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ORIGINAL ARTICLE

Analysis of the influence of geometric parameters of laser-produced texturing on carbide tools in Ti6Al4V turning

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Abstract

This study focuses on analyzing the influence of different groove texture geometries on carbide cutting tools for turning Ti6Al4V titanium alloy, exploring how different parameters (depth, width, spacing, direction, and distance from the cutting edge) affect machining performance. This work contributes to the advancement of machining techniques, promoting more efficient and sustainable processes, with potential practical applications in industries. The objectives include reducing machining forces while minimizing machining cost. The methodology employed advanced technologies, such as femtosecond lasers, to produce defect-free textures without thermal damage or microcracks. Initial results demonstrated that textured tools can significantly improve the machining process by reducing machining forces. The results showed that texture direction and distance from the cutting edge were the most influential parameters, while texture dimensions had a lesser impact. Furthermore, the effects of textures were found to vary with feed rate, highlighting the need for specific optimizations for different cutting regimes (such as roughing or finishing).

Keywords Laser texturing · Ti6Al4V · Tool texture optimization · Cemented carbide · Machining

1 Introduction

The titanium alloy Ti6Al4V has become one of the most widely used materials in high-performance applications, primarily due to its exceptional properties. Industries such as aerospace, biomedical, and automotive benefit from its excellent strength-to-weight ratio, remarkable corrosion resistance, and biocompatibility. Despite these advantages, machining Ti6Al4V remains a significant challenge. When subjected to conventional machining processes, its low thermal conductivity, combined with its high chemical reactivity, leads to accelerated tool wear, increased machining forces, and elevated temperatures at the cutting interface [1]. These factors make the material highly demanding in terms of manufacturing efficiency and cost.

From an engineering perspective, the difficulty in machining Ti6Al4V lies in the combination of its mechanical and thermal properties. Its low thermal conductivity limits heat dissipation, resulting in localized thermal gradients that exacerbate tool wear and surface degradation. Additionally, the high strength of Ti6Al4V, especially at elevated temperatures, imposes additional stresses on cutting tools, necessitating innovative machining approaches. The high reactivity of titanium with oxygen and nitrogen also results in the formation of hard and brittle compounds that further contribute to tool wear [1]. From an interdisciplinary standpoint, machining Ti6Al4V represents a convergence of materials science and mechanical engineering challenges. While materials science governs aspects such as thermo-mechanical behavior, chemical affinity, and wear mechanisms at the tool–workpiece interface, mechanical engineering addresses chip formation, force generation, heat dissipation, and process stability during cutting operations.

The search for improved machining strategies has led researchers and engineers to explore innovative solutions. Among these, the application of textured tools has emerged as a promising approach. According to works such as [2, 3],

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introducing micro- or nanoscale textures on the rake face of cutting tools can enhance lubrication, reduce friction, and optimize chip evacuation. These textures act as micro-reservoirs for cutting fluids or create controlled interruptions in the contact between the tool and the workpiece, resulting in improved machining performance.

The application of textured cutting tools has seen rapid advancements in academic research over the past decade. Studies have demonstrated how textures can be optimized for different machining conditions, offering benefits such as reduced machining forces, lower tool temperatures, and improved wear resistance. This has opened new possibilities for transitioning textured tools from controlled laboratory environments to industrial applications [4]. However, challenges remain in scaling up the production of textured tools, ensuring consistency, and validating their performance under diverse industrial conditions. Overcoming these challenges could enable the widespread adoption of textured tools in industries such as aerospace and automotive, revolutionizing machining practices.

Additionally, it has been observed that textures influence heat dissipation during the cutting process [5]. By minimizing heat accumulation at the cutting interface, textured tools can extend tool life and contribute to more consistent surface finishes on the machined part. The importance of these benefits is emphasized by the growing demand for high-precision components and reduced manufacturing costs across various sectors.

From a materials science perspective, the success of textured tools depends on the interaction between the tool material, the textured surface, and the workpiece material. For example, the chemical compatibility of Ti6Al4V with the tool plays a significant role in adhesive wear. The dimensions and orientation of the textures must be optimized to achieve a balance between mechanical strength and lubrication efficiency. These considerations highlight the interdisciplinary nature of laser-textured tool design, requiring understanding from both mechanical engineering and materials science.

The importance of tailoring textures for specific machining operations cannot be overlooked. Roughing operations, characterized by higher material removal rates, often demand textures that prioritize durability and thermal management. Conversely, finishing operations focus on achieving superior surface quality, requiring textures that promote lubrication and minimize surface defects [6]. This dual focus underscores the need for comprehensive studies, such as the present one, to meet the diverse requirements of modern machining.

This study focuses on analyzing the influence of different groove texture geometries on carbide cutting tools for turning Ti6Al4V titanium alloy. The primary objective is to understand how different texture parameters—such as depth, width, spacing, direction, and distance from the cutting edge—affect machining outcomes. Through a systematic experimental approach, the research seeks to identify optimal texture configurations that minimize machining forces. Femtosecond laser technology was used for texturing, which enables precise control over texture geometries without introducing heat-affected zones or microcracks on the tool surface.

These tools enable comprehensive exploration of parameters and facilitate the identification of statistically significant factors and interactions. The variables studied were determined based on initial exploratory experiments. However, most studies in the literature report only broad dimensional intervals for textured surfaces, without identifying which specific geometric configurations are truly effective. This lack of quantitative definition limits industrial reproducibility and scalability. Therefore, identifying statistically validated "best-point" geometries is essential for transitioning laser-textured tools from laboratory experimentation to commercially viable industrial applications.

2 Methodology

Based on information gathered from the literature review [7–43] and the available equipment, strategic combinations of variables related to textures were proposed for the experiments, blending previous approaches that investigated titanium machining with textured tools. This review was fundamental to define the values of the geometric parameters of the textures to be investigated. Among them, the following stand out:

- Direction: The textures were designed as linear channels in directions parallel and perpendicular to the primary cutting edge of the tool, as suggested by the literature, which identifies these directions as potentially improving machinability.
- Dimensions (depth, width, spacing): Two levels of depth were analyzed, maintaining correlation with width and spacing between the textures. This balance aims to avoid stress accumulation effects that could lead to tool breakage during cutting. The levels of these variables were determined through preliminary pre-tests.
- Distance from the Cutting Edge: A variable still underexplored but with potential impact on texture performance during cutting. Two different distances, also defined in pre-tests, will be tested.
- Feed Rate and Cutting Speed: Tests were conducted at two speed levels: one high value for titanium alloy

machining and another within a usual range for this material.

The levels of the input variables texted are given in Table 1. In defining these values, we considered the dimensional ranges commonly reported in the literature (including the articles and review papers referenced in this work) but intentionally extended them to explore a wider and still unexplored domain, enabling the statistical model to move toward an optimal texture configuration rather than remaining constrained to previously studied intervals. The experiments consisted in the turning of the Ti6Al4V with textured and untextured cemented carbide tools. The tests were conducted on textured tools, whose dimensions were defined based on average values found in the literature for titanium turning operations. Analysis of variance (ANOVA) was used through the STATISTICA software to identify the texture parameters with the greatest influence on machining forces. Eight different texture types were used, varying direction, depth, and distance from the primary cutting edge. Furthermore, two feed rates were used in the machining tests, thus configuring a complete factorial design of type 2^4 with replicates and triplicates of the tests. This feed rate variation is critical for exploring chip-tool contact length and its impact on machining performance. Smooth tools were also tested under the same machining conditions for comparison purposes. For each evaluated condition, a series of measurements were performed to generate sufficient data for calculating average values of the analyzed parameters. Machining force was considered as the output variable.

The cutting speed was fixed at 70 m/min, and the cutting depth was set to 1 mm, typical values for turning titanium alloys. Because chip–tool interaction and thermal behavior differ substantially between roughing and finishing, two representative feed-rate ranges were selected in this study (one typical of roughing and one typical of finishing) to demonstrate that texture performance is regime-dependent and that optimal geometries may vary between these two industrial conditions. The tests were conducted with an abundant application of Vasco 7000 cutting fluid from Blaser Swisslube, at a concentration of 7%, with a flow rate of 10 l/min and a pressure of 1.2 bar. The tools used were uncoated cemented carbide, specifically designed for machining titanium alloys, with the ISO code SPUN120304, class H13A, and the tool holder CSDPR 2525 M12, both manufactured by Sandvik Coromant.

The textures were produced using a femtosecond laser, which was polarized and configured with an emission centered at 800 nm, a temporal width of 30 fs, a maximum pulse energy of 200 μJ, and a repetition rate of 10 kHz. For the machining process, the laser beam was delivered into a "PRJ0221-Femtolasers" workstation from Laser Engineering Applications.

Force tests were conducted using a Kistler dynamometer model 9265-B, known for its high precision in measuring machining force components. During the experiment, the forces involved in the cutting process were measured using a dynamometer, which recorded three main components: the machining force, the feed force, and the passive force. The machining force acts in the primary direction of the tool's movement and is responsible for material removal. The feed

Table 1 Variables of stage 1: full factorial 2^4 design

Conditions	Types of Textures	Texture Variables			Cutting Variable
		Direction [°]	Distance From Cutting Edge [μm]	Dimensions: Depth [μm], Width [μm], And Spacing [μm]	Feed Rate [Mm/Rev]
1	T1.1	0	75	20-40-40	0,1
2	T1.2	90	75	20-40-40	0,1
3	T1.3	0	225	20-40-40	0,1
4	T1.4	90	225	20-40-40	0,1
5	T1.5	0	75	60-120-120	0,1
6	T1.6	90	75	60-120-120	0,1
7	T1.7	0	225	60-120-120	0,1
8	T1.8	90	225	60-120-120	0,1
9	T1.1	0	75	20-40-40	0,3
10	T1.2	90	75	20-40-40	0,3
11	T1.3	0	225	20-40-40	0,3
12	T1.4	90	225	20-40-40	0,3
13	T1.5	0	75	60-120-120	0,3
14	T1.6	90	75	60-120-120	0,3
15	T1.7	0	225	60-120-120	0,3
16	T1.8	90	225	60-120-120	0,3

force acts in the direction of the tool's displacement, influencing process stability and efficiency. The passive force, on the other hand, acts perpendicular to the machined surface, affecting the deflection of both the workpiece and the tool. With these measured values, the machining force was calculated as the resultant of the three recorded forces. This calculation was performed by summing the square of each force and then taking the square root of the result. The machining force is the force analyzed in this study, playing a key role in evaluating the process of behavior and the mechanical efforts involved in the operation. The forces were recorded in real-time at a frequency of 100 Hz and analyzed later to evaluate the impact of textures under different cutting conditions. Each test lasted an average of 15 s, ensuring process stabilization and reliable data collection.

Figure 1 illustrates the cutting edge of a textured tool, in this case the T1.7 condition. It can be seen that the textures occupy a square area of 9 mm^2. The image highlights some references to determine the geometric parameters of the groove-type texture. Line "A" indicates the main cutting edge, and line "B" indicates the direction of the texture groove. In this example, lines "A" and "B" are parallel, that is, the angle between the lines is 0° and therefore the "Direction" parameter of the texture is equal to 0° in this example. This "Direction" parameter is sometimes cited in the literature as a reference to the direction of chip flow, but in this present work, it was decided to use the main cutting edge as a reference.

Also in Fig. 1, we can see a distance "C" between lines "A" and "B", this distance is the "Distance From Cutting Edge", which defines the beginning of the first texture. This parameter "Distance From Cutting Edge" is essential. If it is too high, the chip may have little contact with the textured surface, and the texture in turn may generate a low or even zero effect during cutting. However, if the "Distance From Cutting Edge" is too low, the texture may weaken the mechanical resistance of the cutting tool and accelerate the appearance of cracks in the textures, as these may end up acting as a stress accumulator.

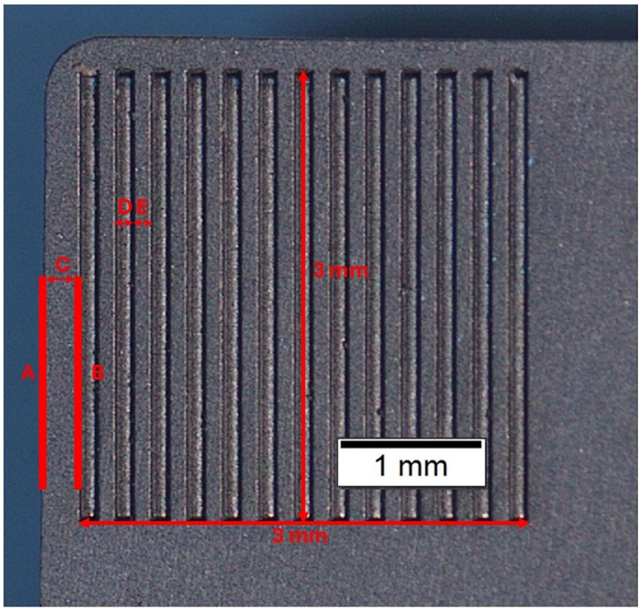

Fig. 1 Image of a cutting edge of a textured tool (in this case condition T1.7). The image highlights some references to determine the geometric parameters of the groove-type texture

The "Dimensions" of the texture can be seen in the distances "D" and "E", which are respectively "Width" and "Spacing" and have the same value, which is numerically equal to twice the "Depth" of the texture. The size of the "Width" and "Depth" can impact on the texture's mechanism, varying between effects such as reducing the contact area between chip and tool, adhesion effect, anchoring, and debris retention. The size of the "Spacing" impacts the intensity with which these effects will be applied to the process.

3 Results and discussion

The use of femtosecond lasers was crucial for obtaining defect-free textures. The precision in geometric control of the textures allowed a reliable evaluation of their influence without interference caused by flaws in the texturing process. Additionally, the analysis of the obtained data reinforces the importance of expanding study ranges for future experiments, ensuring broader coverage of evaluated conditions.

Figure 2 presents the results of machining forces for a feed rate of 0.1 mm/rev, comparing the eight analyzed texture types. The orange line represents the value obtained for the untextured (smooth) tool, serving as a reference for analyzing the impact of textures in machining. Red bars indicate textures that resulted in increased average machining forces compared to the smooth tool, while green bars represent textures that promoted a reduction in the average machining force.

It is observed that some textures resulted in lower machining forces compared to the smooth tool, suggesting a beneficial effect of texturing on the tool-chip interface. Conversely, some textures showed inferior performance, with force values higher than those of the smooth tool, which may be associated with a negative effect on lubrication or stability of the tool-chip contact. Relatively high error bars in some textures indicate greater variability in the data, which will be analyzed in future studies for a better understanding of the involved factors. It is important to emphasize that this behavior directly supports one of the main gaps identified in the literature: despite extensive discussion of textures, most authors still provide only dimensional intervals instead of

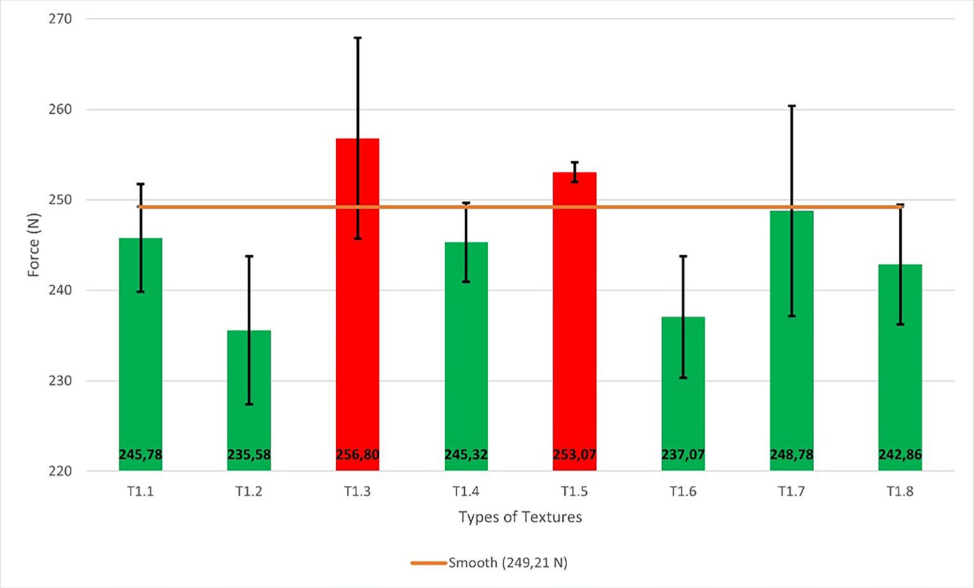

Fig. 2 Average Machining Forces for a Feed Rate of 0.1 mm/rev

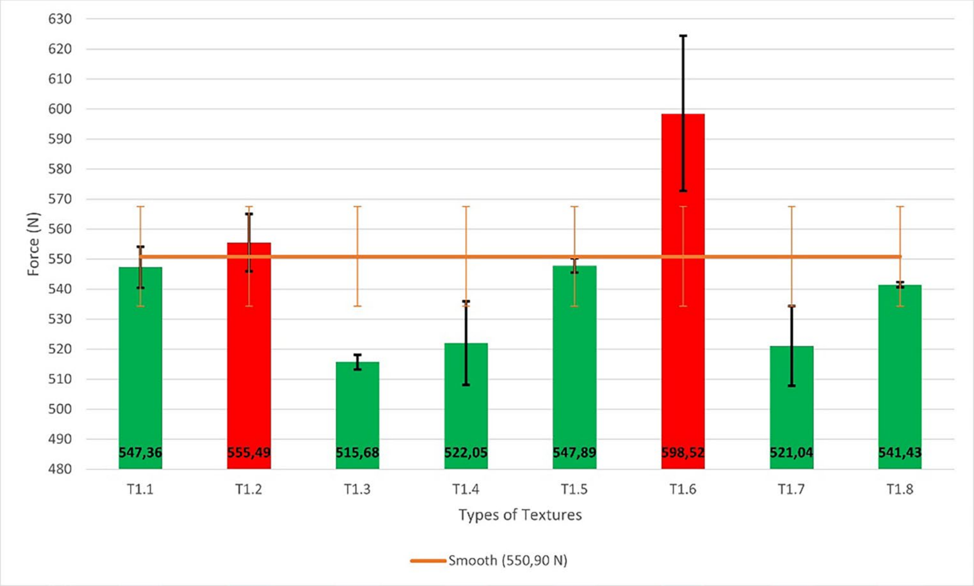

Fig. 3 Average Machining Forces for a Feed Rate of 0.3 mm/rev

statistically supported geometries. By establishing parameter significance, this work advances the definition of optimal texture configurations rather than generic ranges.

The relatively high error bars observed in some textured conditions indicate increased variability in the machining forces. These larger variations were predominantly associated with texture configurations that resulted in higher average forces than the smooth tool, in which vibrations were observed during machining, suggesting unstable chip–tool interaction. Such instability may be related to intermittent contact, groove clogging, or fluctuations in lubrication effectiveness. Furthermore, it should be noted that, due to the narrow force scale adopted in the graphs, relatively small absolute force variations may visually appear as large error bars.

Figure 3 presents the results of machining forces for a feed rate of 0.3 mm/rev. Unlike the behavior observed at 0.1 mm/rev, where textures parallel to the cutting edge showed the best results, at this higher feed rate, the trend reversed. Textures with greater distance from the cutting edge resulted in lower machining forces. This suggests that the interaction between the chip and the textured surface may be differently influenced depending on the applied feed rate, directly impacting material removal efficiency and process stability. This may indicate that different processes such as roughing or finishing may require different textures.

Once again, red bars represent textures that resulted in forces higher than those of the smooth tool, while green bars represent those that reduced machining forces. The observed variations reinforce the need for further studies

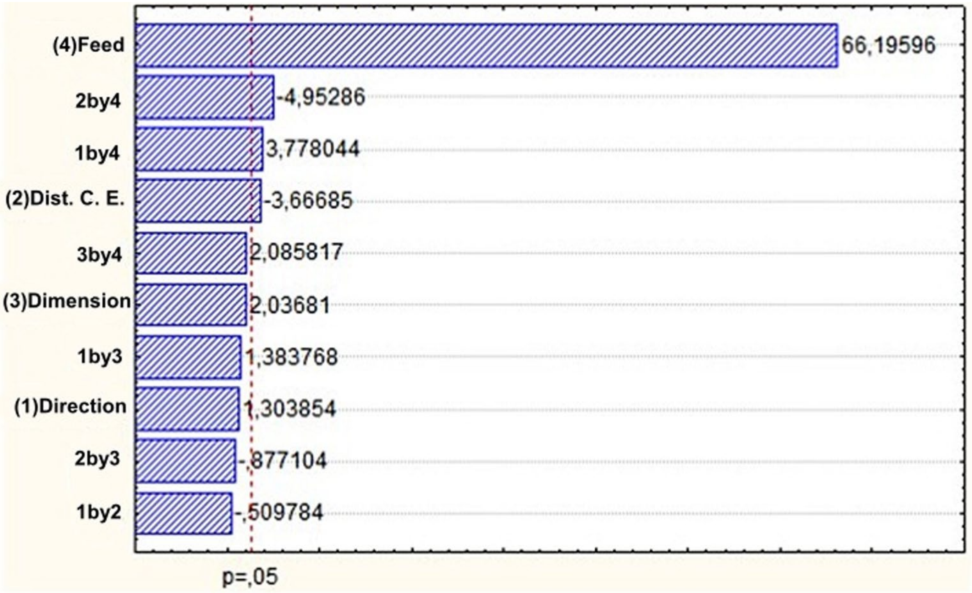

Fig. 4 Influence of parameters on machining force generated from an Analysis of Variance (ANOVA)

on the interaction between different texture parameters and cutting conditions to better understand the mechanisms involved and refine textured geometries.

There are instances where perpendicular textures reduced the machining force at lower feed rates but worsened it at higher feed rates, while parallel textures had the opposite effect. This likely indicates that the mechanism of texture interaction changes with the feed rate. At lower feed rates, a perpendicular texture to the cutting edge facilitates chip flow, but at higher feed rates, probably the flow clogs the channels, increasing chip friction. Conversely, a parallel texture hinders chip flow at lower feed rates, but at higher feed rates, it does not act as a barrier to chip flow. Instead, it reduces the contact area, favoring a reduction in forces. As expected according to previous review studies such as [2], the influence of the grooves is governed by chip–tool interaction mechanisms: at lower feed rates, the textures may reduce the real contact area and guide chip flow, whereas at higher feed rates the increased chip thickness may promote clogging or instability inside the grooves, reversing their effect.

Figure 4 shows the Pareto's chart, highlighting the influence of parameters on machining forces based on statistical analysis. Through ANOVA, it was possible to identify the parameters and their significance in the process. As expected, feed rate was the most influential factor in machining titanium, accounting for the largest variation in machining force. Individually, the distance of the cutting edge variable was significant, but the parameters of texture direction and dimension did not show statistical significance. However, texture direction became significant when varied in conjunction with feed rate. On the other hand, texture dimension did not show relevant impact under any tested conditions.

The study confirmed that among the evaluated parameters, texture direction and the distance from the cutting edge had the most significant impact on machining forces, while texture dimensions were the least influential. This behavior might be related to the range of variation adopted in this study, which may not have been broad enough to capture the full impact of this parameter. In view of this, it is possible to affirm that in the database found in the literature, researchers usually investigate textures with dimensions remarkably close to each other.

4 Conclusion

This study enabled the identification of the most influential parameters affecting machining forces. The study determined which texture parameter most influences machining forces in Ti6Al4V machining. This outcome provides a quantitative pathway toward identifying a best-point texture configuration, which is a necessary condition for industrial adoption. Because commercial implementation requires precise and repeatable geometries—not dimensional intervals—this study establishes an essential step toward transferring laser texturing technology into industrial machining practice. The results indicated that texture direction and distance from the cutting edge significantly impact on the process, whereas texture dimensions were the least influential. The analysis revealed that the distance from the cutting edge and the texture direction play crucial roles in this process. Additionally, the variation in feed rate significantly affects the texture's behavior, underscoring the necessity for specific optimizations tailored to different cutting conditions.

With these results, the future work will progress to the next phase, emphasizing the identification of optimal texturing conditions. Future work will focus on the optimization of the most influential texture parameters using statistically based techniques, such as response surface methodology (RSM), to identify optimal geometries for specific cutting regimes. A more refined experimental design will facilitate the determination of the most effective configurations, paving the way for practical applications of these findings in industry. Consequently, this study contributes to advancing machining techniques, fostering more efficient and sustainable processes. The research will advance to the next phase, focusing on identifying the optimal texturing conditions. Through a more refined experimental design, it will be possible to determine the most efficient configurations, favoring the practical application of these findings in the industry. Thus, this study contributes to the advancement of machining techniques, promoting more efficient and sustainable processes.

The analysis conducted revealed that certain parameters, such as the distance from the cutting edge and the texture direction, play significant roles in reducing machining forces. Furthermore, it was identified that the influence of the texture varies according to the applied feed rate, indicating that texture optimization must take the specific cutting regime into account. Indicating that different processes, such as roughing or finishing, may require distinct types of textures.

Although the texture dimension was identified as the least influential parameter, the analysis suggests that broader intervals might reveal greater relevance. Subsequent stages will aim to optimize the parameters identified as the most important, with the goal of developing textured tools that outperform smooth tools in performance.

This study highlights the importance of advanced technologies, such as femtosecond lasers, which were crucial for the success of the initial analyses, enabling defect-free textures that accurately represent the expected behavior under real machining conditions.

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Declarations

Conflicts of interest/Competing interests The authors declare that they have no conflicts of interest or competing interests related to this work.

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