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EVALUATION OF TOOL WEAR AND BURR FORMATION IN MICRO-DRILLING TITANIUM TI-6AL-7NB

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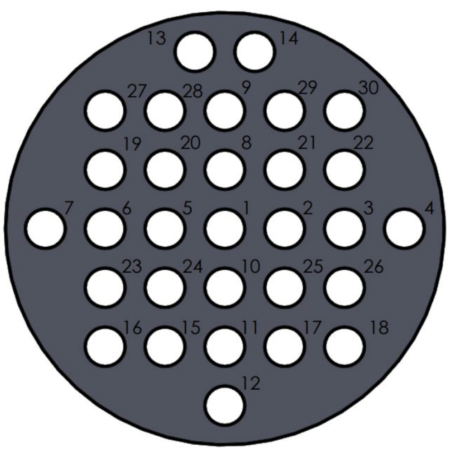
Graphical abstract



Abstract

Titanium, renowned for its corrosion resistance and strength, is extensively utilized across various industries. Titanium alloy Ti-6Al-7Nb, also known as Titanium 367, is particularly favoured for total hip prostheses, especially in femoral stems, due to its excellent corrosion resistance and biocompatibility. This alloy is also employed in knee replacements, dental procedures, and maxillofacial applications for screws, plates, and implants, highlighting its versatility in the medical field. However, machining titanium alloys presents significant challenges due to their poor machinability. This study investigates the impact of selected cutting parameters, including spindle speed and feed rate, as manipulated variables while maintaining point angle as a constant variable on micro-drilling using 2mm uncoated carbide drills. The experimental analysis identifies three phases of tool wear: initial, steady, and severe. The results indicate a linear increase in flank wear with higher spindle speeds and feed rates. Burr height is notably higher at increased spindle speeds and feed rates. Burr height is primarily influenced by feed rate, which determines chip load and material removal per revolution. The individual effects of these parameters on burr formation are significant. At the highest spindle speed, a crown burr with a drill cap is formed due to intense friction and heat, which softens the material and facilitates cap formation over the exit hole. This study validates a predictive model for burr height and tool wear, providing a foundation for parameter optimization in real-world applications. The model enables the determination of optimal spindle speed and feed rate combinations to minimize burr formation and enhance machining efficiency.

Keywords: Tool wear, Burr formation, Titanium, Micro drilling

Abstrak

Titanium, yang terkenal dengan rintangannya terhadap kakisan dan kekuatannya, digunakan secara meluas di pelbagai industri. Aloi titanium Ti-6Al-7Nb, juga dikenali sebagai Titanium 367, sangat disukai untuk prostesis pinggul total, khususnya dalam batang femoral, kerana rintangan kakisan dan biokompatibilitinya yang cemerlang. Aloi ini juga digunakan dalam penggantian lutut, prosedur pergigian, dan aplikasi maksilofasial untuk skru, plat, dan implan, menekankan keserbagunaannya dalam bidang perubatan. Walau bagaimanapun, pemesinan aloi titanium menghadapi cabaran yang ketara disebabkan oleh kebolehan mesin yang rendah. Kajian ini menyiasat kesan parameter pemotongan terpilih, termasuk kelajuan spindle dan kadar suapan, sebagai pemboleh ubah yang dimanipulasi sambil mengekalkan sudut titik sebagai pemboleh ubah tetap dalam penggerudian mikro menggunakan gerudi karbida tanpa salutan berukuran 2mm. Analisis eksperimen mengenal pasti tiga fasa kehausan alat: awal, stabil, dan teruk. Hasil menunjukkan peningkatan linear dalam kehausan sisi dengan kelajuan spindle dan kadar suapan yang lebih tinggi. Ketinggian burr adalah lebih tinggi pada kelajuan spindle dan kadar suapan yang meningkat. Ketinggian burr dipengaruhi terutamanya oleh kadar suapan, yang menentukan beban cip dan pengeluaran bahan setiap pusingan. Kesan individu parameter ini terhadap pembentukan burr adalah signifikan. Pada kelajuan spindle tertinggi, burr mahkota dengan penutup gerudi terbentuk disebabkan oleh geseran dan haba yang intensif, yang melembutkan bahan dan memudahkan pembentukan penutup di atas lubang keluar. Kajian ini mengesahkan model ramalan untuk ketinggian burr dan kehausan alat, memberikan asas untuk pengoptimuman parameter dalam aplikasi dunia sebenar. Model ini membolehkan penentuan kombinasi kelajuan spindel dan kadar suapan yang optimum untuk meminimumkan pembentukan burr dan meningkatkan kecekapan pemesinan.

Kata kunci: Kehausan alat, Pembentukan burr, Titanium, Penggerudian mikro

1.0 INTRODUCTION

Drilling is the process of creating a hole in an element. When dealing with micron-scale sizes, the technique is referred to as micro-drilling. This specialized form of drilling, using drill bits with diameters of two millimeters or less, is crucial for applications requiring extremely small holes. The lack of a standardized definition for micro-drilling typically hinges on the hole's diameter, with 2 mm serving as a threshold. At this size, the geometry of drill bits undergoes significant changes, affecting the web thickness and margin steps. Unlike larger drill bits that tend to wear out before fracturing, micro-drilling tools with diameters of 2 mm or less often face issues like fractures [1]. Figure 1 shows the geometry of twist tpe micro drill.

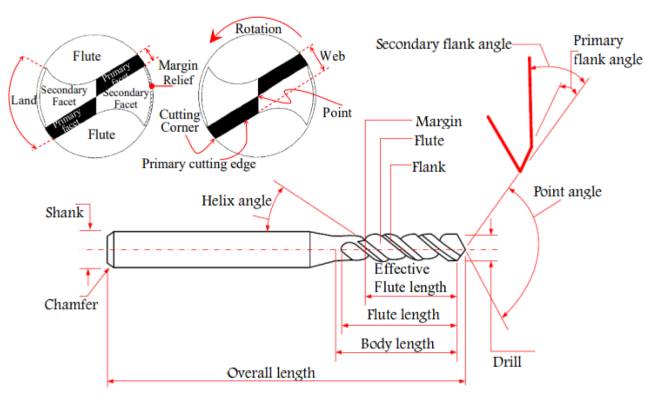


Figure 1 Geometry of twist type micro drill [1]

Therefore, a precise definition considering these modifications is essential. Conventional micro-drilling is widely used due to its ability to produce holes with high surface integrity, exhibiting excellent circularity, uniformity, and surface roughness in a short operational time [2]. According to Rawat *et al.* (2009)[3], conventional micro-drilling is less prone to heat distortion and requires fewer surface finishing steps, making it a preferred technique for achieving smoother, more uniform, and rounded surfaces. Ti-6Al-7Nb is an alpha-beta titanium alloy composed of 6% aluminium and 7% niobium, developed in 1977. This alloy shares characteristics with the cytotoxic Ti-6Al-4V alloy containing vanadium but offers superior bio-tolerance and mechanical properties. Ti-6Al-7Nb is characterized by a body-centered β phase stabilized with niobium and a hexagonal α phase stabilized with aluminium, making it suitable for orthopedic and dental implants due to its high strength-to-weight ratio, strong corrosion resistance, and excellent biocompatibility. Tool life, tool wear, and burr formation are critical factors in evaluating surface integrity in micro-drilling. Achieving high surface quality enhances resistance to corrosion, reduces wear and friction, and extends tool life.

Various studies have examined the nuances of micro-drilling to address these challenges. For instance, Chang and Lin (2012) [4] explored the effects of drilling parameters on hole characteristics in alumina ceramic, finding that feed rate significantly affected hole dimension and circularity. Prasanna *et al.* (2014) [5] optimized process parameters for micro-drilling Ti-6Al-4V under dry conditions, balancing tool life and hole quality. Other researchers [6] Elajrami *et al*. (2013) studied aluminium alloy 2024-T3, determining that an optimal combination of feed rate and rotating speed minimized tool wear and maximized hole quality. One of the latest studies on microdrilling was conducted on a 3D printed CoCrMo alloys by Patar et. al. [7] with the effort to investigate the tool wear and machinability of this printed materials.

2.0 MATERIALS AND METHODOLOGY

In this study, the workpiece material is Titanium 367 (Ti-6Al-7Nb) and its mechanical properties is shown in Table 1. The workpiece, with dimensions of diameter 22mm and thickness 4 mm, was prepared in advance of the experiment. A total of 30 2mm through holes is drilled on the Titanium Ti-6Al-7Nb workpiece of thickness 4mm and diameter 22mm. Gap between each hole is 1mm as shown in Figure 2. A fixture was fabricated and mounted on the machine table to hold the sample during the experiment. The drilling process started from the center of specimen.

Figure 2 Drilled Ti-6Al-7Nb holes

For this study, ISO 8688-2 was adopted as a standard for tool wear failure. ISO 8688-2 provides suggested criteria to create uniform standard for assessing the tool life. The guidelines state that the average wear depth should not be greater than 0.3 mm for uniform flank wear. For this study, two parameters are being investigated, the spindle speed and feed rate. Experiments are conducted under flood cooling conditions. The changes in experimental parameters are shown in Table 2. For each combination of experiments, the response variables, including tool wear and burr formation, are measured. Measurements of tool wear are taken every 10 holes up to 30 holes. Measurements are recorded for burr height and burr shapes are observed at exit surfaces of the last 30th hole as exit burr is much significant compared to earlier holes.

Table 1 Mechanical property of Ti-6Al-7Nb

Properties	Values
Density (g/cm^3)	4.52
Elastic Modulus (GPa)	105
Tensile Strength (MPa)	1000
Elongation (%)	12
Yield Strength (MPa)	900
Melting Point (K)	1860
Specific Heat (J/kg·K)	560
Ductility	0.15
Hardness (MPa)	2900

Table 2 Machining Parameters

Parameters		Values		
Factors	Units	Low Level	Center Point	High Level
Spindle speed	Rpm	8000	9000	10000
Feed Rate	mm/min	800	900	1000

3.0 MACHINING SETUP

The machining is carried out using the DMG MORI 50 CNC machining center as shown in Figure 3 and its specification is shown in Table 3. Flood coolant is preset into the CNC machine.

Figure 3 DMG MORI 50 CNC machine

Table 3 Specifications for DMG MORI 50 CNC machine

Specifications	Values
Mechanism for Table Movement	X-axis: 650 mm Y-axis: 520 mm Z-axis: 475 mm
Range of Spindle Speed	20 – 14, 000 rpm
Maximum Trust Force for X,Y,Z axis	4.8 kN
Maximum Load	300 kg
Maximum Tool Length	300 mm
Clamping Area	630 x 500 mm
Rapid Transverse	42 m/min

In this experiment, the tool life criterion is based on the ISO 8688-2 standard. According to this criterion, the limit for tool wear in micro drill bits is set at 0.3mm. Any wear value exceeding this limit is considered a failure. The flank wear of the micro drill bits is specifically taken into consideration. Due to limited material resources, the wear values of the drill bits are measured after every 10 holes drilled, up to the 30th hole. As for the cooling method used in this experiment, the flood coolant is chosen. The coolant used in this study is TOYO-G C70, a premium-grade water-soluble cutting oil, boasting a non-corrosive and multi-purpose nature. Formulated with precision from highly refined mineral oils and a specialized additive package, it offers outstanding lubricity and stability. Its application is designed to diminish heat generation during the removal process, mitigate contamination concerns. The physical and chemical properties of the lubricant are tabulated in Table 4.

Table 4 Physical and chemical properties of TOYO-G

Property	Specification
Appearance	Liquid at room temperature
Colour	Original Oil
Odor	Petroleum odor
Pour point	-20°C/-4°F
Flash Point	212°C/413.6°F
Specific Gravity/Density	0.890
Solubility in water	Soluble, become milky white colour

The Common Main Objective (CMO) Stereo Microscope demonstrates outstanding capabilities as an equipment, providing detailed, clear, and precise photos. The CMO Stereo Microscope (Figure 4) is used for diagnosing and evaluating tool wear while the Philips XL40 Scanning Electron Microscope (SEM) is used to observed burr formations.

Figure 4 CMO stereo microscope

4.0 RESULTS AND DISCUSSION

Titanium Ti-6Al-7Nb, with a thickness of 4 mm, was subjected to through-hole micro-drilling using nine distinct sets of micro-drilling parameters. Up to thirty holes were drilled, with measurements taken after every ten holes. The drill's flank face was used to assess wear. The flank wear of the uncoated carbide tool was measured and evaluated using a CMO stereo microscope. Average values for the wear measurements were taken during the experiments to ensure accuracy. All nine sets of micro-drilling parameters underwent evaluation and observation. The gathered information was then organized and presented in Table 5 and a graph of tool wear vs the number of holes is tabulated in Figure 5. Tables 6, 7 and 8 display the tool's flank face following the completion of the 10th, 20th, and 30th holes for 8000 rpm to 9000 rpm and 10000 rpm spindle speeds. These photos visually represent the tool's flank face, making it easier to analyze and assess the trend and condition of tool wear in more detail.

Table 5 Experimental results of tool wear

Experiment Number	Hole No	Manipulating Factor		Tool Wear (mm)	Tool Life (min)
		Spindle speed (rpm)	Feed Rate (mm/min)		
1	10	8000	800	0.095	17.29
	20			0.134	
	30			0.180	
2	10	8000	900	0.096	16.85
	20			0.140	
	30			0.192	
3	10	8000	1000	0.098	13.16
	20			0.168	
	30			0.206	
4	10	9000	800	0.135	15.91
	20			0.177	
	30			0.209	
5	10	9000	900	0.160	14.44
	20			0.188	
	30			0.235	
6	10	9000	1000	0.159	12.16
	20			0.204	
	30			0.255	
7	10	10000	800	0.187	14.74
	20			0.283	
	30			0.297	
8	10	10000	900	0.191	9.44
	20			0.292	
	30			0.300	
9	10	10000	1000	0.231	5.77
	20			0.300	
	30			0.322	

Table 6 Tool wear progression (8000 rpm)

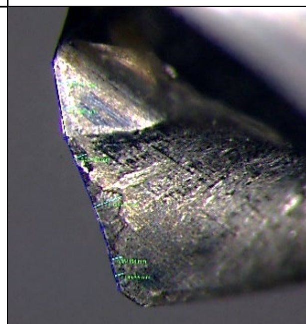
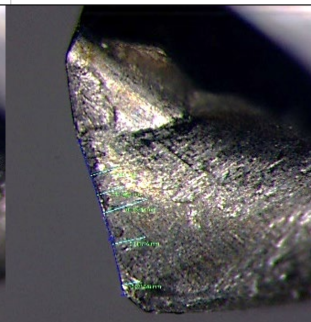
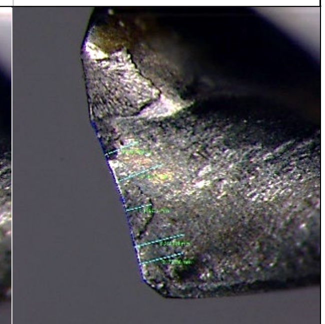
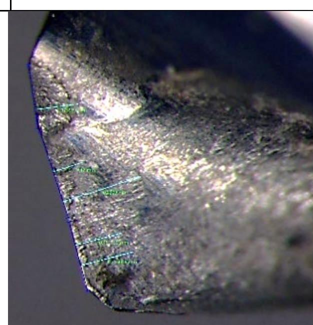
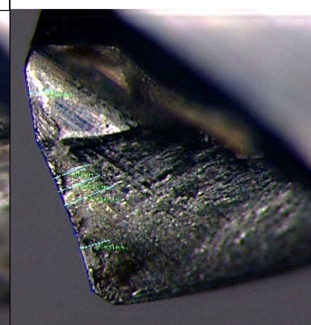
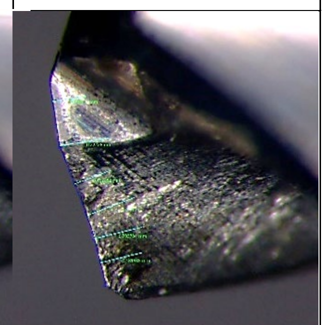
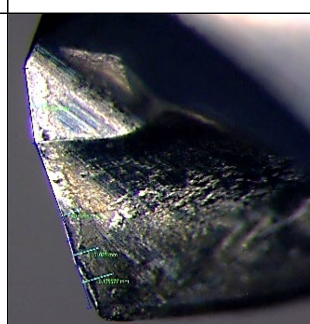
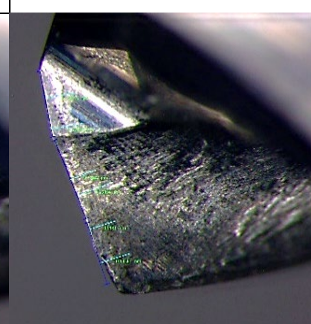
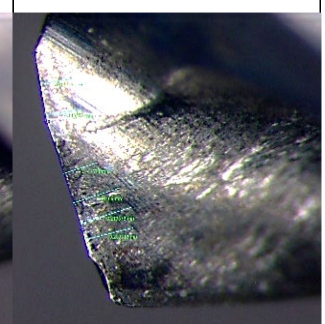
	Spindle Speed (rpm)	No of Hole		
	8000	10th Hole	20th Hole	30th Hole
Feed Rate (mm/min)	800			
	Tool Wear (mm)	0.095	0.134	0.180
	900			
	Tool Wear (mm)	0.096	0.140	0.192
	1000			
	Tool Wear (mm)	0.098	0.168	0.206

Table 7 Tool wear progression (9000 rpm)

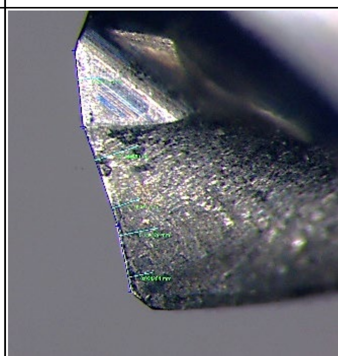
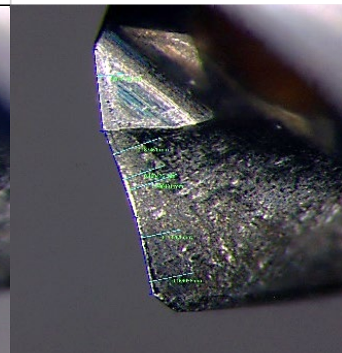
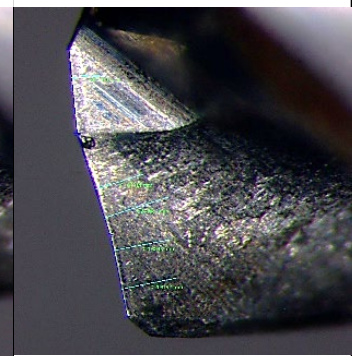
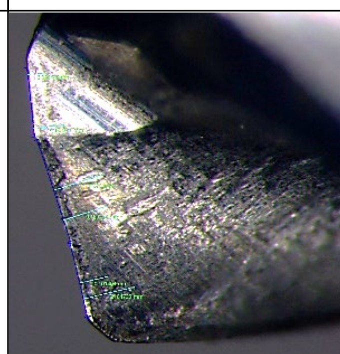
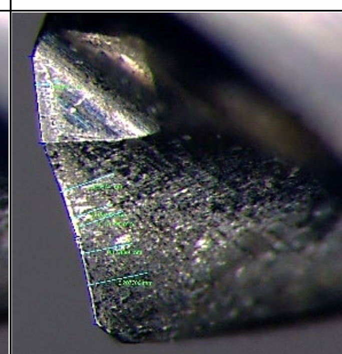
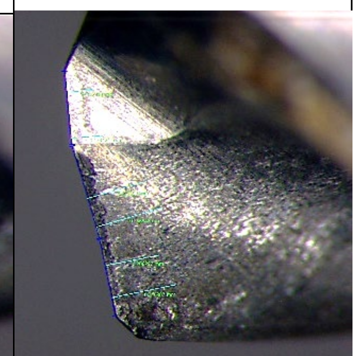
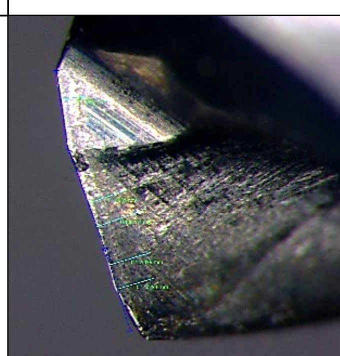
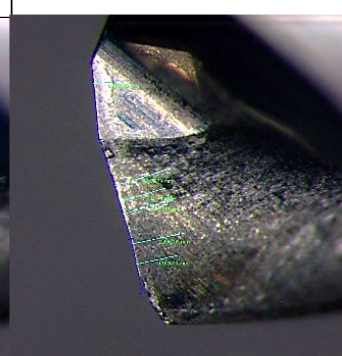
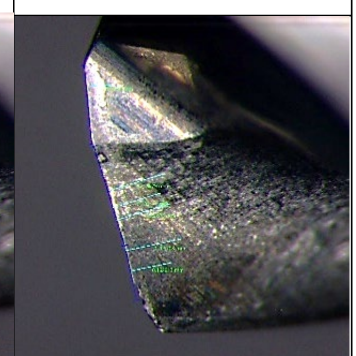
	Spindle Speed (rpm)	No of Hole		
	9000	10th Hole	20th Hole	30th Hole
Feed Rate (mm/min)	800			
	Tool Wear (mm)	0.135	0.177	0.209
	900			
	Tool Wear (mm)	0.160	0.188	0.235
	1000			
	Tool Wear (mm)	0.159	0.204	0.255

Table 8 Tool wear progression (10000 rpm)

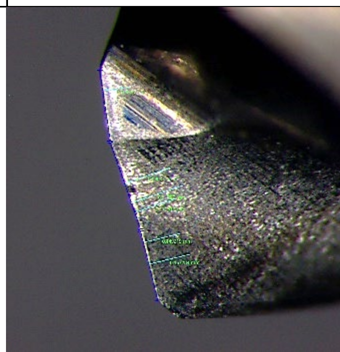
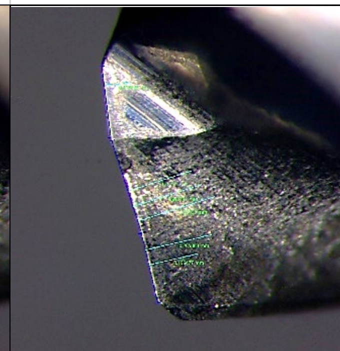
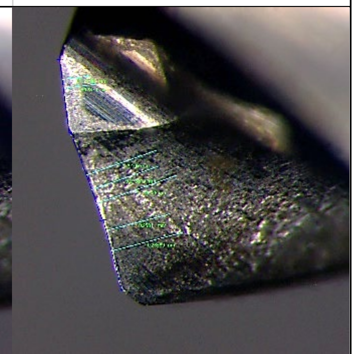
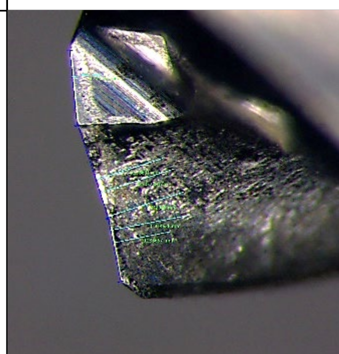
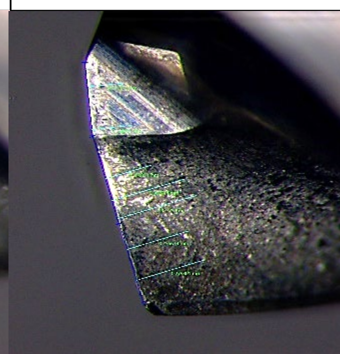
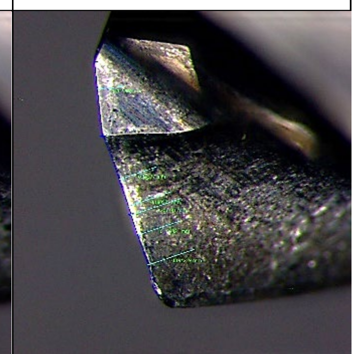
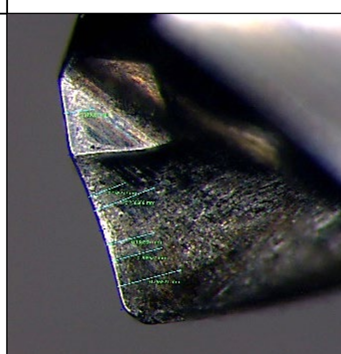
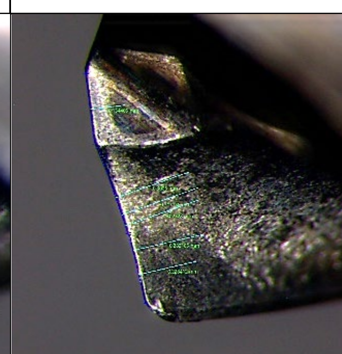
	Spindle Speed (rpm)	No of Hole		
	10000	10th Hole	20th Hole	30th Hole
Feed Rate (mm/min)	800			
	Tool Wear (mm)	0.187	0.283	0.297
	900			
	Tool Wear (mm)	0.191	0.292	0.300
	1000			
	Tool Wear (mm)	0.231	0.300	

Figure 5 shows the tool wear progressively increases during the first wear phase (0–10 holes). Tool wear increases consistently during the steady wear period (10–20 holes). Ultimately, the flank wear rises during the severe wear phase (20–30 holes). The tool wear fell short of the 0.3 mm rejection criteria for this parameter configuration. There's a comparatively high level of wear during the early wear phase since the cutting edge is new. Following this phase, the drill moves into the steady wear phase, during which the rate of wear stabilizes and finds a state of balance. A certain amount of tool wear causes the cutting edge to lose its sharpness, increasing the amount of frictional heat produced at the tool-chip contact. This causes a sharp increase in tool wear, signaling the start of the rapid wear phase, during which wear on the flank face becomes more severe [8]

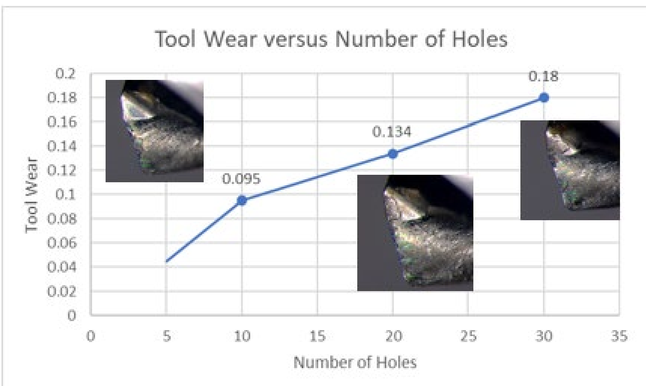


Figure 5 Graph of tool wear vs number of holes

4.1 Analysis of tool wear against machining variables

a) VS Spindle Speed

Tool wear is closely related to spindle speed, which is demonstrated by the bar chart in Figure 6, which displays an identical upward trend for tool wear at spindle speeds of 8000 rpm, 9000 rpm, and 10000 rpm. The tool wear values for 8000 rpm and 9000 rpm spindle speeds did not surpass the tool life threshold for failure after drilling 30 holes, despite the rise in wear. Nevertheless, the tool life criteria are met at higher feed rate settings of 900 and 1000 mm/min in spindle speeds of 10,000 rpm, meaning the tool needs to be rejected and cannot be continued for the machining process. This implies that the spindle speed of 10,000 rpm is too high for this specific finding. This data is consistent with the research conducted by Dang *et al*. (2019) [9], which reported that greater spindle speeds led to larger drilling forces, which in turn caused higher cutting temperatures and wear amounts.

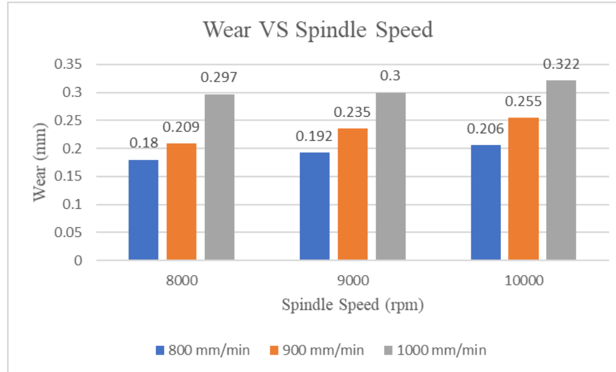


Figure 6 Tool wear vs spindle speed

b) VS Feed Rate

Figure 7 shows the graph tabulated for tool wear vs feed rate. After micro-drilling 30 holes, the tool wear values for these feed rates did not surpass the tool life threshold for failure. The tool life condition is particularly met at the greater feed rates of 900 mm/min and 1000 mm/min with the highest spindle speed setting of 10000 rpm. To be more precise, the tool can't be used for more than 20 holes at 1000 mm/min or more than 30 holes at 900 mm/min. This indicates that spindle speeds of 10,000 rpm in conjunction with feed rates of 900 mm/min and 1000 mm/min are inappropriate for this specific investigation. This result is consistent with research on Titanium Ti-6Al-4V drilling by Suresh *et al*. (2015) [10], which showed that a low feed rate is the best combination for maximum tool wear.

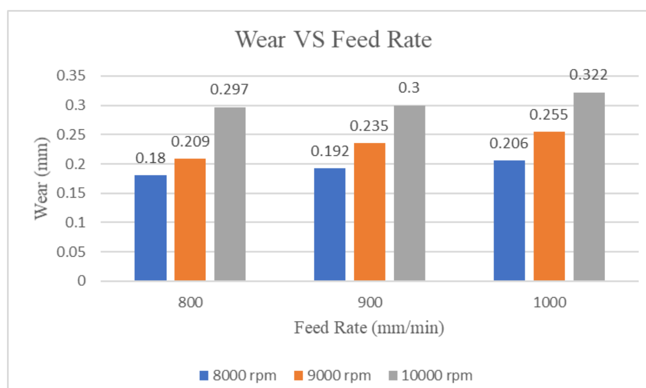


Figure 7 Tool wear vs feed rate

Burr height was measured using a Philips XL40 Scanning Electron Microscope (SEM). Average values for the burr height measurements during the experiments were taken to ensure accuracy. Burr height of the exit burr at the last 30th holes was taken for analysis in each experiment. And it was found that the burr heights in the last holes were the highest, making them the most significant aspect of burr analysis. The worn drill resulted in high friction and high cutting temperature thus hindered the coolant's ability to enter the hole, leading to more deformation [11]. This occurred because the worn drill bit created greater thrust forces during drilling, which caused more severe plastic deformation. A thicker burr develops at the exit hole as a result of the layer underneath the drill becoming more plastically deformed. The burr height and burr shape are visually represented in Table 9, making it easier to analyze and assess the trend and condition of the burr in more detail. The image of burr height is taken at magnification of 200 times while image of burr shape is taken at 60 times.

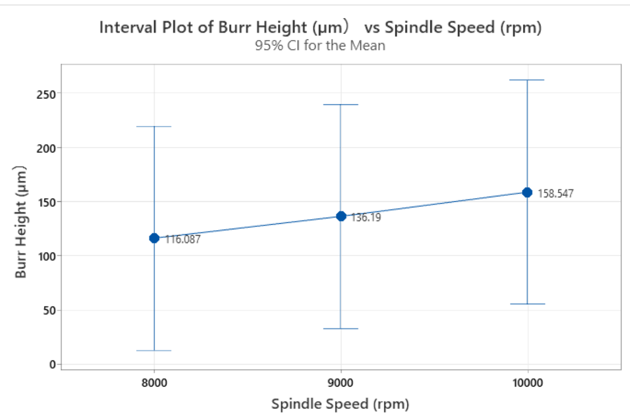


Figure 8 Interval plot for burr height against spindle speed

The experiment focused on the last 30th hole at the exit surface of the Titanium Ti-6Al-7Nb specimen. Studies revealed that the degree of plastic deformation at the entry holes is lower than at the exit holes. The greater torque that these hole boundaries sustain is the cause of the enhanced deformation at the exit surface (Perçin *et al*., 2016) [12]. Furthermore, it was reported that the wear of after drilling the last hole causes the greatest thrust force, plastic deformation, and the development of the greatest burrs, resulting in the highest burr heights [11]. The graph in Figure 8 clearly illustrates the positive linear association between spindle speed and burr height using the statistical program Minitab. The burr height climbed steadily from 80.98 µm to 118.45 µm as the spindle speed increased from 8000 rpm to 9000 rpm.

The burr height then raised consistently from 118.45 µm to 154.32 µm with a subsequent rise in spindle speed from 9000 rpm to 10000 rpm. These results are consistent with the theory: as drilling torque rises in tandem with increased spindle speed, friction and plastic deformity on the drilled surface become more intense. Due to the thermal softening characteristic of titanium Ti-6Al-7Nb at high temperatures, increasing spindle speed results in larger drilling pressures. The wear rate of drill accelerates as a result of this increase. Increased burr formation is caused by a combination of factors such as excessive heat, worn drills, and substantial plastic distortion on the material [13].

Table 9 Burr heights and shape after micro drilling Ti-Al-7Nb

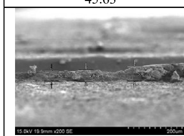
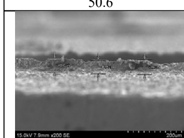
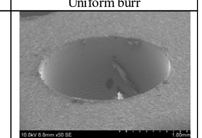
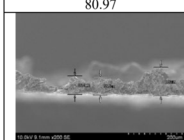
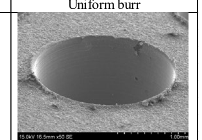
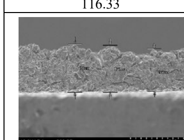
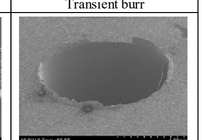
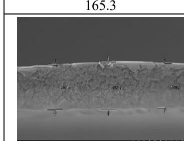
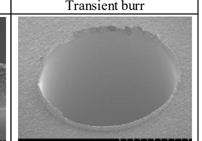
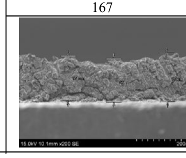
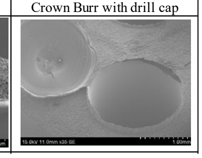
Experiment Number	Spindle Speed (rpm)	Feed Rate (mm/min)	Burr Height (µm)	Burr Shape
1	8000	800	45.63 	Perfect scenario 
2	9000	800	50.6 	Uniform burr 
3	10000	800	80.97 	Uniform burr 
4	8000	900	116.33 	Transient burr 
5	9000	900	165.3 	Transient burr 
6	10000	900	167 	Crown Burr with drill cap 

Figure 9 presents a clear analysis of the association between burr height and feed rate. The burr height grew drastically from 59.07 µm to 149.543 µm as the feed rate increased from 800 mm/min to 900 mm/min, and the burr height continued to increase from 149.543 µm to 202.213 µm when the feed rate increased from 900mm/min to 1000mm/min. The burr shape changed from perfect scenario and uniform burr in the lower feed rate of 800mm/min to transient burr and crown burr at 900mm/min and then to crown burr at 1000 mm/min. These results reinforce the findings of previous research, which observed that faster workpiece movement over the tool surface is made possible by greater feed rates leading to larger uncut chip thickness [14]. Because of an elevated uncut chip thickness, the workpiece moves at greater speeds, which increases the tool-workpiece contact and may cause more noticeable burr development and plastic deformation.

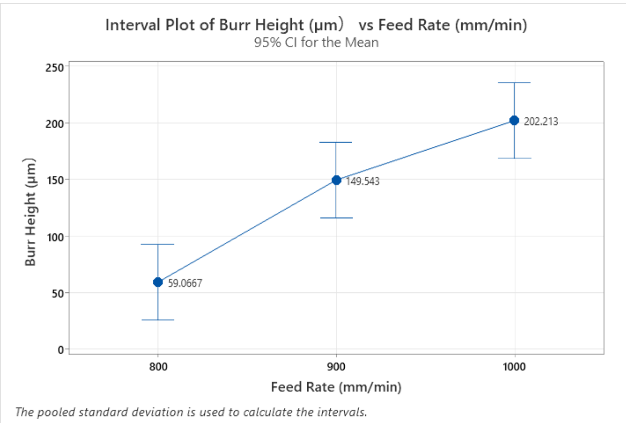


Figure 9 Interval plot of burr height against feed rate

5.0 CONCLUSION

Aimed to evaluate the effects of micro-drilling settings on tool wear and burr formation on titanium Ti-6Al-7Nb. An experimental investigation was carried out to examine the impact of feed rate and spindle speed on burr development and tool wear. Furthermore, flank wear was most common at the maximum spindle speeds of 10,000 rpm and feed rates of 1000 mm/min. The study showed that increasing spindle speed and feed rate resulted in increased tool wear and decreased tool life, attributed to the considerable heat produced during the cutting operation, which lowers cutting force. The results demonstrated that the greatest tool life, lasting 17.29 minutes, occurred at a spindle speed of 8000 rpm and a feed rate of 800 mm/min. Therefore, longer tool life was achieved with lower spindle speed and feed rate combinations.

Higher burr height results from increased spindle speed and feed rate in burr formation. With a spindle speed of 10,000 rpm and a feed rate of 1000 mm/min, the greatest burr height of 227.67 µm was formed, generating a crown burr with a drill cap. Conversely, the lowest burr height was produced at lower spindle speed and feed rate parameters. The feed rate turned out to be the main factor influencing burr height. Increasing the feed rate causes a direct increase in cutting impact, localized heat, plastic deformation, and mechanical strain by utilizing more material in each pass. This results in larger, harder-to-control chips with greater burr sizes. The primary factor influencing burr height was the feed rate. Increasing the feed rate directly raises cutting forces and burr formation by engaging more material per pass, causing greater mechanical load, plastic deformation, and localized heat.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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