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TI6AL4V TURNING WITH FEMTOSECOND LASER TEXTURED TOOLS: OPTIMIZATION OF TEXTURE GEOMETRIES

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Abstract. *Machining the Ti6Al4V alloy is challenging due to its mechanical properties, such as high strength, low thermal conductivity, and very reactive against all the tool materials available. To address these challenges and enhance process efficiency, strategies such as tool texturing have emerged as promising alternatives. This research investigated the effect of groove-type textures produced by femtosecond laser on the rake face of carbide tools during the turning of the Ti6Al4V (grade 5) alloy, using flooding application of cutting fluid. Various texture configurations were studied, with a particular focus on texture orientation, dimensions, and distance from the cutting edge, as well as feed rate as a key cutting parameter. The objective was to understand the impact of these textures on machining performance and optimize the process, primarily by analyzing cutting forces and workpiece roughness as response parameters. Initially, the texture characteristics were defined based on average values found in the literature for turning Grade 5 titanium, ensuring a well-founded approach to selecting the experimental conditions. To optimize the process, a CCD (Central Composite Design) and RSM (Response Surface Methodology) were used, allowing statistically organized experiments to be conducted. This method enabled the development of predictive models that help understand the behavior of textured tools under different machining conditions. The results showed that the effectiveness of texturing is not uniform across all feed rate ranges investigated. In certain conditions, textures reduced cutting forces and improved the quality of the machined surface, while in others, they did not provide significant benefits, although the cutting forces were more sensitive to texture variations than workpiece surface roughness. Overall, the results of this study demonstrate that femtosecond laser texturing of tools is a promising strategy for improving the turning of the Ti6Al4V alloy.*

Keywords: *Laser texturing, Titanium Ti6Al4V, texture optimization, machining, turning*

1. INTRODUCTION

The titanium alloy Ti6Al4V has become a material of choice for numerous high-performance applications, thanks to its outstanding combination of properties. Sectors such as aerospace, biomedical, and automotive industries leverage their superior strength-to-weight ratio, excellent corrosion resistance, and biocompatibility. However, despite these advantages, machining Ti6Al4V poses significant challenges. Its poor thermal conductivity coupled with high chemical reactivity leads to rapid tool wear, increased cutting forces, and elevated temperatures at the cutting zone when using conventional machining techniques. These issues make the manufacturing of this alloy both demanding and costly [1].

From an engineering standpoint, the machining difficulty of Ti6Al4V stems from the interplay between its thermal and mechanical characteristics. Its inability to efficiently dissipate heat causes localized thermal gradients, which accelerate tool wear and degrade surface quality. Additionally, the alloy maintains high strength even at elevated temperatures, subjecting cutting tools to severe mechanical stresses. Its strong affinity for oxygen and nitrogen further contributes to tool deterioration through the formation of hard and brittle compounds.

Driven by the need to improve machining performance, researchers have turned their focus to innovative techniques. One particularly promising solution is the application of textured cutting tools. Studies such as [2] indicate that introducing micro- or nano-scale textures on the rake face can enhance lubrication, lower friction, and facilitate chip evacuation. These textures serve as micro-reservoirs for lubricants or create controlled interruptions in the tool–workpiece contact, resulting in enhanced machining efficiency.

Over the past decade, research into textured cutting tools has gained considerable attention. Experimental results show that when meticulously designed, tool textures can significantly reduce cutting forces, decrease tool temperatures, and improve wear resistance. This progress has opened avenues for moving textured tools beyond research labs into industrial manufacturing [3]. Nonetheless, challenges persist in scaling the production process, ensuring uniform texture quality, and validating tool performance under varied industrial conditions. Addressing these obstacles is crucial to enabling the broader adoption of textured tools, particularly in industries like aerospace and automotive.

Further research has also demonstrated that surface textures influence heat generation and thermal management during machining [4]. By mitigating heat buildup at the tool–chip interface, textured tools contribute to longer tool life and produce more consistent surface finishes on the machined parts. These benefits are especially relevant given the increasing demand for high-precision components and cost-effective manufacturing solutions across multiple sectors.

From a materials science perspective, the effectiveness of textured tools depends on the complex interaction between the tool material, the textured surface, and the workpiece. The chemical compatibility between Ti6Al4V and the tool material plays a vital role in minimizing adhesive wear. Furthermore, the dimensions, orientation, and distribution of textures must be carefully optimized to balance mechanical integrity with lubrication efficiency. This highlights the interdisciplinary nature of designing laser-textured tools, requiring collaboration between mechanical engineering and materials science disciplines.

Tailoring texture designs to specific machining tasks is a critical consideration. For example, roughing operations, which involve high material removal rates, require textures that prioritize durability and thermal control. In contrast, finishing operations demand textures that enhance lubrication and minimize surface imperfections to achieve excellent surface quality [5,6]. This dual requirement underscores the necessity of comprehensive studies like the present one to support diverse machining needs.

This research specifically investigates the optimization of texture geometries for carbide cutting tools employed in turning Ti6Al4V. The main goal is to evaluate how different texture parameters (such as depth, width, spacing, orientation, and proximity to the cutting edge) impact machining performance. Through a systematic experimental framework, the study aims to identify the optimal texture configurations that reduce cutting forces and tool wear while maintaining or improving surface finish quality. Emphasis is placed on using femtosecond laser technology, which allows precise texture fabrication without causing heat-affected zones or microcracks on the tool surface.

The methodology integrates advanced design of experiments approaches, including Response Surface Methodology (RSM) and Central Composite Design (CCD). These techniques enable a comprehensive analysis of the parameter space and help identify key factors and their interactions that significantly influence response parameters.

2. MATERIALS AND METHODS

Based on the information gathered from the literature [7–11] and the constraints of the available equipment, a set of strategic combinations of texture parameters was developed for the initial experimental pre-tests. This approach integrated methodologies from prior studies focused on titanium machining with textured cutting tools. The key factors considered in the design of experiments were as follows:

- Direction: Textures were applied in the form of linear grooves oriented either parallel or perpendicular to the primary cutting edge. These directions were selected based on prior evidence suggesting their potential to improve machinability. The groove directions applied to the rake face of the tools in this study were initially set at 0 degrees and 90 degrees, corresponding to orientations parallel and perpendicular to the cutting edge, respectively. This choice was guided by the average trends observed in the literature, which frequently adopt these directions due to their considerable influence on chip formation mechanisms, friction reduction, and heat dissipation at the tool–workpiece interface during machining operations.
- Dimensions (depth, width, spacing): based on preliminary tests, the texture dimensions were defined as 20 μm in depth, 40 μm in width, and 40 μm in spacing. Width and spacing were scaled proportionally. This proportionality was adopted to prevent stress concentration that could otherwise lead to premature tool failure.
- Distance from the cutting edge: Despite being underexplored in the literature, the distance between the texture and the cutting edge was considered a variable of interest due to its potential influence on performance. Two distance levels, determined through pre-testing, were incorporated. The selected distances from the cutting edge to the beginning of the texture were 75 μm and 225 μm. These values were

chosen based on average values reported in the literature, while also extending the upper limit to explore potential effects beyond the commonly studied ranges.

- Feed rate and cutting speed: Experiments were conducted at two cutting speeds—one representing a high-speed regime for titanium alloys and the other corresponding to typical machining conditions for this material. The initial feed rates selected for this study were 0.1 mm/rev and 0.3 mm/rev. These values were defined based on average feed rates commonly reported in the literature for turning operations involving titanium alloys. This range was chosen to represent distinct machining conditions: a lower feed rate associated with finishing operations, aiming for better surface quality, and a higher feed rate representative of roughing conditions, where material removal rate becomes a priority.
- Lubrication strategy: Tool life tests were carried out under two lubrication conditions: conventional flood cooling and the application of a solid lubricant (molybdenum disulfide, MoS_2) embedded within the textures. MoS_2 was evaluated for its potential as an environmentally sustainable alternative to liquid coolants.

The textures were fabricated on the rake face of cemented carbide cutting tools using a femtosecond Ti:sapphire laser system in conjunction with a Femtopower Double amplifier operating at 10 kHz. Both devices were manufactured by Femtolasers Produktions GmbH.

Figure 1 illustrates the rake face of a textured cutting tool, highlighting the main geometric parameters that were systematically varied in this study. These parameters include the groove direction, the distance from the cutting edge to the start of the texture, and the groove dimensions (depth, width, and spacing). This visual representation is fundamental to understanding how each texture characteristic influences the cutting performance, particularly in terms of cutting force reduction and surface quality improvement.

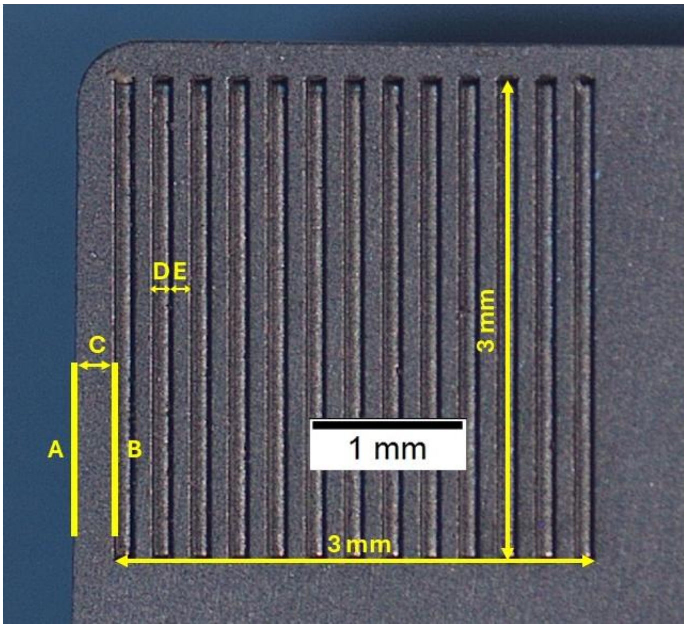

Figure 1. Image of the rake face of a textured tool. The image identifies the dimensional parameters of the groove-type texture varied.

The cutting forces were recorded using a Kistler 9265-B dynamometer, renowned for its precision in force measurement during machining. Each test was carried out over an average duration of 15 seconds, ensuring process stability and consistent data acquisition. The equipment was configured to capture all three force components (cutting, feed, and radial) with a frequency of 1000 Hz, providing a comprehensive assessment of the mechanical behavior of textured tools compared to smooth ones.

The surface roughness of the titanium workpiece after machining was measured using a Taylor Hobson Surtronic S-128 surface roughness tester. For each machined surface, three measurements were taken, spaced 120° apart by rotating the cylindrical workpiece. A Gaussian filter was applied with a cut-off value of 0.8 mm, a sampling length of 100 µm, and an evaluation length (Lm) of 4 mm. These parameters were selected based on the NBR ISO 4288 standard (Geometrical product specifications: Rules and procedures for the assessment of surface texture). The roughness parameters analyzed were Ra – arithmetic average roughness, Rq – root mean square roughness, and Rz – average maximum height of the profile. Data processing and analysis were performed using the TalyProfile Lite software.

Through preliminary tests, the results were used to develop a Central Composite Design (CCD) within the framework of Response Surface Methodology (RSM). This enabled the determination of optimal texture parameter combinations that minimized cutting forces or enhanced other performance metrics. The optimized conditions were subsequently validated against the results from smooth tools to quantify performance improvements.

Figure 2 presents an example of an optimized texture configuration derived from the CCD-RSM analysis. This optimum was achieved by systematically varying texture parameters (depth, width, spacing, direction, and distance from the cutting edge) under diverse machining conditions. The selected texture configuration was then benchmarked against a smooth tool to evaluate its effectiveness.

After that, the optimal texture geometry was used to investigate the combined effects of cutting speed, texture presence (smooth vs. textured), and the application of MoS_2. This phase was based on a full factorial design, assessing response variables including tool life, cutting forces, surface roughness, and chip morphology.

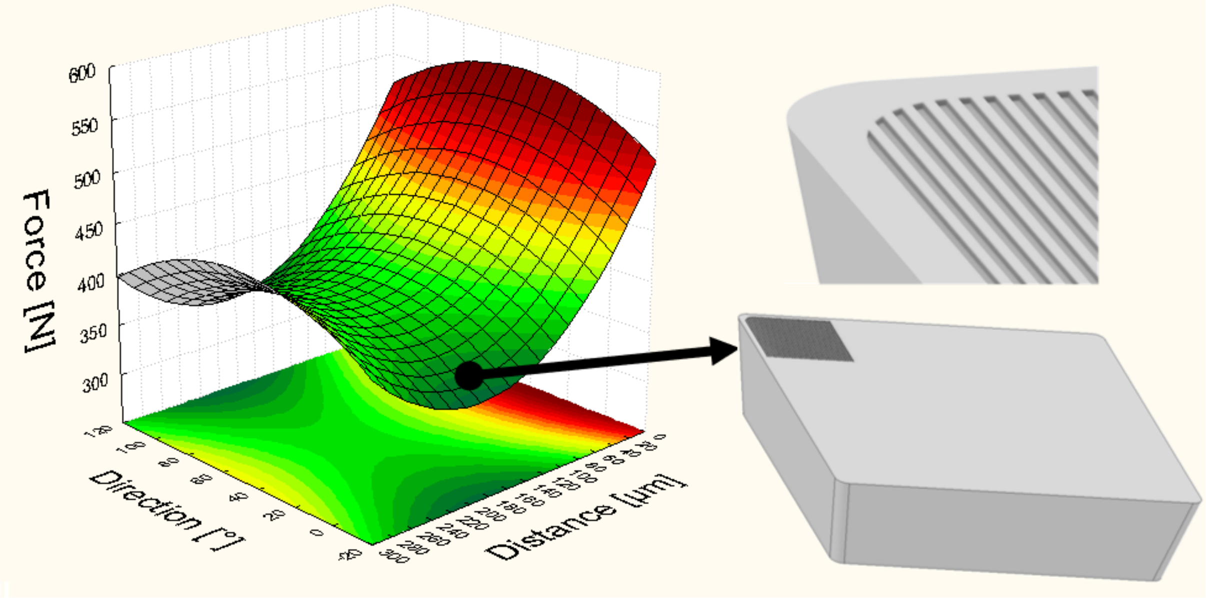

Figure 2. An example of RSM indicating the optimum point for some texture parameters. Illustrative graph generated from pre-tests.

3. RESULTS AND DISCUSSION

3.1 Optimization results

The texture dimension parameter (depth, width, and spacing) was identified as the least influential within the range investigated. As a result, the subsequent optimization process focused exclusively on the remaining geometric parameters of the texture (namely, groove direction and distance from the cutting edge) which demonstrated a more significant impact on machining performance indicators such as cutting force and surface roughness.

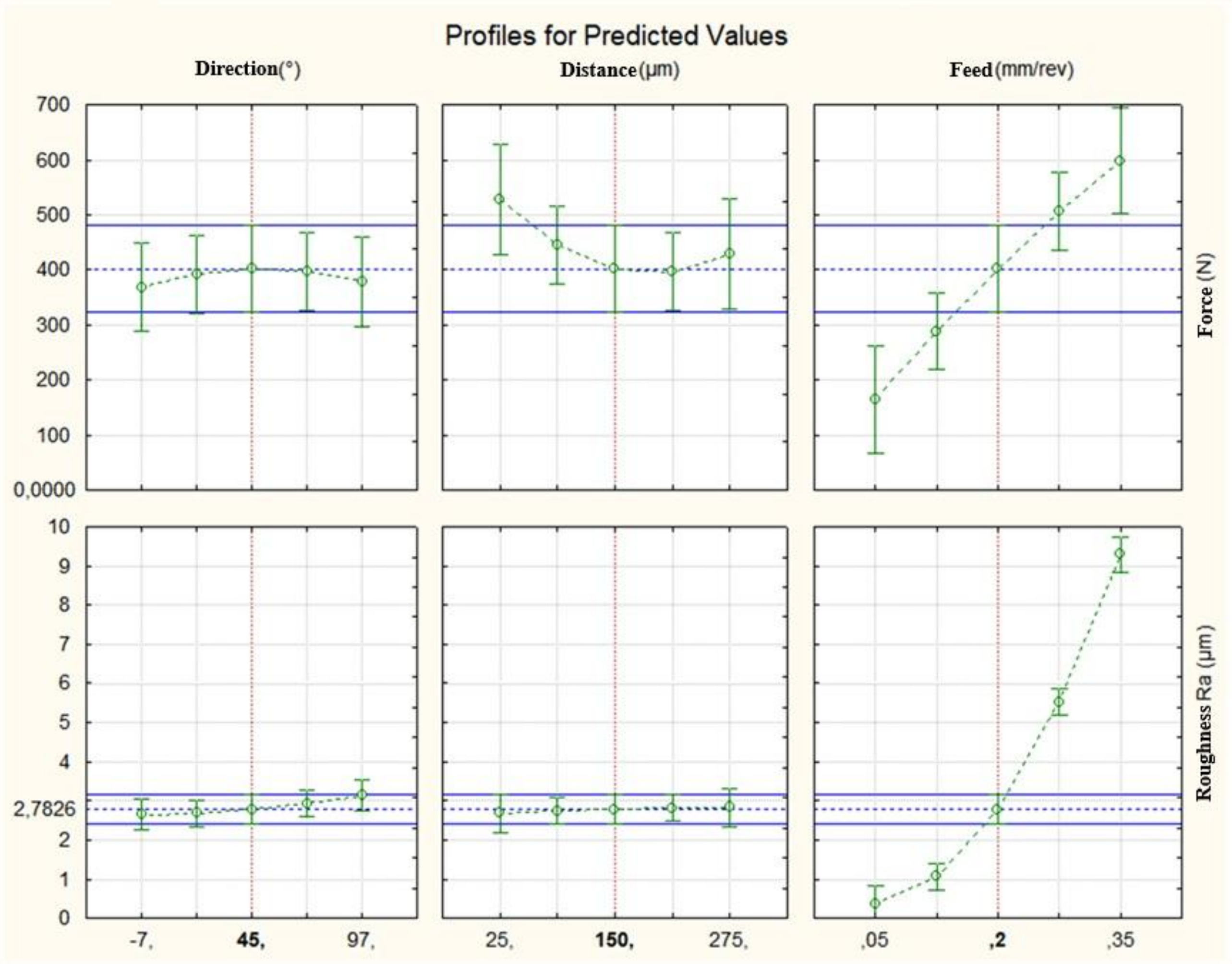

Figure 3. Analysis of the Predicted Profiles for Cutting Force and Surface Roughness

The Figure 3 presents profile plots for the predicted values of cutting force (N) and surface roughness Ra (μm) as functions of three input parameters: groove direction (°), distance from the cutting edge (μm), and feed rate (mm/rev). These plots are instrumental in identifying the optimal texture parameters that minimize both cutting force and surface roughness.

The analysis of the response surface profiles revealed that groove direction, distance from the cutting edge, and feed rate significantly influence cutting force and surface roughness. Regarding groove direction, the lowest cutting forces were observed when the grooves were aligned either parallel (0°) or perpendicular (90°) to the cutting edge, suggesting that these orientations minimize friction and enhance chip flow. However, when surface roughness is also considered, the optimal direction becomes more evident: the 0° orientation consistently resulted in the lowest Ra values, while increasing the groove angle direction led to a gradual deterioration in surface finish. This indicates that textures aligned parallel to the cutting edge are more effective in reducing surface irregularities. Thus, although both 0° and 90° orientations contribute to lower cutting forces, only the parallel direction (0°) offers simultaneous benefits for surface quality, making it the most balanced configuration when optimizing for both performance metrics.

As for the distance from the cutting edge, the results demonstrated a clear minimum in cutting force at approximately 200 μm. Distances significantly closer (e.g., 25 μm) or farther (e.g., 275 μm) from the edge led to an increase in cutting force, possibly due to ineffective positioning of the texture in relation to the chip formation zone. Interestingly, this parameter had a negligible effect on surface roughness, which remained relatively constant across the tested range. This finding suggests that the mechanical engagement of the texture with the chip is more sensitive to distance than the formation of the final surface finish.

Feed rate was found to have a pronounced effect on both cutting force and surface roughness. As feed rate increased, both parameters rose significantly, consistent with expectations due to the greater cross-sectional area of the removed chip and higher mechanical loading. While higher feed rates are often desirable for improving productivity, this gain comes at the cost of increased tool stress and surface degradation, reinforcing the need for careful trade-off analysis in practical applications.

In summary, when both cutting force and surface roughness are considered simultaneously, the combination of a groove direction at 0°, a distance of 200 µm from the cutting edge, and the lowest feasible feed rate within process constraints offers the most favorable outcomes. This highlights the importance of multi-objective optimization in the design of textured cutting tools, where surface integrity and machining efficiency must be jointly addressed. While optimizations based solely on cutting force might tolerate perpendicular textures, incorporating surface quality criteria clearly points to parallel grooves as the more robust solution for industrial applications.

The groove direction was optimized to align approximately parallel to the cutting edge (0°), as this orientation yielded both reduced cutting forces and lower surface roughness. As for the distance from the cutting edge to the start of the textured region, the optimal value identified through response surface analysis was approximately 182 µm. For practical and manufacturing purposes, this distance was rounded to 200 µm in the final configuration. This slight adjustment maintained the benefits observed during testing while facilitating reproducibility in industrial settings.

3.2 Machining results with optimized texture

To validate the performance of the optimized texture configuration under realistic machining conditions, a new experimental phase was conducted using a Romi Multiplic 35D CNC lathe. This section presents the procedures, parameters, and results associated with these validation tests, which aimed to assess the practical applicability of the textured tools beyond the initial controlled design of experiments. The use of an industrial-grade CNC lathe allowed for the reproduction of conventional production conditions and enabled the evaluation of tool behavior under consistent, programmable, and repeatable machining cycles.

The tool was tested under two distinct cutting regimes to assess its robustness: a finishing condition (cutting speed of 100 m/min, feed rate of 0.1 mm/rev, depth of cut of 1 mm) and a roughing condition (cutting speed of 70 m/min, feed rate of 0.3 mm/rev, depth of cut of 2 mm). These tests confirmed that the selected parameters were effective across different machining scenarios, demonstrating the versatility of the optimized texture design under varying mechanical and thermal loads.

By applying the previously defined optimal texture—characterized by reduced groove dimensions, parallel orientation to the cutting edge, and a distance of 200 µm from the tool tip—this results served to confirm the benefits observed in earlier pre-tests and to investigate the robustness of the texturing strategy in a more representative manufacturing environment.

Figure 4 shows the average cutting forces measured for three tool conditions: smooth (untextured), textured without MoS_2, and textured with MoS_2. Across both finishing and roughing operations, the textured tools outperformed the smooth tools, confirming that the presence of surface texturing contributes to reduced machining forces. Notably, the addition of MoS_2 further enhanced this effect, particularly under roughing conditions, where cutting forces were significantly higher.

The only condition in which texturing yielded a detrimental effect during bar turning was in terms of cutting force under finishing conditions, specifically when MoS_2 was applied to the textured grooves. However, when considering the error bars, it becomes evident that some individual tests within this condition outperformed the untextured tool. On average, though, the results were less favorable. This variability may be attributed to the high cutting speeds characteristic of finishing operations, which could have led to the rapid and complete depletion of the solid lubricant. The abrupt transition from a lubricated to a non-lubricated state may have disrupted the chip flow dynamics, thereby negatively affecting the cutting process.

This suggests that textures alone are effective in reducing tool–chip contact friction and facilitating chip flow, but the incorporation of a solid lubricant enhances this effect by providing continuous lubrication at the interface. The difference in cutting force reduction between the textured and MoS_2-coated tools was more pronounced during roughing, indicating that the benefits of solid lubrication become more evident under higher thermal and mechanical loads.

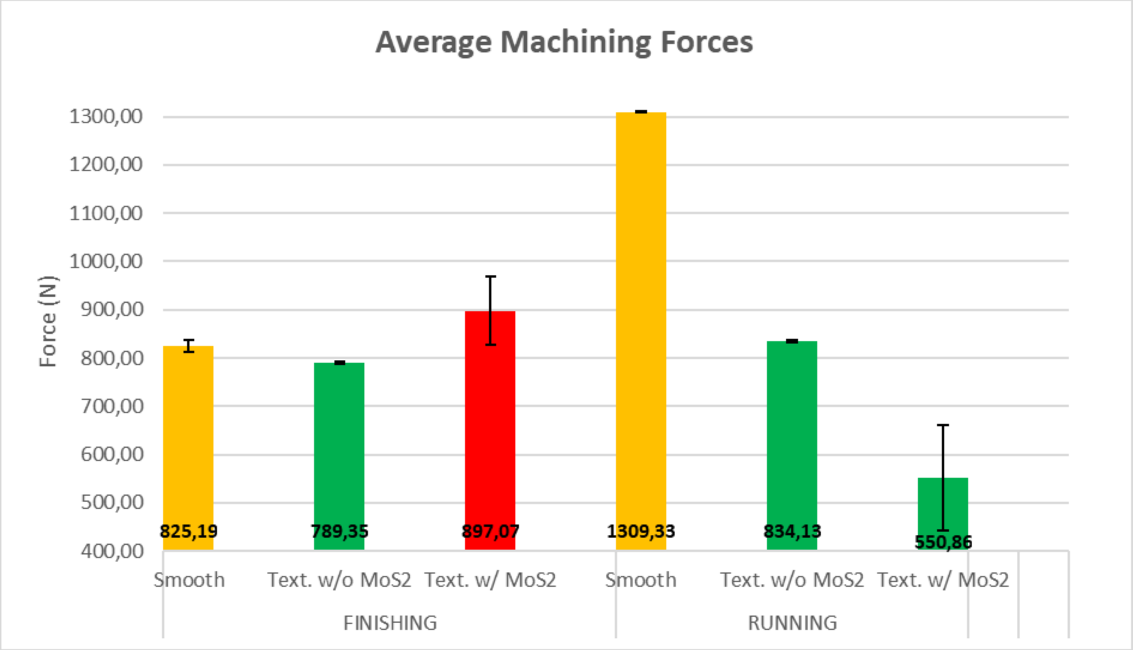

Figure 4. Average machining forces of the optimized texture with (w/) and without (w/o) MoS_2 compared to a smooth tool

Figure 5 illustrates the Ra values obtained for each tool configuration under finishing and roughing conditions. As expected, roughing operations led to higher roughness levels due to the increased feed rate. Even under roughing conditions, the textured tool with MoS_2 achieved better surface quality than the smooth tool under finishing parameters—demonstrating the strong potential of this approach.

Among the three configurations, the textured tool with MoS_2 consistently delivered the lowest Ra values. This outcome reinforces the hypothesis that groove-type textures aligned with the cutting direction help in chip evacuation and reduce vibration, while MoS_2 contributes to smoother cutting by reducing friction at the tool–workpiece interface.

The surface roughness improvement from MoS_2 is relatively more significant under finishing conditions. This suggests that in lower-load scenarios, the lubrication effect becomes more critical in controlling minor surface irregularities, while in roughing, the mechanical removal action dominates the surface formation mechanism.

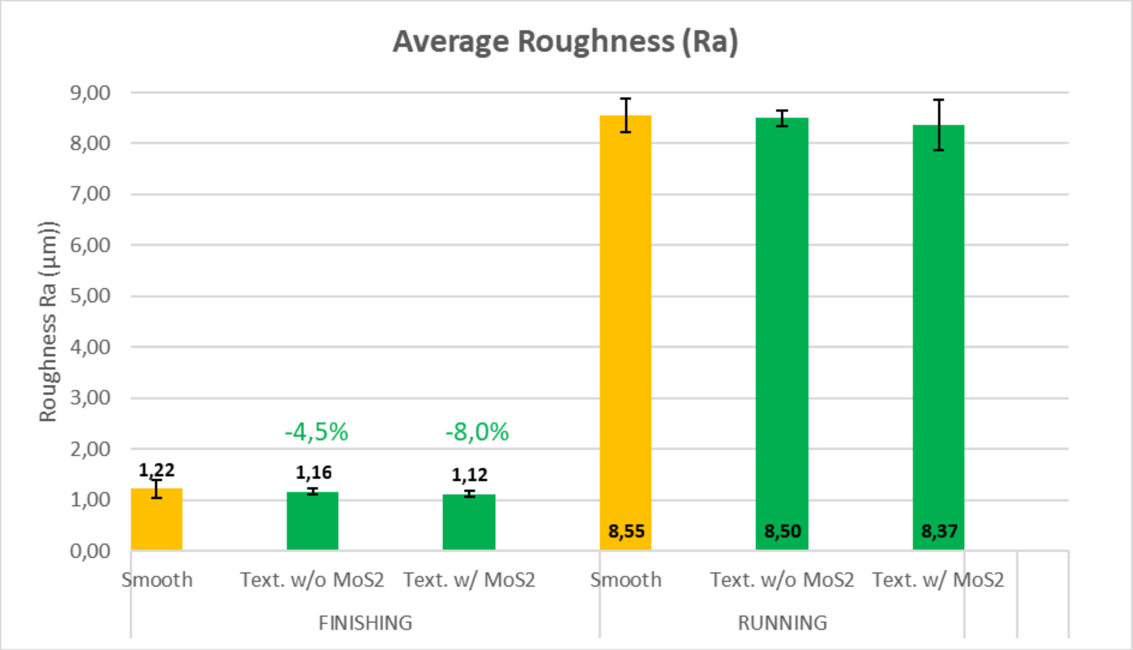

Figure 5. Average roughness (Ra) of the optimized texture with (w/) and without (w/o) MoS_2 compared to a smooth tool

4. CONCLUSIONS

This study evaluated the effect of femtosecond laser-generated textures on the machining performance of Ti6Al4V alloy using cemented carbide cutting tools. After optimizing the geometry of the grooves through experimental design and response surface analysis, the final configuration—grooves 20 µm deep, 40 µm wide, and spaced at 40 µm, oriented at 0° (parallel to the cutting edge) and positioned 200 µm from the tool tip—was tested under both finishing and roughing conditions. The textures were applied with and without the addition of a solid lubricant (MoS_2), allowing for a comprehensive evaluation of their effectiveness.

In terms of cutting forces, the results revealed distinct behaviors depending on the cutting regime. Under finishing conditions, the dry textured tool produced a modest reduction of 4.3% compared to the smooth tool. However, when MoS_2 was added to the grooves, the cutting force unexpectedly increased by 8.7%, marking the only scenario in which texturing negatively affected machining performance. This result suggests that, at lower loads and reduced chip formation intensity, excess solid lubricant may interfere with the chip–tool contact or even destabilize the chip flow, leading to increased mechanical resistance. On the other hand, in roughing operations, where thermal and mechanical demands are significantly higher, the effects were far more beneficial: the dry texture reduced cutting force by 36.3%, and the addition of MoS_2 enhanced this reduction to an impressive 57.9%. These findings underscore the positive interaction between micro-texturing and solid lubrication under high-stress conditions, where both friction and heat generation are critical factors.

With regard to surface roughness, improvements were also recorded, albeit with a less dramatic contrast. During finishing, the dry textured tool reduced the average roughness (Ra) by 4.5%, while the texture with MoS_2 led to a total reduction of 8.0% relative to the untextured tool. Under roughing conditions, the enhancements were more modest, with Ra decreasing by 0.6% using the dry textured tool and 2.1% when MoS_2 was applied. These results indicate that texture and lubrication are more effective in controlling surface integrity during finishing operations, likely due to their influence on contact uniformity and the reduction of micro-vibrations. In roughing, the dominant mechanism is material removal at high volume and force, which tends to overshadow subtler tribological effects.

In conclusion, the application of femtosecond laser textures significantly improved tool performance, especially when aligned parallel to the cutting edge and supplemented with MoS_2. While dry textures alone offered measurable benefits, the presence of solid lubricant proved essential for maximizing gains in high-load machining scenarios. However, the unexpected negative effect of MoS_2 in finishing suggests that lubrication strategies must be adjusted based on cutting regime, emphasizing the importance of process-specific surface engineering. These findings support the adoption of laser-textured tools with tailored lubrication as a robust and scalable solution for machining titanium alloys in both precision and heavy-duty contexts.

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