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Microtexturing for Enhanced Machining: Evaluating Tool Performance in Laser-Processed Cutting Inserts

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This study explored the significance of microtexturing on cutting tools to improve tribological performance and reduce friction in machining operations. Drawing inspiration from biomimetic structures, this study focuses on laser surface microtexturing and evaluates its impact on the cutting forces and tool wear. Experiments involved the microtextures of dots with a specific emphasis on a fiber laser-processed pattern. While long-term tests reveal the formation of negative protrusions on textured tools, reduced variability in cutting forces suggests potential benefits for stable machining processes and increased tool longevity. These findings underscore the intricate relationship between microtexturing patterns and tool performance, offering insights into the broader implications of energy-efficient machining.

Keywords: Microtexturing, Tribology, Laser Surface Processing, Cutting Forces, Cutting Tool

1 Introduction

Conventional machining is fundamental to the manufacturing industry, contributing up to 23 % of the overall production costs. Surface machining and refinement at the micrometric and submicrometric scales have emerged as pivotal manufacturing technologies that reduce the friction between the tool and chip. This has led to growing interest in structuring surfaces aimed at altering the tribological or microfluidic properties. The foundation of microtexturing lies in the examination of biomimetic structures, mirroring friction-reducing properties akin to shark skin motion through water [1–3].

Surface modification is well known across diverse technical domains owing to its benefits, such as diminishing tool wear and reducing the coefficient of friction between the tool and workpiece. For typical cutting tools, high pressure and temperature prevail on the contact zones, notably on the tool rake face and flank side. In such instances, the cutting fluid struggles to penetrate these contact areas during cutting operations. Surface microtextures on the rake face and flank of the tool serve as microreservoirs for the process fluid, effectively introduced into the tool-chip interface. This facilitates enhanced tool lifespan and surface quality under higher cutting conditions. Properly created microtexturing also reduces the required cutting forces for material removal [2], [4]. The use of cutting fluids is gradually becoming restricted owing to environmental concerns and lower production costs. Several newly developed cutting fluids such as plant-based cutting fluids, gas-based cooling fluids, and nanolubricants offer alternative and environmentally friendly options. However, the use of these cutting fluids incurs additional costs. [4], [5].

Furthermore, lubrication and cooling constitute the primary functions of the cutting fluids. These fluids are costly, toxic, and hazardous if improperly handled. Almost every cutting fluid tends to focus more on cooling, that is, dissipating the heat generated during cutting, rather than reducing the friction of chips on the tool's face or back. The surface texturing of cutting tools aims to enhance the lubrication efficiency of cutting fluids. In microtexturing, lubrication can be in the form of process fluids or solid lubricants. It has been found that microtextures, such as dots, dimples, microcavities, channels, or grooves, created on the surface of the tool via surface texturing and subsequently filled with lubricant, can function as lubricant reservoirs, leading to reduced friction and wear at the tool-chip interface. The surface texture also captured the impurities. Some potential texturing patterns are depicted in Figure 1 [1], [4], [6–7].

The methods employed for microtexturing of cutting tools are highly contingent upon the specific functions of each application for which texturing is intended. The quality of the texture relies significantly on the manufacturing methods, underscoring the importance of detailed knowledge concerning the pertinent parameters of each technique [9].

The following section provides an overview of the most commonly used techniques in industries and research settings for producing micro/nanotextures tailored for tribological applications.

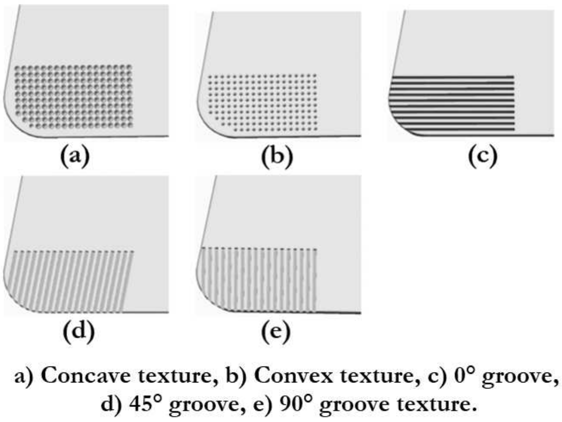

Fig. 1 *Microtexturing patterns [8]*

1.1 Microtexturing of cutting tool surfaces using lasers

Laser surface microtexturing utilizes stimulated radiation emission to produce a monochromatic focused beam of light. Various types of lasers exist, which are primarily distinguished by the type of active material. The use of lasers for microtexturing is particularly advantageous owing to the low divergence of the laser beam. Laser technologies enable numerous modifications of surface properties, facilitating alterations in frictional characteristics. Such alterations can be strategically utilized to influence the behavior of cutting tools at the interface between the existing chip and actual cutting edge of the tool. Surface texturing or other modifications of cutting tool surfaces through laser technologies may result in reduced machining forces, diminished heat generation, decreased wear intensity, and ultimately prolonged tool lifespan, leading to reduced production costs [1], [9–10]. A simplified laser texturing scheme is shown in Figure 2.

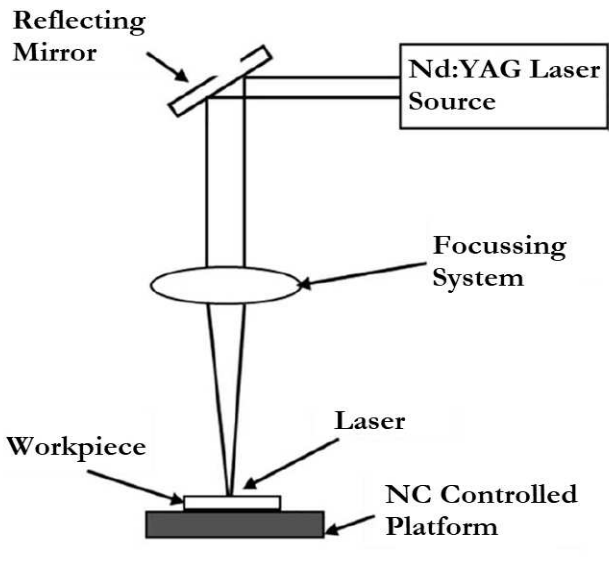

Fig. 2 *Simplified principle of laser microtexturing [9]*

1.2 The current research in the field of microtexturing of cutting tools

The trends and findings regarding micro-textured patterns on cutting tools are illustrated in the following chapter. Each of the microtexturing techniques employed, along with the specific design and shape of the textures, presents its own set of advantages and disadvantages.

The experiment conducted by Kümmel [11] provided evidence that the utilization of dot-textured tools exhibited a higher longevity than tools textured with line patterns. The investigation involved the assessment of wear on the tool flank and rake face employing various texturing methods, with a feed rate (f) of 0.05 mm/rev, cutting speed (v_c) of 100 m/min, depth of cut (a_p) set at 1 mm, and the utilization of cutting fluid. The workpiece materials examined encompassed SAE 1045 carbon steel subjected to turning operations with uncoated cemented carbide tools.

The application of parallel texturing (aligned with the cutting edge) on the tools demonstrated a reduction in friction of up to 6 %. The referenced article conducted Finite Element Method (FEM) simulations to compare tools with textured surfaces against non-textured ones. The machining conditions involved a cutting speed (v_c) of 182 m/min, a depth of cut (a_p) of 0.203 mm, and a feed rate (f) of 0.152 mm/rev, all of which were performed without lubrication. The materials investigated in this study comprised cubic boron nitride as a tool material and AISI52100 steel as a workpiece material subjected to turning operations. The aforementioned study was conducted by Kim et al. [12].

Yu [13] revealed a reduction in tool wear and a modification in chip morphology through simulations and experiments conducted on a textured tool. These studies aimed to assess the tool wear, cutting forces, and cutting temperatures during turning operations. The machining parameters encompassed a cutting speed (v_c) of 1000 m/min, a range of depths of cut (a_p) from 5 to 25 μm, and a feed rate (f) of 0.005 mm/rev, all of which were performed without lubrication. The materials examined consisted of uncoated cemented carbide tools and the workpiece material AW6061 aluminum alloy, employed in turning operations.

The utilization of elliptical textures resulted in lower coefficients of friction, cutting temperatures, and cutting forces compared to other tools, both textured and nontextured. Jianxin et al. [14] evaluated the cutting performance of MoS2-filled tools with textured rake faces employing different geometric textures. The machining conditions comprised a range of cutting speeds (v_c) from 60 to 300 m/min, a depth of cut (a_p) set at 0.5 mm, and a feed rate (f) of 0.1 mm/rev, all performed without lubrication. The studied materials included WC/Co tools and carbon steel workpiece materials used in turning operations.

The textured tool, both with and without the WS2 coating, demonstrated a higher cutting performance compared to nontextured tools in the research article by Xie et al. [15]. In addition, the cutting forces, cutting temperature, and coefficient of friction decreased. The investigation focused on evaluating the cutting performance of textured tools coated with WS2 and their uncoated counterparts, specifically examining dry cutting conditions. The machining parameters included cutting speeds (v_c) ranging from 50 to 250 m/min, a depth of cut (a_p) of 0.3 mm, and a feed rate (f) of 0.1 mm/rev. The materials utilized were WC/TiC/Co tools and hardened steel employed in turning operations.

Increased longevity was observed by Da Silva [16], specifically in the case of parallel-textured surfaces, indicating reduced abrasion wear. This study conducted a comparative analysis of the durability of nontextured inserts and textured inserts. The machining parameters encompassed a cutting speed (v_c) of 350 m/min, a depth of cut (a_p) set at 2 mm, and a feed rate (f) of 2.5 mm/rev, employing process fluid lubrication. The investigated materials included WC/Co cutting inserts and AISI 1050 carbon steel, which were utilized in turning operations.

2 Materials and methods

The objective of this study is to experimentally investigate, during turning operations, the influence of various microtexturing patterns created using a fiber laser on the rake face of uncoated replaceable cutting inserts with a flat cutting surface. The impact of these microtexturing patterns will be assessed based on insights from current research in this field, where appropriately designed microtextures are anticipated to enhance the lifespan of cutting inserts. The examination of these cutting inserts during machining focuses on observing the effects of the generated microtexture on selected parameters related to the magnitude of the cutting force components acting on the cutting tool during machining operations.

For measuring the cutting forces on the machining tool, a piezoelectric dynamometer 9129AA from the manufacturer Kistler was employed. This multicomponent dynamometer is suitable for measuring the three components of the resultant force vector and the three components of the resultant moment vector. Comprising four three-component force sensors mounted inside the dynamometer, it is constructed from anti-corrosive material and is also resistant to fluid ingress [17].

The turning tool constitutes an integral part of the assembly responsible for chip removal from the material, and its cutting portion experiences the highest forces during machining operations. Therefore, a turning toolholder with replaceable cutting inserts from the manufacturer Seco, designated as PSBNR2020K12 [18] (Figure 3), was selected.

Specifically, these replaceable cutting inserts with microtexturing effects are mounted onto this right-handed tool, featuring a clamping part size of 20 × 20 mm, to investigate the influence of microtexturing.

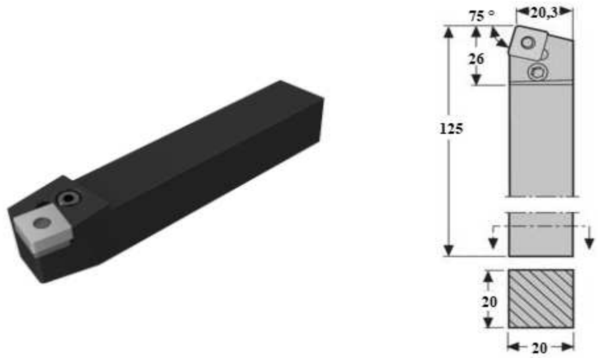

***Fig. 3** Dimensions and shape of the cutting tool [18]*

Replaceable cutting inserts manufactured by Seco were selected for the purposes of the experiment within the scope of the research. The selected type [19] (Figure 4) was SNMA120416 TK0501. This selection was made owing to its compatibility with the turning tool. The cutting insert, with a flat cutting surface, consisted of tungsten carbide grains bonded with cobalt. Primarily designed for machining cast iron materials, these inserts will be employed in machining test non-alloy structural steel 1.0060 (E335) to facilitate clearer observation of their wear patterns.

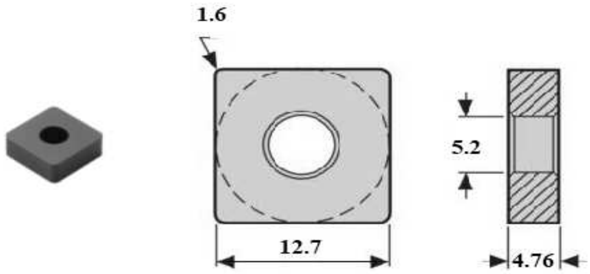

***Fig. 4** Shape and parameters of the replaceable insert [19]*

2.1 Microtexture on the rake face

For the experimental requirements, it was necessary to create textured patterns on the cutting surfaces of the replaceable cutting inserts from Seco, as mentioned above. The fabrication of the proposed texturing patterns was conducted using a tabletop laser marking station equipped with a fiber laser, specifically the LaserFiber LFQ20-T [20]. The apparatus is described as follows: it has an output power of 20 W, operates at a wavelength of 1064 nm, and functions at frequencies ranging from 5 to 200 kHz. The equipment used is shown in Fig. 5.

Fig. 5 *Fiber laser and technical parameters [20]*

The grid of the textured patterns was based on the designs depicted in Figure 1, where the noticeable patterns consisted of dots and lines. These patterns form miniature indentations for the dots and grooves on the cutting surface of the tool. In the dot pattern, seven rows of dots were laser-engraved following a "zig-zag" pattern within an area of 2.3 x 1.05 mm when placed entirely at the edge.

The dot texture element width was 100 μm and the depth was approximately 50 μm for each dot. During the fabrication of textures, the following input parameters were employed for the dots: laser power of 20 W, Laser-on time per dot of 5 s, and beam frequency of 100 kHz. The texture spacing parameters and results are shown in Figure 6.

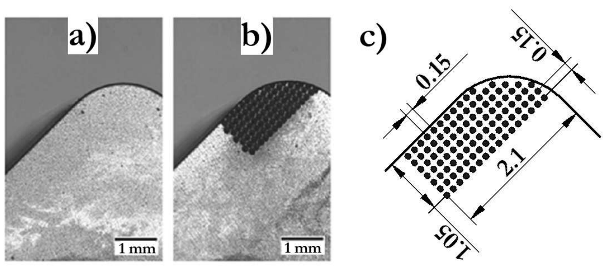

Fig. 6 *Face surface of the cutting inserts, a) plain rake face, b) texture of the dots, c) texture position and spacing*

2.2 Experimental Set-Up

The experimental setup was assembled for a successful measurement execution. The adaptation elements were sequentially bolted to the Kistler measuring dynamometer, enabling attachment to the cutting tool head and lathe tool holder, housing the lathe tool, and the cutting insert. This configured assembly was then connected to a data collector and amplifier (Kistler 5167A). Subsequently, the Kistler setup was linked to DynoWare measurement software.

The experiment was conducted on a turn-mill machining center NTX 1000, where a test circular semi-finished product ⌀ 50 CSN 425510.12 – 1.0060 (E335) measuring 500 mm in length was clamped into the chuck. Preparations were made on this semi-finished product before measurement, where the front face and perimeter were removed to eliminate burrs that might influence the measurements. In addition, the shape of the semi-finished product was adjusted to ensure a consistent measured segment length.

The testing measurement was performed on the prepared semi-finished product, moving along the axis of rotation, and the machining path was 50 mm for every cut. Individual tests of microtextured patterns on the cutting surface of replaceable cutting inserts were conducted in a long-term scenario. The machined section from the test rod was cut every 10 cuts using a band saw, followed by the preparation of a new semi-finished product segment and subsequent measurement after another 10 cuts. The cutting conditions employed during the machining are cutting velocity v_c = 250 m/min, feed f = 0,5 mm/rev and depth of cut a_p = 1 mm.

The cutting forces were measured in the long-term tests. For both the plain insert without texture and the dot-textured cutting insert, 50 cuts were conducted, measuring every 5th cut. In the case of the line-textured insert, 10 cuts were made to measure each cut. These tests aimed to monitor prolonged machining using a textured replaceable cutting insert without the application of a process fluid.

The short-term tests involved measuring the cutting forces and surface quality following a single cut programmed via CNC on the workpiece material 1.0060 (E335).

Tab. 1 *Characterization of force components in machining process*

Dynamometer Convention	Standard	Symbol in Graphs
Fx	Fp – passive force	▲
Fy	Fc – cutting force	■
Fz	Ff – feed force	●

The cutting forces were measured using an assembled measuring setup comprising a dynamometer. The measured components of the cutting forces adhere to standardized conventions and experimental investigations [21, 22], as illustrated in Figure 7, where the symbol labeling of individual cutting force components used in the measurement graphs is indicated in Table 1.

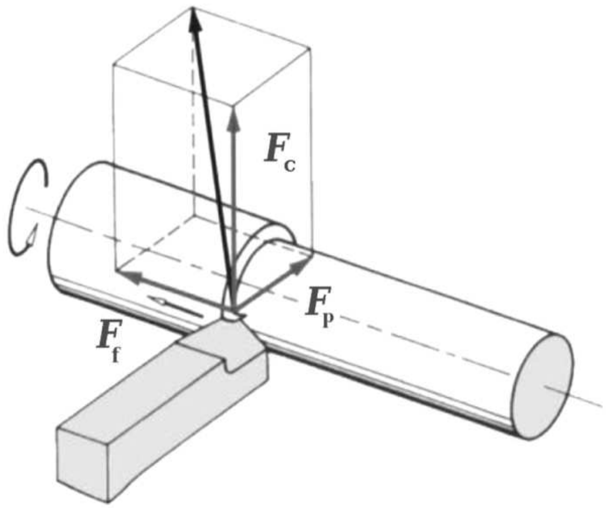

Fig. 7 *Measured components of cutting forces [21]*

3 Results

The subsequent chapter focuses on illustrating the depiction of cutting inserts captured on the Zygo 8000 optical profilometer before and after long-term machining. In addition, the conditions of the rake surface of the cutting insert were monitored. Furthermore, the results of the cutting forces are also reported.

In this test, the long-term wear of the non-textured replaceable cutting inserts was measured without the use of a process fluid. As shown in Figure 8, the surface of the insert was thermally affected after machining, and grooves were formed on the insert at the location where the chip moved on the rake face. The deformation of the material at the boundary corresponding to the depth of the insert wear was observable in both the 2D and 3D images of the cutting insert.

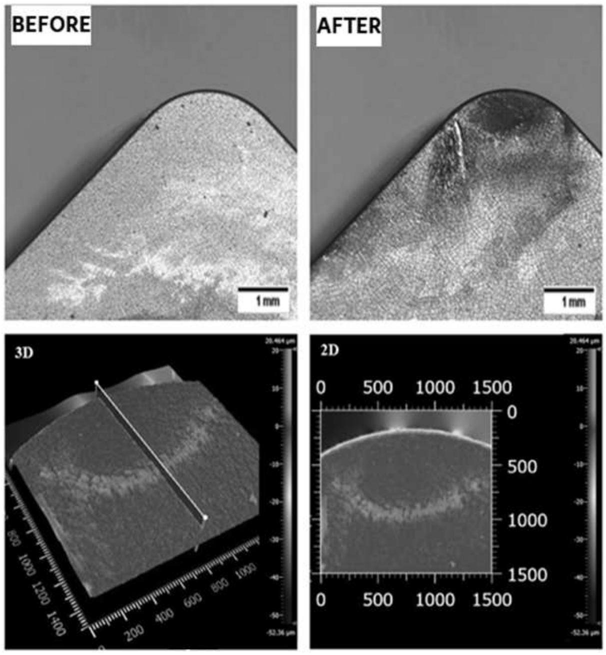

Fig. 8 *Plain rake face of cutting insert captured on optical profilometer before (left side) and after (right side) long-term machining*

In Figure 9, the creation of a surface after subjecting the cutting insert to long-term testing without the use of process fluids is evident. Additionally, after exposure to long-term testing, the material of the insert began to deform and create a protrusion approximately 600 μm away from the edge.

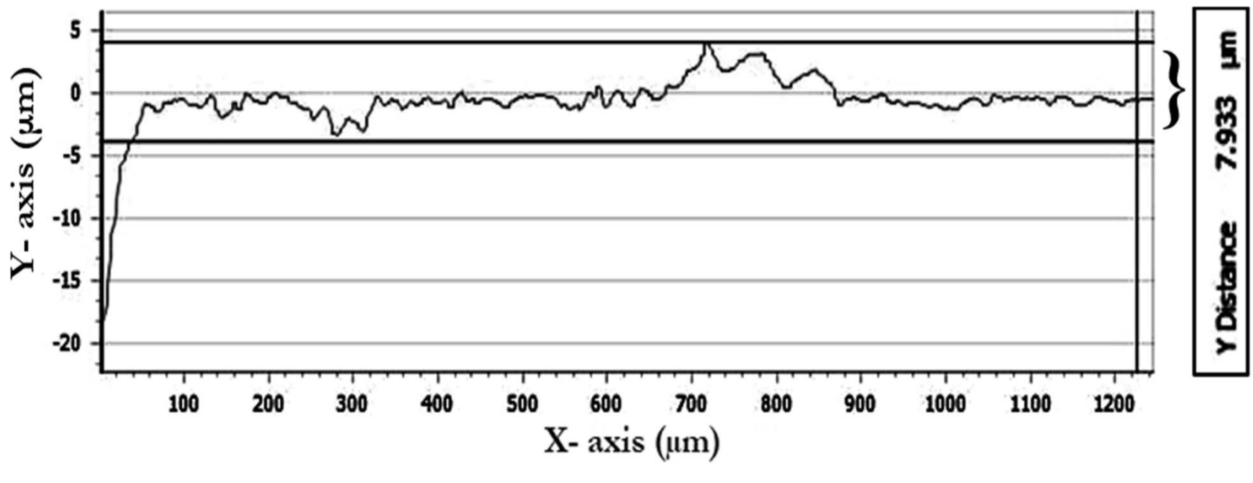

Fig. 9 *Height irregularities on rake face of the cutting insert without texture*

The cutting forces measured using the Kistler dynamometer were processed using the DynoWare measurement software. A representative graph of the frequencies, with 25 000 recorded values per second, is depicted in Figure 10, which also shows the tool approach and exit. The evaluated cutting forces were selectively extracted from the segment in which the cutting insert was fully engaged in the cut. The selected segment was demarcated by vertical bold lines, and the average values of the individual force components were computed from this chosen interval.

The graph illustrating the magnitude of the force components (Fx, Fy, and Fz) for every 5th cut is presented in Figure 11, with their respective average values from the selected segment indicated. The data points were fitted with a polynomial trend curve, offering the best characterization of the observed values. The cutting force values exhibited substantial similarity, and the cutting forces remained stable throughout the test.

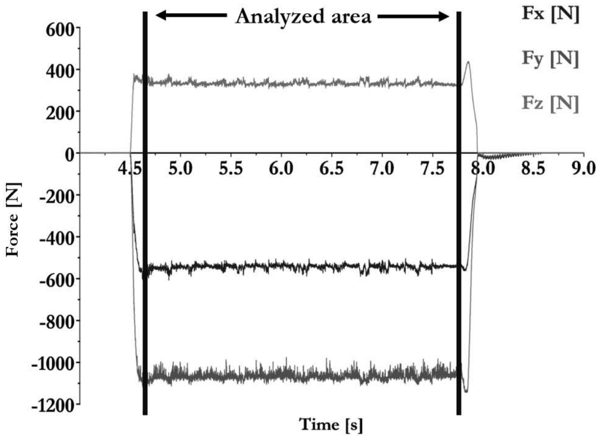

Fig. 10 *Measurement of the cutting forces from the individual run of the cutting insert without texture*

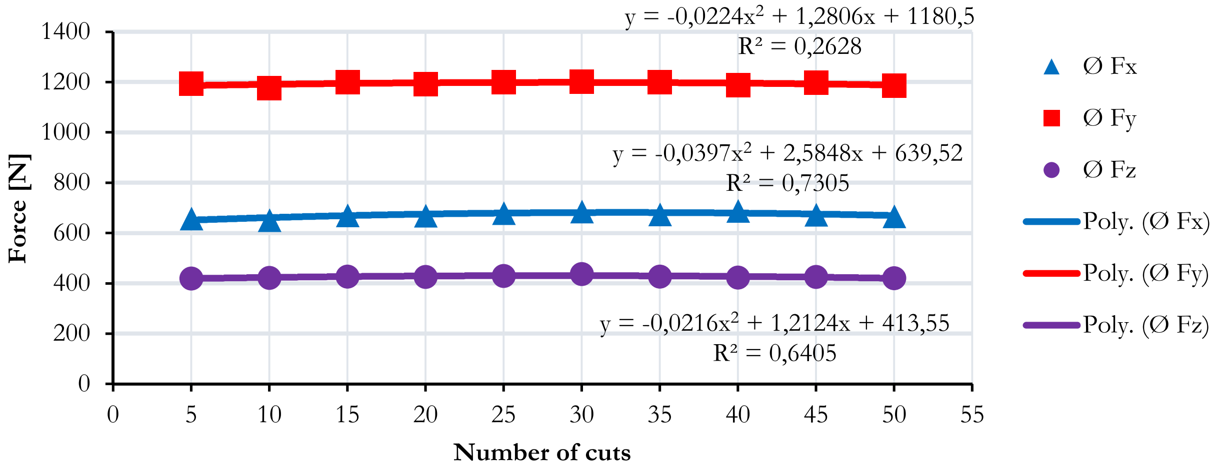

Fig. 11 *Cutting forces in the long-term machining by insert without texture*

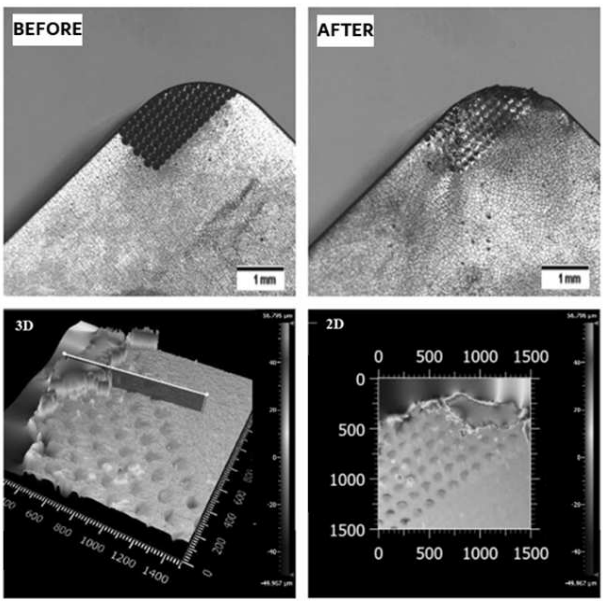

Fig. 12 *Rake face of cutting insert with dot texture captured on optical profilometer before (left side) and after (right side) long-term machining*

In the second long-term test, the investigation focused on texturing with a pattern of dots without the use of a process fluid. As is evident from Figure 12, substantial damage occurred on the replaceable cutting insert upon completion of the test. The textured dot pattern underwent nearly complete deformation along the cutting edge during machining. Most of the textured holes were filled with the workpiece material. A closer examination of the 2D image revealed that the cutting insert began to fracture at the edge. Microtexturing also led to the adverse phenomenon of the formation of protrusions on the cutting edge. The resulting buildup of molten material was visible in the 3D image.

Figure 13 illustrates the surface profile after machining, where a layer of protrusions on the cutting edge reaching heights of up to 50 μm is clearly discernible. The selected segment represents one of the textured dots, which is irregularly filled with material, whereas the original unfilled dot has a depth of approximately 50 μm, which is now reduced to only 10 μm.

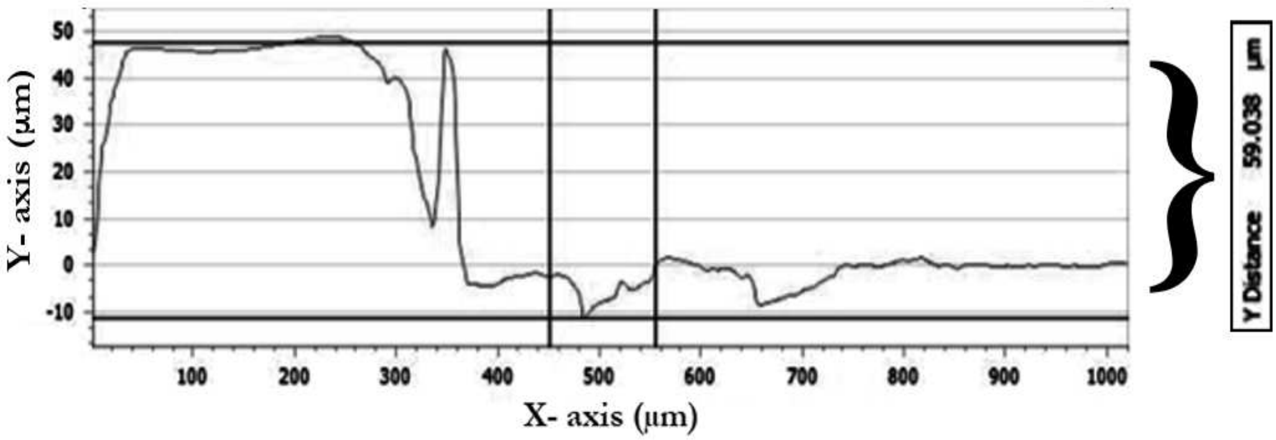

Fig. 13 *Height irregularities on rake face of the cutting insert with texture of dots*

The progression of the magnitudes of the force components (Fx, Fy, and Fz) is depicted in Figure 14, illustrating the development of the average values during the long-term test. The individual data points were fitted using polynomial regression, providing the best characterization of the measured values. The cutting force values remained highly consistent throughout the measurement, even in the case of a significant protrusion formation on the cutting edge. The forces remained stable and the texturing process had a minimal impact on the cutting forces.

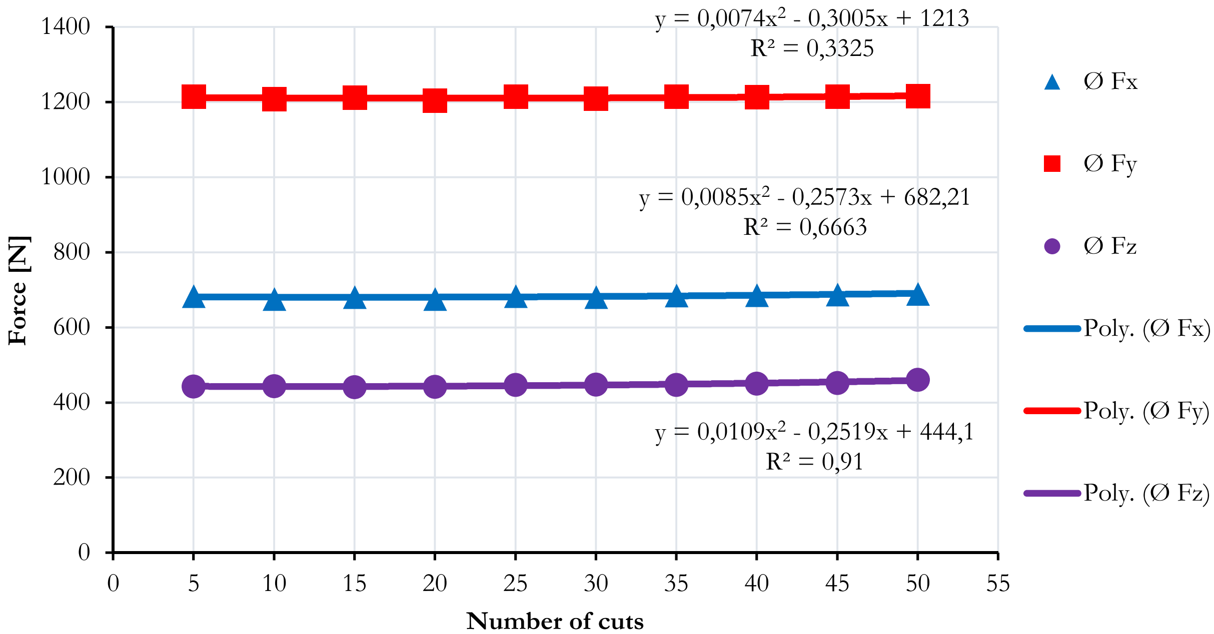

Fig. 14 *Cutting forces in the long-term machining by insert with texture of dots*

4 Discussion

By comparing the long-term tests of cutting inserts with and without dot texturing, both conducted without the use of process fluid, the influence of texturing on the tool was observed. The components of the cutting forces were monitored and compared along with a variability bar representing the maximum and minimum measured values. The measured cutting forces were compared after every 25 cuts, representing the midpoints of the long-term tests.

From the graphs in Figure 15 for the individual components of the cutting forces below, it can be observed that the textured cutting insert with texturing exhibited slightly higher cutting forces in all components, which were approximately 20 N higher. However, the error bars representing the maximum and minimum measured values of the cutting forces were lower in the case of the textured cutting insert, indicating a more stable cutting process.

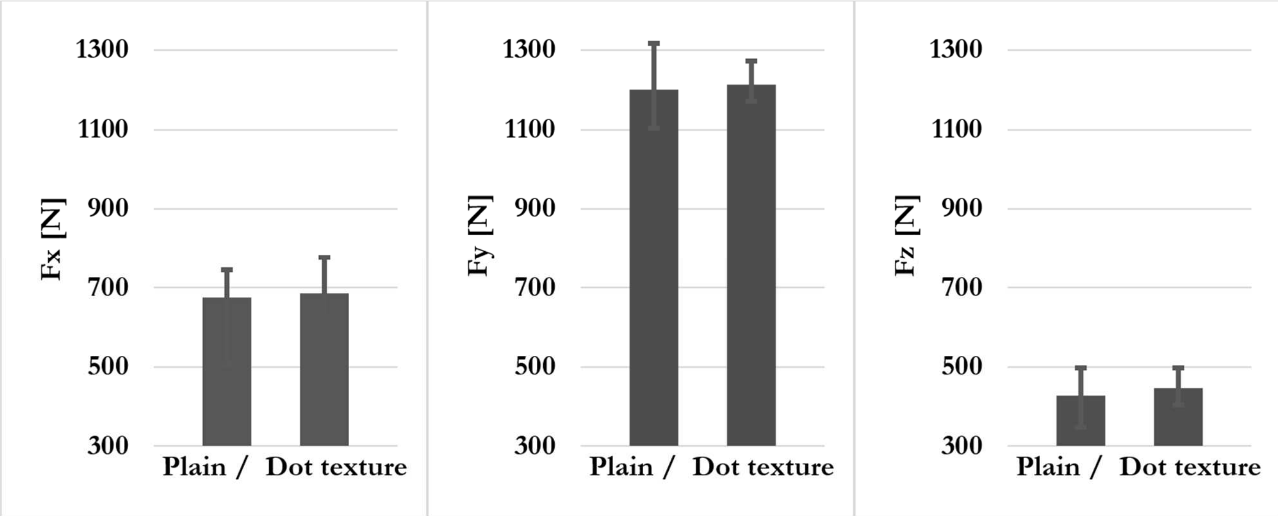

Fig. 15 *Comparison of average force values of cutting inserts without texture (plain) and with dot texture*

In the case of texturing with a dot pattern, the measurements revealed that during the long-term experiment, a negative phenomenon occurred at the edge of the replaceable cutting insert in the form of protrusions. These protrusions are formed by adhering to the workpiece material.

5 Conclusion

This study successfully explored the effects of micro-texturing on the performance and longevity of uncoated replaceable cutting inserts during machining processes, specifically focusing on the implementation of dotted patterns created via a fiber laser on rake flat surfaces. The experimental results highlighted the dual nature of microtexturing impacts, and the creation of dotted patterns led to the formation of protrusions at the cutting edge, adversely affecting the machined surface quality. This phenomenon was attributed to the adherence of the material to the textured dots, which acted akin to a "grater," negatively impacting the surface finish. A summary of the study highlights is as follows:

- Microtexturing of cutting tools improves tribological performance and reduces friction in machining operations.
- Laser surface microtexturing is a key technique for enhancing the tool performance.
- Dot-textured tools exhibit a higher longevity than line-textured tools.
- Parallel texturing can reduce the friction by up to 6 %.
- The findings of this study offer insights into broader implications for energy-efficient machining.
- This study highlighted the intricate relationship between microtexturing patterns and tool performance.

However, a notable positive outcome was the reduction in the variability of cutting forces, attributed to the facilitation of chip sliding along the voids created by the textured dots. This not only suggests an improvement in the stability of the cutting process but also hints at potential enhancements in tool longevity owing to the formation of an air cushion by the textured dots, aiding in a more uniform cutting experience.

The comprehensive analysis revealed that despite the physical alterations observed on the tool surface due to texturing, such as material buildup and edge fracturing, the overall dynamics of the cutting forces remained stable and improved in terms of predictability and stability. This stability, achieved without significantly altering the fundamental force profiles, underscores the complex relationship between tool surface design, operational performance, and wear characteristics in the absence of process fluids.

In conclusion, micro-texturing with dotted patterns, while presenting challenges in terms of surface quality due to protrusion formation, holds promise for reducing force variability and potentially enhancing tool life and operational efficiency. Future investigations, particularly short-term tests, are recommended to further dissect the impact on the machined surface quality and chip formation. Such studies could illuminate pathways to optimize cutting processes for better energy efficiency and tool durability, and also refine the application of surface texturing techniques for broader industrial applications.

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