IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Turning Of Nimonic 80A Material Under Minimum Quantity Lubrication With Untextured Tools And Textured Tools

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Abstract: This machining performance of Nimonic 80A, a nickel-based superalloy, in a turning operation under Minimum Quantity Lubrication (MQL) conditions. The research focuses on the effects of textured and untextured cutting tools on critical performance metrics such as surface roughness, tool wear, and cutting temperature. Experimental findings demonstrate that textured tools significantly outperform untextured ones due to enhanced lubrication retention and reduced friction. Optimal machining conditions were identified using statistical techniques, yielding improved surface quality, extended tool life, and reduced thermal loads. This work highlights the potential of integrating MQL and tool texturing to achieve sustainable and efficient machining for hard-to-process materials like Nimonic 80A.

Keywords**: Nimonic 80A, Minimum Quantity Lubrication, Textured Tools.**

1. INTRODUCTION

Nickel alloys are materials composed primarily of nickel combined with other metals, offering superior durability, corrosion resistance, and high-temperature stability. These alloys, such as Inconel, Monel, and Hastelloy, are essential in aerospace, chemical processing, and power generation due to their strength, oxidation resistance, and ability to withstand extreme conditions. Nimonic 80A is a nickel-chromium superalloy known for its outstanding resistance to high temperatures, oxidation, and stress, making it ideal for high performance. It contains 19-21% chromium, along with titanium, aluminium, and carbon, enhancing its strength and resistance to deformation at elevated temperatures, with a maximum operating temperature of 815°C (1500°F). This alloy is commonly used in turbine blades, exhaust valves, and fasteners, and while machining and welding can be challenging, it is possible with proper treatment. Turning is a machining process that removes material from a rotating workpiece to shape components like cylinders and grooves, with key parameters like cutting speed and feed rate adjusted for precision. CNC turning automates this process, offering high accuracy and efficiency, and is commonly used for mass production of parts with complex geometries in industries such as aerospace and automotive. The process involves tool selection, G-code generation, and repeated machining until the desired shape is achieved. Machining performance is influenced by factors such as tool material, geometry, and cutting parameters. Tool materials like carbide, ceramics, and CBN are chosen based on work material and machining conditions, with coatings extending tool life. The geometry of the tool, including rake angle and nose radius, affects cutting energy, surface finish, and chip flow while cutting parameters such as speed, feed rate, depth of cut impact cutting forces, tool wear, and surface quality. Proper selection and optimization of these factors are crucial for effective machining. Machining nickel-based superalloys is challenging due to the high strength of these materials at elevated temperatures, which increases cutting forces and heat generation. This heat can lead to issues like work hardening, built-up edges, and tool wear, with crater wear being a significant concern that weakens the cutting edge and risks tool failure. Therefore, cutting tools for these alloys must exhibit strong crater wear resistance to ensure performance and longevity. Cutting conditions in machining include dry machining, which eliminates the use of fluids but increases heat and potential material changes, and wet machining, which uses fluids to reduce heat but raises environmental concerns. Minimum Quantity Lubrication (MQL) is an eco-friendly alternative that uses minimal coolant, enhancing tool life, reducing heat, and improving machining efficiency, especially in high-speed operations. MQL offers significant benefits, such as lower fluid usage, safer working conditions, and reduced maintenance costs. Machining performance is primarily evaluated based on product quality, productivity, and manufacturing cost. Surface roughness, a key characteristic, affects factors such as fatigue resistance, dimensional accuracy, and durability, especially in nickel-based superalloys. It is influenced by parameters like feed rate, cutting speed, depth of cut, and tool wear, with proper lubrication and tool edge radius playing important roles in controlling surface quality. Tool wear during machining is influenced by factors such as cutting temperature, stress, material properties, and cutting parameters. Two primary types of wear are flank wear, caused by adhesive and abrasive interactions between the tool and workpiece, and crater wear, which results from high temperatures at the tool-chip interface. Optimizing tool materials, cutting conditions, and machine setup can help minimize wear, extending tool life and reducing costs. Cutting temperature, generated by friction and material deformation during turning, significantly impacts tool life, workpiece properties, and surface quality. High temperatures can lead to increased tool wear, surface degradation, and altered material properties, while effective temperature management through coolants, optimized parameters, and advanced tool materials enhances tool longevity and machining precision. Proper temperature control is vital for achieving high-quality results and maintaining efficiency in manufacturing processes. Tool surface texturing involves engraving patterns on tool inserts to improve lubrication, reduce friction, and enhance cooling during machining. This process also aids in minimizing material adhesion, increasing lubrication, and improving the tribological performance of tools, contributing to sustainability and wear resistance in manufacturing. Various methods are used to create micro and nano textures on tool inserts, with different groove patterns like parallel, perpendicular, and crossed grooves affecting turning performance. These textures improve chip flow and enhance output parameters, such as surface roughness, while also increasing tool life by reducing wear. Surface texturing benefits both dry and wet turning processes without altering the tool material properties. Before surface texturing in turning, it's crucial to ensure that the textured pattern effectively retains cutting fluid to maintain adequate lubrication at the tool-workpiece interface. The position of the groove relative to the cutting edge must be carefully considered, as grooves too close to the edge can weaken the tool, while those too far may not reduce the contact area between the chip and tool effectively.

2. MATERIALS AND METHODS

The experiments were conducted on a CNC machine using Nimonic 80A cylindrical bars with dimensions of 150 mm × 30 mm under a minimum quantity lubrication (MQL) cooling environment. Both surface-textured and untextured tungsten carbide tools were used for comparison. An MQL system with a custom-fabricated setup, equipped with an efficient 1 mm diameter nozzle, was employed to deliver lubricant effectively to the machining contact zone. An emulsion-based oil mixed with water was utilized as the MQL mist to enhance heat dissipation during machining.

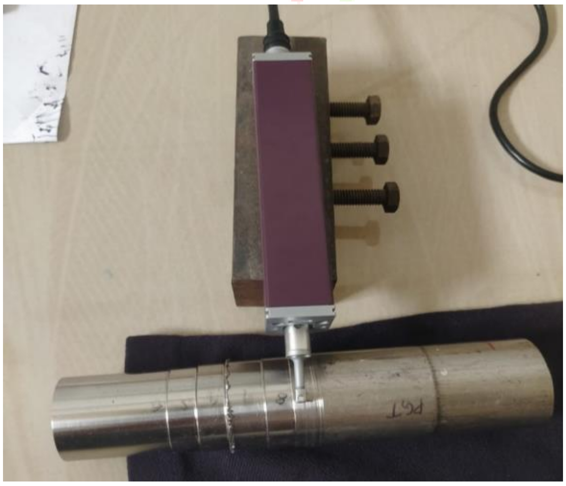


Figure 1. Workpiece material of Nimonic 80A

Figure 2. MQL set up

Table 1. Textured tool details

Workpiece material and dimensions	Nimonic 80A of the cylindrical bar (150*30)
Cutting Inserts	ISO Designation SNMA 120408 Tungsten Carbide insert, CARBOTEC
Machine Tool	LSW SMARTURN make SINUMERIK 828D Basic model CNC machine
Tool Holder	PSBNL 2020K12 WIDIAIN A1
Cooling Environment	Minimum Quantity Lubrication (MQL)
Tool Geometry	Parallel groove lines with equal space with the distance between the lines is 0.1mm and depth of 0.1mm and a distance from the cutting edge is 0.1mm.
Texturing Tool Insert	Laser Surface Texturing Machine

The cutting tools were fabricated from ISO-designated SNMA 120408 tungsten carbide inserts, manufactured by CARBOTEC, and mounted on a PSBNL 2020K12 WIDIAIN A1 tool holder as per the manufacturer's recommendations. The textured tools were produced using a laser machining process, incorporating parallel microgroove lines with a spacing of 0.1 mm, a depth of 0.1 mm, and positioned 0.1 mm from the cutting edge. These grooves, oriented perpendicular to the chip flow direction, were designed to minimize tool-chip contact length. The fabrication process posed challenges to ensure the grooves did not interfere with the insert's cutting edge, requiring precise control.

Figure 3. LMW SMARTURN SINUMERIK 828D BASIC model CNC

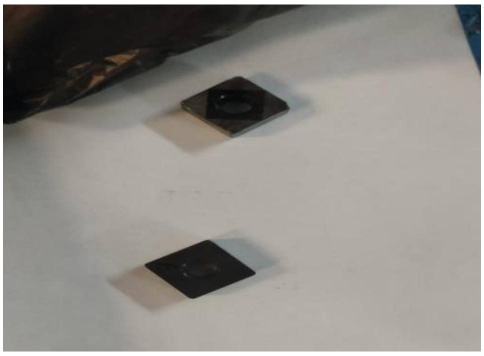


Figure 4. Tool Inserts

Figure 5. PSBNL 2020K12 WIDIAIN A1 Tool Holder

To optimize the experimental process and reduce costs, a Taguchi-based L9 orthogonal array was employed to design the trials. The machining experiments were performed on a 150 mm × 35 mm diameter Nimonic 80A rod. Each experiment was repeated three times to ensure reliability, and the average of the three results was considered for analysis to obtain accurate and consistent output values.

Table 2. Experimental design based on l9 orthogonal array

Exp No.	**Cutting speed (rpm)**	**Feed rate (mm/rev)**	**Depth of cut (mm)**	**Tool type**	
1	600	0.1	0.2	Untextured	Parallel Groove Textured
2	600	0.15	0.4	Untextured	Parallel Groove Textured
3	600	0.2	0.6	Untextured	Parallel Groove Textured
4	920	0.1	0.4	Untextured	Parallel Groove Textured
5	920	0.15	0.6	Untextured	Parallel Groove Textured
6	920	0.2	0.2	Untextured	Parallel Groove Textured
7	1275	0.1	0.6	Untextured	Parallel Groove Textured
8	1275	0.15	0.2	Untextured	Parallel Groove Textured
9	1275	0.2	0.4	Untextured	Parallel Groove Textured

3. RESULTS AND DISCUSSION

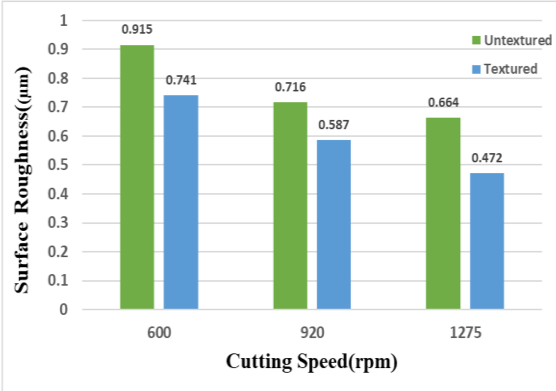
Table 3. Untextured tool results

Exp No.	Untextured type	Cutting speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Surface Roughness (µm)	Rake Wear (mm)	Cutting Temperature (°C)
1	UT	600	0.1	0.2	0.751	0.180	203
2	UT	600	0.15	0.4	0.883	0.252	214
3	UT	600	0.2	0.6	1.112	0.245	228
4	UT	920	0.1	0.4	0.714	0.268	232
5	UT	920	0.15	0.6	0.736	0.291	289
6	UT	920	0.2	0.2	0.698	0.256	210
7	UT	1275	0.1	0.6	0.657	0.295	291
8	UT	1275	0.15	0.2	0.619	0.246	272
9	UT	1275	0.2	0.4	0.716	0.299	302

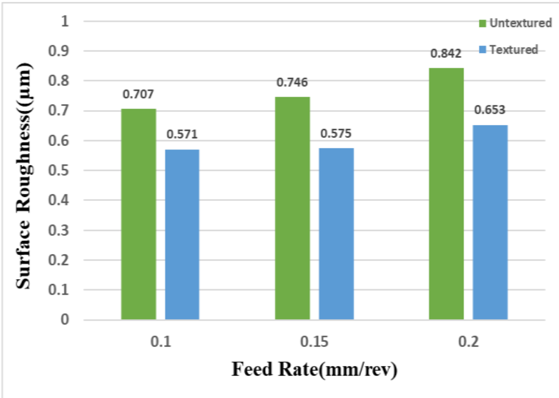
Table 3. Parallel groove textures tool results

Exp No.	Parallel groove texture type	Cutting speed (rpm)	Feed rate (mm/rev)	Depth of cut (mm)	Surface Roughness (µm)	Rake Wear (mm)	Cutting Temperature (°C)
1	PGT	600	0.1	0.2	0.645	0.131	153
2	PGT	600	0.15	0.4	0.762	0.207	163
3	PGT	600	0.2	0.6	0.817	0.216	171
4	PGT	920	0.1	0.4	0.577	0.202	213
5	PGT	920	0.15	0.6	0.621	0.210	238
6	PGT	920	0.2	0.2	0.563	0.177	232
7	PGT	1275	0.1	0.6	0.492	0.201	245
8	PGT	1275	0.15	0.2	0.343	0.192	242
9	PGT	1275	0.2	0.4	0.580	0.215	289

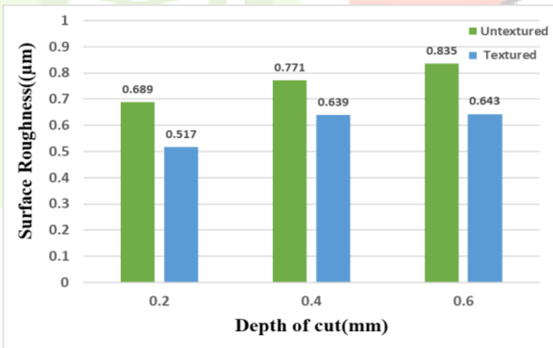
3.1 Comparison of Tools on Surface Roughness



a) surface roughness vs cutting speed



b) surface roughness vs. feed rate



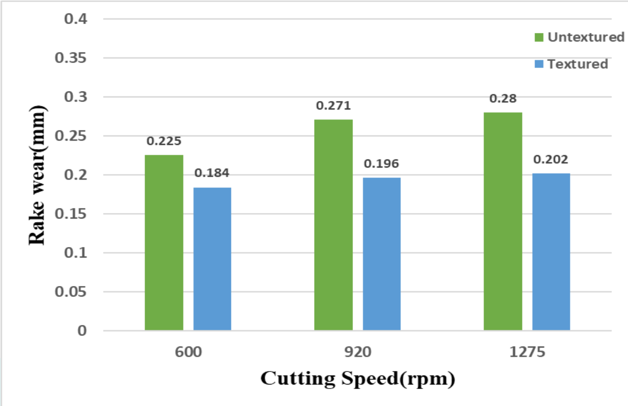
c) surface roughness vs depth of cut

Fig 6 a to c: Graph variation between cutting tool Surface Roughness

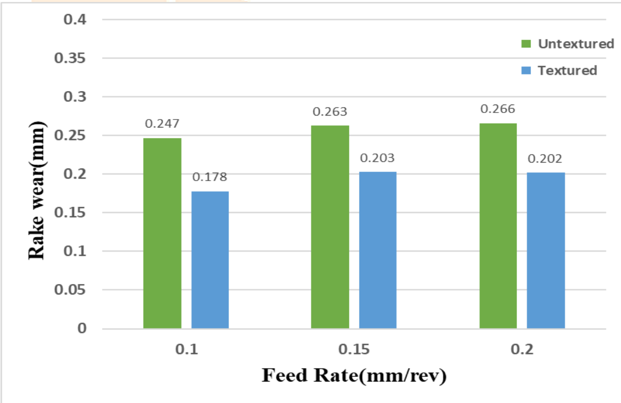
The impact of MQL (Minimum Quantity Lubrication) cooling combined with different cutting tools on surface roughness, focusing on the effects of cutting speed, feed rate, and depth of cut. Findings indicate that surface roughness decreases as cutting speed increases for all tool types. The parallel-grooved textured tool outperformed the untextured tool, reducing surface roughness by 19.01%, 18%, and 28.91% at cutting speeds of 600 rpm, 920 rpm, and 1275 rpm, respectively. The textured tool's superior performance is attributed to its ability to reduce tool-chip contact length, enhance heat dissipation, and leverage the lubricating effect of the MQL system, achieving the most significant improvement at the highest speed of 1275 rpm.

When analyzing feed rate, surface roughness was observed to increase with higher feed rates for all tools. The parallel-grooved textured tool consistently delivered smoother finishes compared to the untextured tool, achieving reductions of 19.23%, 22.92%, and 22.44% at feed rates of 0.1 mm/rev, 0.15 mm/rev, and 0.2 mm/rev, respectively. The best improvement, 22.92%, occurred at a medium feed rate of 0.15 mm/rev. Similarly, varying depths of cut showed that the textured tool significantly reduced surface roughness by 24.96% at 0.2 mm, 17.12% at 0.4 mm, and 22.99% at 0.6 mm. The textured tool's efficiency stems from optimized chip removal, reduced cutting forces, and improved cooling, making it highly effective under MQL cooling. The greatest improvement was observed at a 0.2 mm depth of cut, highlighting the textured tool's capability to enhance machining performance across varying conditions.

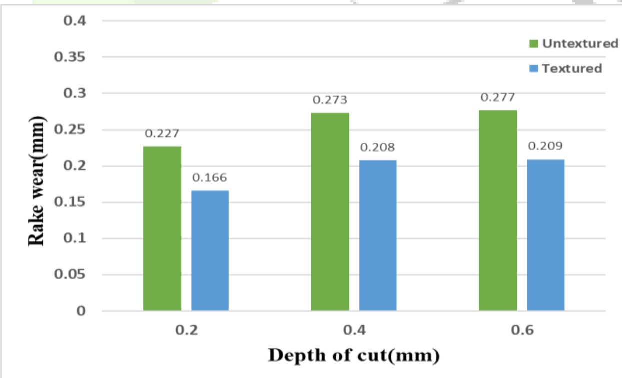
3.2 Comparison of Tools on Rake Wear



a) surface roughness vs cutting speed



b) surface roughness vs. feed rate



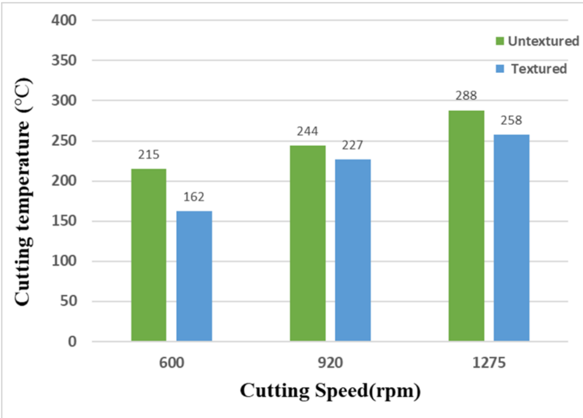
c) surface roughness vs depth of cut

Figure 7 a to c: Graph variation between cutting tool Rake Wear

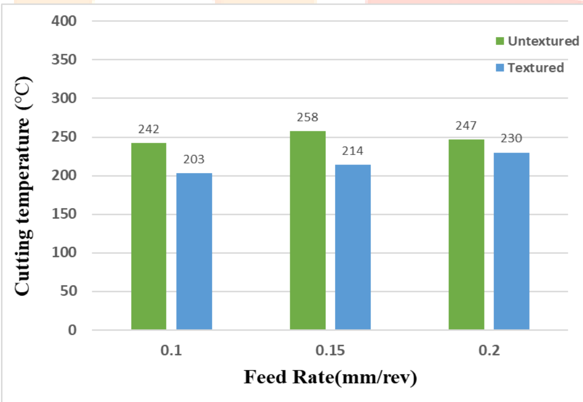
The influence of MQL (Minimum Quantity Lubrication) cooling on rake wear was assessed by varying cutting speeds, feed rates, and depths of cut with untextured, circular pit, and parallel-grooved textured tools. An increase in cutting speed led to higher rake wear, but the parallel-grooved textured tool consistently exhibited better performance. At a cutting speed of 600 rpm, it reduced rake wear by 18.22% compared to the untextured tool. This reduction further improved to 27.67% at 920 rpm and reached 27.85% at the maximum speed of 1275 rpm. The superior performance of the grooved tool is attributed to its unique design, which enhances coolant retention, improves heat dissipation, and minimizes wear at the cutting zone.

Similarly, as feed rates increased under MQL cooling, rake wear also rose, though the parallel-grooved textured tool consistently outperformed the untextured tool. At a feed rate of 0.1 mm/rev, it reduced rake wear by 27.93%, while at 0.15 mm/rev, the reduction was 22.81%. When varying depths of cut, the textured tool also proved more effective, achieving a 26.87% reduction in wear at a depth of 0.2 mm. At depths of 0.4 mm and 0.6 mm, it achieved reductions of 23.80% and 22.99%, respectively. The grooved tool's ability to enhance cooling, reduce cutting forces, and facilitate efficient chip removal contributed to its superior wear resistance, particularly at lower feed rates and shallower cuts.

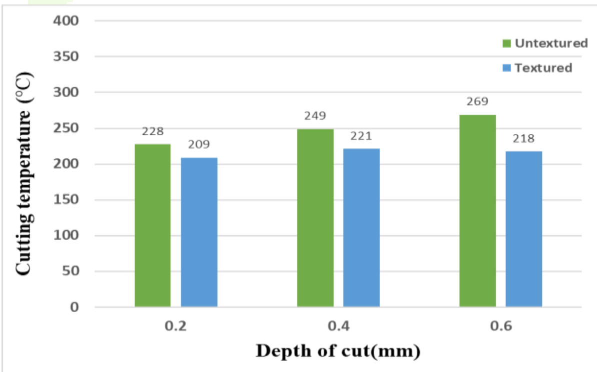
3.3 Comparison of textured tools on Cutting Temperature



a) Cutting temperature vs cutting speed



b) Cutting temperature vs. feed rate



c) Cutting temperature vs depth of cut

Figure 8 a to c: Graph variation between cutting tool Cutting Temperature

The influence of MQL (Minimum Quantity Lubrication) cooling on cutting temperatures was examined by varying cutting speeds, feed rates, and depths of cut using untextured and parallel-grooved textured tools. An increase in cutting speed resulted in higher cutting temperatures for both tools, with the untextured tool generating significantly more heat due to increased friction at the tool-chip interface. The parallel-grooved textured tool consistently showed superior performance, effectively reducing cutting temperatures by enhancing lubricant retention and distribution in the machining zone. At a cutting speed of 600 rpm, the textured tool reduced the temperature by 24.65% compared to the untextured tool. At 920 rpm, it achieved a 6.96% reduction, with the most significant improvement observed at the lowest speed. These findings underscore the role of tool texture in mitigating heat generation during machining.

Similarly, variations in feed rates and depths of cut highlighted the benefits of the textured tool under MQL conditions. As feed rates increased, cutting temperatures rose for both tools, but the textured tool demonstrated notable reductions. For instance, at a feed rate of 0.15 mm/rev, the textured tool achieved a 17.05% reduction in cutting temperature compared to the untextured tool. Regarding depths of cut, the textured tool also outperformed the untextured tool, particularly at higher cutting depths. At a depth of 0.6 mm, the textured tool reduced the cutting temperature by 18.95%. Overall, the textured tool's ability to enhance cooling efficiency and reduce thermal loads highlights its effectiveness in maintaining lower machining temperatures, even under challenging conditions.

4. CONCLUSION

The findings of this study demonstrate the effectiveness of using Minimum Quantity Lubrication (MQL) with textured tools in enhancing the machining performance of Nimonic 80A alloy. Key observations include:

- **Surface Roughness:** The parallel groove textured tools demonstrated a significant improvement in surface roughness compared to untextured tools across all cutting parameters. At a cutting speed of 1275 rpm, the maximum reduction in surface roughness was 28.91% (0.472 µm vs. 0.664 µm). The textured tools also performed consistently well at varying feed rates, achieving a reduction of up to 22.92% at 0.15 mm/rev. Depth of cut influenced surface roughness improvements, with the highest reduction of 24.96% observed at 0.2 mm depth of cut. These results highlight the effectiveness of textured tools in enhancing surface finish, particularly at higher cutting speeds and optimal feed rates.

- **Rake Wear:** Textured tools significantly reduced rake wear compared to their untextured counterparts, with improvements observed across all process parameters. At a cutting speed of 1275 rpm, the maximum reduction of 27.85% was achieved (0.202 mm vs. 0.280 mm). Lower feed rates yielded the best results, with a 27.93% reduction at 0.1 mm/rev. Similarly, a depth of cut of 0.2 mm led to the highest improvement of 26.87%. These reductions indicate that textured tools effectively minimize tool wear, particularly at higher cutting speeds and lower feed rates, ensuring longer tool life and better machining efficiency.

- **Cutting Temperature:** Textured tools also reduced cutting temperature significantly under MQL conditions. At 600 rpm cutting speed, the largest reduction of 24.65% was recorded (162°C vs. 215°C). Feed rate optimization showed a maximum temperature reduction of 17.05% at 0.15 mm/rev, while the highest improvement with a depth of cut (18.95%) was achieved at 0.6 mm. These findings emphasize that textured tools not only enhance machining efficiency but also reduce thermal stresses during turning, contributing to better process stability and improved tool performance under challenging machining conditions.

- The use of MQL combined with parallel grooved textured tools significantly improved machining performance metrics, including surface roughness, rake wear, and cutting temperature, compared to untextured tools during the machining of Nimonic 80A alloy.

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