Investigating Drilling Efficiency: A Study on Indexable Centerless Drilling of Ti-6Al-4V Alloy

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Research Article

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Abstract

Titanium Alloy (Ti-6Al-4V), is highly regarded in the aerospace industry due to its exceptional strength-to-weight ratio. The alloy's low thermal conductivity and high tensile strength pose machining challenges, leading to increased tool temperatures and mechanical stress. The conventional use of solid carbide drills is hindered by substantial tool wear. To improve tool life, prior research has delved into various cutting strategies, ranging from flood cooling to minimum quantity lubrication (MQL), enduring challenges persist. This study introduces an innovative approach, leveraging Titanium Aluminum Nitride (TiAlN) coated indexable centerless inserts to bore holes in Ti-6Al-4V under three distinct cutting conditions: dry, flood cooling, and MQL. These conditions are scrutinized across varied feed rates (60 mm/min, 100 mm/min, and 120 mm/min) with a fixed spindle speed of 1200 rpm. The study's primary focus is on key output parameters, including surface roughness (SR), tool life, and cutting temperature. From the parametric and surface topographic analysis, the findings reveal that under the flood cutting approach with a 60 mm/min feed rate, the indexable inserts excelled when drilling Ti-6Al-4V. This combination delivered a better surface quality (Ra = 1.66 µm), extended tool life (27814.27 mm\(^3\) material removed and 18 holes drilled), and lower cutting temperature (881°F). Additionally, scanning electron microscopy (SEM) analysis corroborates that most common types of wear observed were abrasion, delamination, cracking, and edge fracture.

1. Introduction

Titanium alloys, renowned for their exceptional strength-to-weight ratio, corrosion resistance, and biocompatibility, have established themselves as vital materials in aerospace, medical, and industrial applications. Among these alloys, Ti-6Al-4V stands out as a particularly versatile and widely used variant [1]. Due to the above-mentioned properties, the demand for Ti-alloys has increased up to 1360K tons (50% of Ti-6Al-4V) annually [2]; there is an increase of 4.7% globally every year [1]. However, machining of Ti-6Al-4V, a task often encountered in manufacturing, presents a complex and demanding challenge due to the unique properties of the material. As these alloys are characterized by their high strength, low thermal conductivity, low coefficient of thermal expansion, and tendency to work-harden, making conventional metal cutting processes, less effective. Major problems are as follows:

- the temperature of the cutting zone increases up to 1000 ºC because of the low thermal conductivity which resists the heat flow from the cutting zone to the chips;
- Ti-6Al-4V leaned towards cutting the tool's coating, thus, increases the tool wear because of the chip's adhesion;
- larger cutting forces and torque are required for the machining of Ti-6Al-4V because it keeps its hardness and strength even at higher temperatures [2–3].

For aircraft production, the drilling operation is very important as almost 100,000 holes have been drilled in a single engine craft [4] that is almost 40–60% of the material removal process [5]. Therefore, drilling of Ti-6Al-4V alloys requires a profound understanding of the material's characteristics and behavior under machining conditions. Significant research is dedicated to study the essential considerations for successful drilling, including cooling strategies, drilling strategy, tool selection, and cutting parameters [6–11].
In the context of machining, dry drilling is considered an eco-friendly alternative, but it faces challenges when working with low thermal conductivity materials like titanium alloys, leading to high temperatures and tool failure [6–7]. To combat this, the traditional method of flood cooling, employing oil-based systems, has long been used to ease the machining of tough materials like titanium [12]. Cutting fluids are critical in flood cooling, reducing temperatures and friction, enhancing tool life and workpiece quality [13–15]. However, mineral-based cutting fluids pose environmental and safety concerns, driving the manufacturing community's shift towards biodegradable vegetable-based oils as a more sustainable choice [16–18]. With the detrimental impact of conventional cutting fluids on hole surface quality and environmental concerns in mind, the MQL (minimum quantity lubrication) method has emerged as an eco-efficient, cost-effective alternative. MQL employs a minimal amount of cutting fluid, typically a mixture of oil and air, which is directed precisely onto the tool's cutting edge. While MQL has been effective in reducing cutting forces by approximately 6.5% [19], it still faces limitations when dealing with hard-to-machine materials [20]. To address this, researchers have explored cryogenic strategies involving liquid nitrogen and liquid carbon dioxide, comparing their results with traditional flood coolant and MQL. This investigation has revealed a notable reduction in cutting forces, with decreases of 9% and 10%, respectively [2]. Additionally, the use of graphene oxide as a cutting fluid has demonstrated a remarkable 17.21% reduction in cutting force compared to traditional fluids [21]. In a separate study, researchers have successfully reduced burr height by employing cryogenic oil, while the use of boron oil-based MQL has shown promise in improving the surface quality of holes [22]. Furthermore, the integration of MQL with MoS4 has proven effective in enhancing surface integrity, irrespective of the tool's geometry [23]. When considering factors such as surface roughness (SR), cutting temperature, cutting force, tool wear, chip formation, surface morphology, and hardness, the research indicates that the most optimal combination is MQL with a mixture of 20 percent MoS2 and 80 percent cotton seed oil [24].

In the realm of drilling strategies, it has been observed that step drilling significantly extends tool life, offering a threefold increase compared to continuous drilling [25]. However, it's worth noting that step drilling can introduce challenges related to chip adhesion and the formation of a build-up edge (BUE), adversely affecting hole surface quality, including aspects like surface roughness, accuracy, and roundness. When dealing with the continuous drilling of titanium alloys, several critical issues surface, including burr formation, the development of a build-up edge, and the diffusion of chips. These issues are primarily attributed to the material's high chemical reactivity, which is further exacerbated by the elevated drilling temperatures [26–27].

In terms of tool selection for hard material machining, indexable drilling and solid-type twist drills are two distinctive cutting tool options commonly employed in the field. Indexable drills, with their replaceable inserts featuring multiple cutting edges, offer versatility and cost-effectiveness for a wide spectrum of materials. They are distinguished by their precision and effective chip evacuation mechanisms, attributes arising from the insert and body design. Consequently, indexable drills are well-suited for high-speed and high-feed drilling applications, surpassing solid drills in this regard [28–30]. Additionally, the cost factor favors indexable drilling as it eliminates the need for regrinding, recoating, and maintaining spare tools, rendering it a more economical choice [31]. Notably, when dealing with challenging materials like Inconel 718, known for its toughness, indexable drills have demonstrated remarkable performance at a feed rate of 0.08mm/rev, successfully mitigating issues such as surface defects and chip adhesion [32].
Non-conventional machining methods provide effective solutions to the limitations of conventional techniques. Laser drilling, utilizing a CO2-based laser, excels in micro-hole machining, ensuring high-quality results [33]. Process variables like flushing pressure, laser power, and pulse frequency influence characteristics such as taper, spatter area, and heat-affected zone. An influential parameter revealed by a study is laser power [34]. Additionally, another study emphasizes that the choice of pulse width, pulse frequency, and trepanning speed can regulate cutting temperature and hole quality [35]. However, it's crucial to note that laser drilling involves high radiation and temperature levels, leading to concerns about recast layer formation and the heat-affected zone. Therefore, operating the equipment requires special care. Electric-discharge machining (EDM) has been explored as an approach for creating holes in titanium alloys, employing combinations of graphite and CuW electrodes. The findings indicate a notable material removal rate of 22.5 × 10³ mm³/min with a hole depth of 0.5 mm when using a graphite electrode, whereas CuW electrodes yielded a rate of 4 × 10³ mm³/min [36]. However, a key challenge associated with EDM is the effective removal of debris, particularly in deep hole drilling applications. Furthermore, the workpiece material must possess conductivity for EDM to be viable [37]. Despite the advantages of EDM, such as precision, the high operational costs and safety concerns associated with non-conventional machining methods limit their utilization in the drilling of titanium alloys. The literature underscores the need to explore alternative approaches to machining titanium alloys that are cost-effective and less environmentally critical or hazardous compared to non-conventional methods.

An evident research gap comes to light within the domain of machining titanium alloys when considering the existing literature and the objectives of the present research. Previous investigations have indeed delved into the use of diverse cutting strategies and tool types for boring holes in titanium; however, there remains a dearth of systematic exploration concerning the performance of an indexable insert drill under various cooling methodologies and distinct feed rates.. It is imperative to bridge this research gap as it is crucial for achieving a comprehensive grasp of machining process for titanium alloys. This endeavor not only stands to boost productivity but also holds the potential to curtail operational expenses. Ultimately, the benefits of this research labor have the capacity to significantly advance the development of more effective and efficient machining techniques, especially pertinent in industries like aerospace, automotive, and medical, where the application of titanium alloys is prevalent.

Section 2 of the paper will provide an in-depth exposition of the materials and methodologies employed in this research. Subsequently, Section 3 will conduct a thorough examination of the findings and engage in a comprehensive discussion. Finally, the paper will reach its conclusion in Section 4, drawing overarching insights and offering recommendations for prospective research endeavors.

**2. Materials and Methods**

The experiments were conducted on a workpiece plate measuring 215×214×13 mm, composed of Ti-6Al-4V alloy with a hardness of 32 HRC. The chemical composition was determined through an energy dispersive method using X-ray spectroscopy (Model Impact S50, USA), and the composition details are presented in Table 1.
For this experimental research, indexable centerless inserts (specifically SMPG 050204 NN LT 3103) were employed. These inserts were affixed to a two-flute tool holder (designated as SPMG 050204 LT DR 12.5 S05-4D) with a 12.5 mm diameter. Two inserts, comprising a central and peripheral insert, were securely fastened onto the holder using screws. They were positioned at an angle of 2.13º in relation to the holder.

The experiment involved manipulating two key process parameters: the feed rate and the chosen machining conditions. Specifically, three distinct feed rate levels (0.05, 0.083, and 0.1 mm/rev) and three different cutting conditions (dry, flood, and minimum quantity lubrication - MQL) were employed, as detailed in references [22–25]. In the case of the flood approach, HD68 straight oil was utilized as the cutting fluid, with a fluid flow rate of 7.5 liters/minute. For minimum quantity lubrication (MQL), biodegradable mustard oil was adopted. The MQL approach implemented an internal mixed method with a flow rate of 25 milliliters/hour, a nozzle angle of 45 degrees, and a standoff distance of 30 mm, utilizing a nozzle with an internal diameter of 1.78 mm. The assessment of Ti-alloy machinability involved the measurement of three distinct response parameters: surface roughness (Ra µm), cutting temperature (ºF), and tool wear (µm). These measurements were taken in accordance with the cutting conditions and other specified input parameters, all detailed in Table 2. The workpiece was drilled (12.5 mm diameter bore) using a CNC Machining Centre, specifically the MCV 600 from Long Chang, Taiwan, as illustrated in Fig. 1. This machining center boasts a rated power of 20 KV and offers a spindle speed range of 8000 rev/min. Notably, a full factorial design of experiments (DOE) was applied throughout the research, and the drilling was carried out using a continuous drilling strategy.

Table 1  
Chemical Composition Of Ti-6Al-4V (%wt)

<table>
<thead>
<tr>
<th>Element</th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>Si</th>
<th>C</th>
<th>N</th>
<th>H</th>
<th>O</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>% (wt)</td>
<td>5.8</td>
<td>5.8</td>
<td>3.9</td>
<td>0.18</td>
<td>&lt;0.01</td>
<td>0.02</td>
<td>0.023</td>
<td>&lt;0.01</td>
<td>89.6</td>
</tr>
</tbody>
</table>

Table 2  
Details Of Machining Variables

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Units</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable Parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed Rate (F.R)</td>
<td>mm/min</td>
<td>60</td>
<td>100</td>
<td>120</td>
</tr>
<tr>
<td>Cutting Conditions</td>
<td></td>
<td>Dry</td>
<td>Flood</td>
<td>MQL</td>
</tr>
<tr>
<td>Constant Parameter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spindle Speed</td>
<td>RPM</td>
<td>1200</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Tool Diameter</td>
<td>mm</td>
<td>12.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cutting Edges/Inserts</td>
<td></td>
<td>2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Depth of Cut</td>
<td>mm</td>
<td>10</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

The experiment proceeded until one of the inserts met the predefined tool wear criteria, which was a flank wear of 200 µm [38]. Tool wear assessments were conducted using a coordinate measuring machine (CE450, Renishaw, Taiwan). Upon reaching the end of their tool life, the worn tools were subject to observation under a scanning electron microscope (S50, FEI, USA). To assess surface roughness and topology, a surface texture
tester (Surftest SV-3000 CNC Ultra-high Precision Surface Roughness Tester, Mitutoyo, UK) was employed. This instrument exhibited a maximum speed of 200 mm/s for each axis and a measurement range of 800µm, 80µm, and 8µm. The measuring speed ranged from 0.02 to 2 mm/s. Additionally, a thermal imager (868s, Testo, USA) regularly measured the machining temperature. These measurements were taken from a standardized distance of 1 meter from the machining region. Finally, parametric analysis and Analysis of Variance (ANOVA) were carried out using Minitab 2022 to analyze the collected data.

3. Results and Discussion

This section provides a comprehensive exposition of the results and the analysis derived from all conducted experiments. A detailed summary of all input parameters and output responses is furnished in Table 3.

Table 3
Experimental Results For Drilling Of Ti-6Al-4V Using Full Factorial Design

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Feed Rate (mm/min)</th>
<th>Cutting Condition</th>
<th>Surface Roughness Ra (µm)</th>
<th>Tool Wear VB (µm)</th>
<th>Temperature (°F)</th>
<th>Volume of Material Removed mm³</th>
<th>No. of Holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>Dry</td>
<td>1.87</td>
<td>210</td>
<td>1192</td>
<td>4861.926</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>Flood</td>
<td>1.66</td>
<td>201</td>
<td>881</td>
<td>27814.27</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>MQL</td>
<td>1.71</td>
<td>205</td>
<td>1037</td>
<td>20347.92</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>Dry</td>
<td>2.01</td>
<td>201</td>
<td>1232</td>
<td>3215.961</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>Flood</td>
<td>1.84</td>
<td>204</td>
<td>935</td>
<td>20511.25</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>MQL</td>
<td>1.96</td>
<td>209</td>
<td>1065</td>
<td>9977.077</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>120</td>
<td>Dry</td>
<td>1.7</td>
<td>201</td>
<td>1234</td>
<td>23999.43</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
<td>Flood</td>
<td>1.77</td>
<td>203</td>
<td>943</td>
<td>21498.83</td>
<td>14</td>
</tr>
<tr>
<td>9</td>
<td>120</td>
<td>MQL</td>
<td>1.83</td>
<td>201</td>
<td>1085</td>
<td>11357.15</td>
<td>6</td>
</tr>
</tbody>
</table>

3.1. Surface Roughness and Surface Topography

Surface roughness for each hole drilled in various experiments underwent three measurements, and the resulting average surface roughness values are documented in Table 3. Notably, the maximum surface roughness recorded was 2.01 µm, occurring under dry conditions at a feed rate of 100 mm/min and a spindle speed of 1200 rpm. Conversely, the minimum surface roughness value, 1.66 µm, was observed during flood conditions, with a feed rate of 60 mm/min and a spindle speed of 1200 rpm. Figure 2 illustrates the main effect plot for surface roughness. It is worth noting that at higher feed rates, the Ra value reached its maximum due to increased resistance to deformation, resulting in greater energy required for plastic deformation. This, in turn, heightened friction in the cutting zone, leading to increased surface roughness.
The cutting conditions exert a substantial influence on surface roughness due to variations in cutting area temperature and debris removal. Elevated temperatures contribute to increased tool wear, resulting in higher friction levels, thereby raising surface roughness values. Specifically, dry drilling conditions can lead to the softening of the metal beneath the surface, ultimately yielding suboptimal surface quality [3]. It’s worth noting that the lowest surface roughness, measuring 1.66 µm, was attained when employing flood cooling, whereas the highest surface roughness was observed in dry cutting conditions with a feed rate of 100 mm/min. This discrepancy can be attributed to the reduction in cutting temperature and the more effective flushing facilitated by flood cooling.

In a study by Balaji M. [39], a solid 10 mm drill bit was utilized with a feed rate of 14 mm/minute and a spindle speed of 600 rpm, resulting in a surface roughness of 4.125 µm under dry conditions. Conversely, in the current research, employing a 12.5 mm indexable drill, a significantly improved surface roughness of 2.01 µm was achieved at a feed rate of 100 mm/min under dry cutting conditions. Percin M. [40] employed a 3 mm diameter uncoated tungsten carbide micro-drill with a feed rate of 70 mm/minute and a spindle speed of 10,000 rpm. Their study produced a surface roughness of 1.3 µm under dry conditions, while minimum quantity lubrication (MQL) yielded a surface roughness of 0.85 µm, and flood cooling resulted in 0.95 µm. Similarly, Shah P. [2] conducted drilling at a feed rate of 100 mm/min and a spindle speed of 5,100 rpm, obtaining a surface roughness of 0.85 µm under flood cooling conditions. Notably, higher spindle speeds tend to lead to improved Ra values. In contrast, the indexable drill employed in this study achieved an Ra value of 1.77 µm, even at a feed rate of 120 mm/min, which is significantly less than the 5100 rpm used in Shah P.’s study.

The surface topography, as depicted in Fig. 3, effectively corroborates the findings from the main effect plot. Notably, the surface topography under dry cutting conditions exhibited comparatively poorer results when compared to flood cooling and MQL. Specifically, experiments 1, 4, and 7 exhibited more substantial variations in surface profile than those observed with flood cooling and MQL. This divergence was attributed to reduced friction within the machining region, resulting in fewer scratches and scars, in stark contrast to dry cutting conditions, which yielded scratches, noise, and scars. In Experiments 7, 8, and 9, the elevated cutting zone temperature contributed to the softening of the work material. This softening effect, in turn, reduced resistance to the cutting tool, facilitating plastic deformation and ultimately resulting in improved surface topography.

### 3.2. Tool Wear

Flank wear measurements for the central and peripheral indexable inserts were conducted using a coordinate measuring machine (CMM). The measurements were carried out until the inserts exhibited maximum flank wear of 200 µm, maintaining a consistent flank wear criteria throughout the experiments [38]. The results of flank wear for each experiment are presented in Table 3, alongside data regarding the volume of material removed and the number of holes drilled using new inserts. Given the consistent flank wear criteria, the volume of material removed and the number of holes drilled serve as key points for discussion.

In flood cooling conditions, a maximum of 18 holes were successfully drilled at a feed rate of 60 mm/min, resulting in the removal of 27,814.3 mm³ of material. In contrast, the minimum was observed during dry
drilling at a feed rate of 120 mm/min, with only three holes drilled and 3,216 mm³ of material removed. The calculation of material removal at the tool wear criteria was executed using Eq. 1.

\[
\text{Volume of material removed} = \text{volume of one hole} \times \text{the number of holes} \quad (1)
\]

As illustrated in Table 3, the performance of the central insert outshone that of the peripheral inserts, primarily due to the relatively lower pressure exerted on the central inserts compared to the peripheral ones. This observation is further elucidated in Fig. 4a-b, which presents the correlation between the volume of material removed and the number of holes drilled in relation to the feed rate and cutting conditions. Notably, the least tool wear was attained at lower feed rate values, while an increase in the feed rate corresponded to reduced material removal.

The minimum number of holes was drilled at a feed rate of 120 mm/min under dry cutting conditions. This outcome can be attributed to the intrinsic characteristics of Ti-6Al-4V, characterized by its lower thermal conductivity. Consequently, higher feed rates and dry cutting conditions elevated the cutting temperature in the cutting zone, imposing increased mechanical stresses on the workpiece. These conditions gave rise to heightened friction and greater tool wear [10]. In a study by Balaji et al. [39], a solid carbide drill was employed, and it exhibited tool wear of 0.3036 mm after drilling just four holes at a feed rate of 14 mm/min and a spindle speed of 1000 rpm [28]. In contrast, in the current research, a notable 18 holes were successfully drilled at a feed rate of 60 mm/min, while even at the higher feed rate of 120 mm/min, a substantial 15 holes were drilled.

Figure 5 showcases SEM images and optical micrographs for each experimental run at the point of reaching the tool life criteria. Notably, at the relatively lower feed rate of 60 mm/min, the primary wear mechanisms observed were abrasion and delamination. Additionally, in flood cooling at 100 mm/min, instances of cracking were also detected. The prevalence of these wear mechanisms can be attributed to the higher mechanical stresses imparted on the cutting edge, particularly at lower feed values, compared to the thermal stresses encountered during the machining process [10]. At higher feed values of 100 mm/min and 120 mm/min, the prevailing wear mechanisms shifted to plastic deformation and abrasion. Experiment 9, in particular, exhibited severe plastic deformation due to the elevated cutting temperature, which led to the plastic deformation of the insert material [10].

It’s noteworthy that, across all experiments, there were no instances of built-up edge, severe chipping, or fractures, even in the dry cutting condition. Edge fracture emerged as the most commonly observed wear mechanism at higher cutting speeds and feed rates [31]. In a study by Khan et al. [32], indexable drilling was employed to drill a total of 27 holes, with the maximum tool wear value reaching 200 µm at a feed rate of 0.02 mm/rev.

### 3.3. Cutting Temperature

Figure 6 displays images of the cutting zone captured using a thermal imager. The challenging thermal properties of Ti-alloys pose difficulties in the machining process. During the cutting operation, the tool temperature increased, leading to tool wear and performance limitations. Hence, thermal analysis emerges as a crucial factor to take into account. The tool temperature significantly influences tool life and hole quality.
In a study by Li and Shih [41], an attempt was made to assess the tool performance in relation to tool temperature. Similarly, this research also recorded the temperature for each experiment, as presented in Table 3 above. The maximum temperature recorded in each experiment was considered. The highest temperature was observed in dry cutting conditions, which explains the shorter tool life in those conditions. Conversely, the maximum tool life was observed with flood cooling, as the flood coolant effectively reduced the temperature, consequently minimizing tool wear. In MQL cutting conditions, the cutting zone temperature increased again due to the insufficient coverage of the cutting zone by the coolant, particularly at the bottom of the hole.

The main effect plots, illustrated in Fig. 7, depict the relationship between cutting temperature and feed rate, as well as cutting conditions. An increase in feed rate corresponded to an increase in cutting zone temperature. Therefore, low feed rate values combined with flood cooling resulted in drilling more holes before reaching the tool wear criteria and achieving a superior surface finish. This observation aligns with findings by Sharman et al. [42], who noted that the temperature of the outer periphery insert was higher than that of the inner insert due to friction with the hole wall, leading to elevated temperatures.

### 3.4. Analysis of Variance

A quantitative analysis of the process parameters was performed via ANOVA at a 95% confidence level ($\alpha = 5\%$), and the findings are detailed in Table 4. The analysis revealed that feed rate and cutting conditions significantly influenced surface roughness, cutting zone temperature, volume of material removed, and the number of holes.

<table>
<thead>
<tr>
<th>Sr. #</th>
<th>Dependent Variable</th>
<th>p-value</th>
<th>R-Sq %</th>
<th>R-Sq (adj) %</th>
<th>Percentage Contribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surface Roughness (µm)</td>
<td>0.041</td>
<td>93.40</td>
<td>86.81</td>
<td>49.9</td>
</tr>
<tr>
<td>2</td>
<td>Volume Of Material Removed (mm3)</td>
<td>0.020</td>
<td>93.42</td>
<td>86.84</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>No. of Holes</td>
<td>0.009</td>
<td>95.27</td>
<td>90.54</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>Temperature (°F)</td>
<td>0.003</td>
<td>99.83</td>
<td>99.66</td>
<td>49.9</td>
</tr>
</tbody>
</table>

### 5. Conclusions

In this study, a series of drilling experiments on Ti-6Al-4V alloy. These experiments were designed to explore the performance of indexable inserts under various cutting conditions. The main conclusions drawn from the current investigations were as follows:

- From main effect plots analysis, it is revealed that the flood and the MQL approaches produced relatively similar results. However, indexable inserts performed better for the drilling of Ti-6Al-4V under the flood cutting approach and feed rate (60 mm/min) to achieve better surface quality ($Ra = 1.66 \mu m$), long tool
life (volume of material removed = 27814.27 mm$^3$ and number of holes = 18), and low cutting temperature (881°F);

- From tool wear measurement, it is observed that the central insert performed better than the peripheral inserts. Furthermore, SEM images demonstrated that the abrasion wear, delamination, cracking and the edge fracture were the most common phenomenon of wear;
- The ANOVA for surface roughness, tool wear, and cutting temperature indicated that both process variables feed rate and cutting environment were significant at 95% confidence interval with 50% contribution each.

Future research should delve into optimizing a wider array of cutting conditions, including cutting speeds, feed rates, and tool coatings, to enhance the performance of indexable inserts in Ti-6Al-4V drilling. Furthermore, a deeper analysis of Ti-6Al-4V material variations and their impact on drilling is essential, while environmental considerations and sustainability factors need to be explored.

**Declarations**

**Author Contributions:** Conceptualization, S.Z. and S.E.; methodology, S.E., A.Q.K. and S.A.; formal analysis, S.Z., S.F.R. and A.Q.K.; data curation, A.Q.K. and S.A.; writing—original draft preparation, S.Z., S.F.R. and A.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** It will be provided on request.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**


Figures

![CNC Machining Center](image1)

![Tool Wear Measurement](image2)

![Drilled Workpiece](image3)

![Surface Roughness and Topology Measurement](image4)

Figure 1

Experimental Details
Figure 2

Main Effect Plot for Surface Roughness
Figure 3

Surface Topography Results
Figure 4

Main Effect Plot a) Volume of Material Removed, b) No. of Holes
Figure 5

SEM Images for Tool Wear Of Indexable Drills
Figure 6

Cutting Temperature Values Against Each Experiment Taken by Thermal Imager
Figure 7

Main Effect Plot for Cutting Temperature (°F)