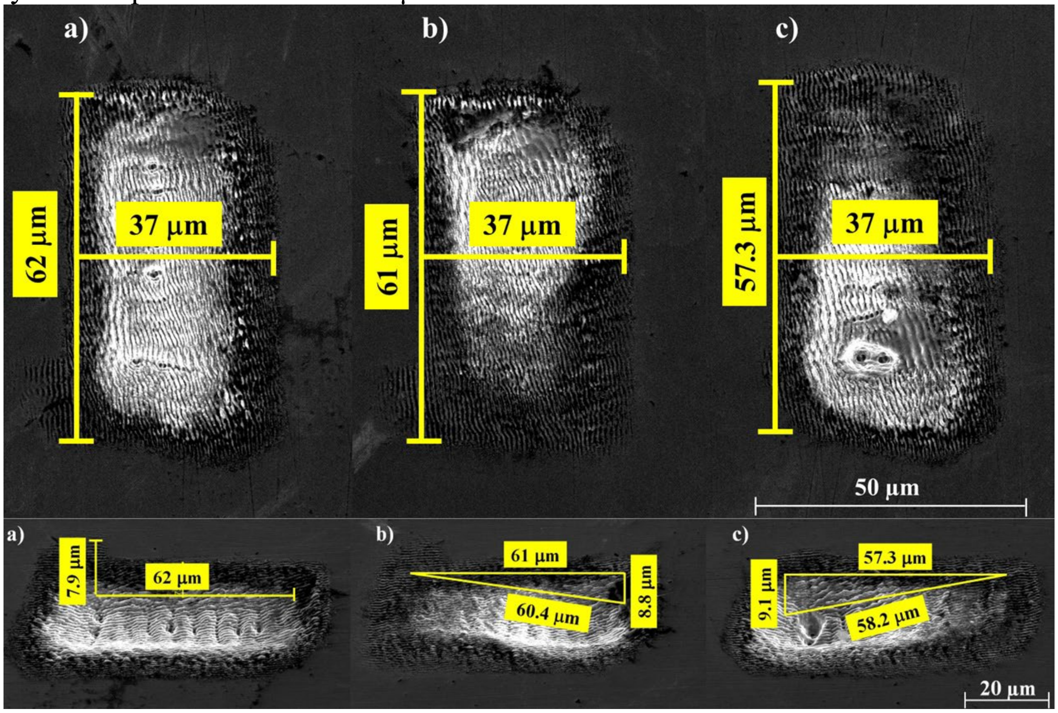

Fig. 6 SEM images of tests on 60 degrees inclined surface: a) flat bottom; b) and c) shows the positive and negative increasing in depth. (All dimensions are in µm).

SEM images also confirm the adopted procedure showing the achievement of a homogeneous distribution of the dimples, especially in the conical inlet zone as visible in Fig. 7.

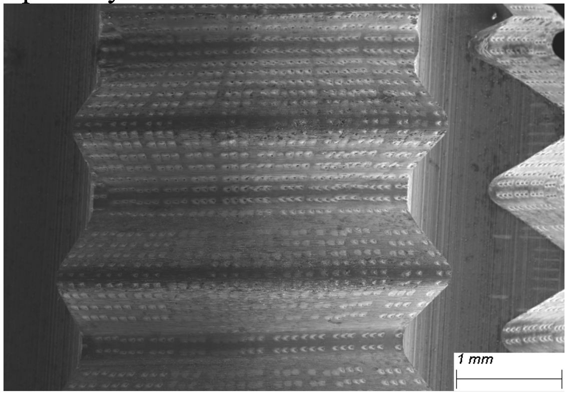

Fig. 7 SEM image of the treated inlet conical zone.

Conclusions

In this study, the possibility to implement a procedure to generate regular dimples on steeply inclined surface is analyzed. It has been shown how picosecond laser sources are suitable technology for metals micro-texturing. The procedure adopted allowed to achieve precise and regular dimples both on planar and inclined surface which was represented by the thread of the commercial tapped tool under investigation. A fully automated method to efficiently texture all the complex geometry of a real tapping tool was moreover presented.

The experimental results obtained were in accordance with the predicted geometry. In fact, maximum dimension of the dimples remained constant from the designed to the realized processing while they have changed due to trigonometry in the case of an inclined surface. The depth reached by the dimples of about 8 μm were interesting to probe in the next future the possibility to work under MQL conditions during tapping operations.

As subsequent studies, starting from the presented results, cutting tests will be performed to compare the thrust force from machining using textured and conventional SECO tapped tool.

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