

THE EFFECT OF DIFFERENT CUTTING TOOL MATERIALS AND MACHINING PARAMETERS ON THE SURFACE ROUGHNESS OF BIOMEDICAL-GRADE TITANIUM ALLOYS

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Abstract

Titanium alloy (Ti6Al4V) is one of the hardest and strongest alloys used in modern manufacturing industries, particularly in medical implants, due to its exceptional strength-to-weight ratio, high corrosion resistance, and lightweight properties. This study investigates the impact of different cutting tool materials and machining parameters on the surface roughness of biomedical-grade titanium alloy. The research is motivated by the alloy's low thermal conductivity and strong chemical affinity with cutting tool surfaces at high temperatures, which complicates machining. The Taguchi method was employed to optimise machining parameters. Results show that cutting speed and depth of cut significantly influence the surface roughness of the titanium alloy. Using a tungsten carbide insert, the surface roughness achieved was 0.957 μm with machining parameters set at 125 m/min, 0.05 mm/rev, and 1.5 mm. In contrast, employing a polycrystalline diamond insert yielded the lowest surface roughness of 0.316 μm at the minimum cutting speed and depth of cut, with parameters of 68 m/min, 0.1 mm/rev, and 1.0 mm. This improvement is attributed to the low friction coefficient and excellent heat conductivity of polycrystalline diamond. However, the study has limitations in optimising other crucial machining performance factors, such as tool wear, cutting forces, and temperature generation. Further investigation into the combined effects of these parameters on the machining process is necessary to achieve optimal outcomes.

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1.0 INTRODUCTION

Titanium alloy (Ti-6AL-4V) is one of the most utilised alloys across various industries, particularly in medical applications. This alloy is notable for its hardness, surpassing certain steel grades while remaining lightweight. Its applicability in medical instruments derives from its durability, low weight, and exceptional corrosion resistance (Moran *et al.*, 2022). Ti-6AL-4V is extensively employed in the biomedical sector for producing orthopedic, cardiovascular, and dental implants due to its low thermal conductivity, high yield strength (reaching 550-600 °C), and excellent biocompatibility (Hwang *et al.*, 2020; Festas *et al.*, 2020).

Machining Ti6AL-4V presents significant challenges primarily due to its high hardness, ductility, and formidable strength. The processing of titanium-based biocompatible materials for implants is complex, especially when producing intricate geometrical features with surface quality (Salikhyanov *et al.*, 2022; Dagara *et al.*, 2018). The critical factor for medical implants is the surface roughness of machined biomedical-grade alloy, which plays a key role in determining their quality. Manufacturers enhance their operations by examining how machining parameters and cutting inserts affect surface roughness. The material's low thermal conductivity can lead to significant temperature increase due to strong interaction between the cutting tool and workpiece, resulting in a reduced tool lifespan. Its machinability is further compromised by low elastic modulus and high strength, which persist at elevated temperatures (Khalik *et al.*, 2023; Palanikumar *et al.*, 2022).

Additionally, cutting temperatures can escalate to exceptionally high levels, leading to chatter and fluctuations during machining. An increased tool wear rate directly deteriorates the quality of the machined surface. Throughout the machining process, it is crucial to meet various conditions, such as minimising time spent and maintaining a low cost per unit of material. Furthermore, excessive trial runs should be avoided. Identifying the optimal combination of cutting variables that satisfy all output criteria can be challenging under these constraints (Ma *et al.*, 2024; Khan & Maity, 2018).

Numerous studies have been conducted to discover effective methods for enhancing the machinability of titanium alloys. High-speed steel (HSS) cutting tools are one type of tool used for machining titanium alloys. It convincingly demonstrates that HSS tools become ineffective for machining titanium and similar alloys when the cutting speed is too high, for example greater than 30 meters per minute (Rahman *et al.*, 2006). Consequently, it is possible to process both highly alloyed and general-purpose grades of titanium. However, it is always a significant concern that the cutting speed should not be over the limit, which is 30 meters per minute.

Alternatively, tungsten carbide inserts can be utilised for machining titanium alloys. Their higher resistance to abrasive wear compared to HSS tools ensures longer tool life and consistent performance under high-stress conditions, where less durable materials may wear out rapidly. Nevertheless, tungsten carbide inserts have their limitations. Despite their

exceptional performance under normal circumstances, they are susceptible to thermal shock during intermittent cutting of titanium alloys. This potentially leads to cracking and premature tool failure. Although tungsten carbide withstands higher temperatures compared to HSS, it possesses lower thermal conductivity, leading to increased cutting-edge temperatures that affect tool life and workpiece integrity (Masek *et al.*, 2022; Noor & Musfirah, 2022).

Another machining method for titanium alloys employs Polycrystalline Diamond (PCD) inserts. Research by F. Nabhani in 2001 demonstrated that PCD tools significantly reduce tool wear during titanium machining. As titanium carbide forms a protective coating on the tool's rake during machining, PCD tools remain effective even under challenging conditions. According to Chauhan *et al.* (2023), diamond is the most durable cutting tool material in the machining industry, with PCD specifically demonstrating a low friction coefficient that enhances wear resistance compared to other materials. PCD inserts attain high surface polish while significantly extending tool life and minimising the frequency of tool changes and interruptions, which is particularly advantageous for prolonged cutting processes (Sadik *et al.*, 2019).

The relationship between surface roughness of titanium alloys and various cutting tool materials and turning parameters has been the subject of several studies. A study by J. Nithyanandam *et al.* (2015) characterised surface roughness when turning titanium alloy with nanocoated carbide inserts, focusing on parameters such as cutting speed, nose radius, feed, and depth of cut. Their findings indicated that the feed rate had the most significant impact on surface roughness, followed by cutting speed, nose radius, and depth of cut.

Meanwhile, Abdelnasser *et al.* (2020) conducted research on conventional machining of biomedical-grade Titanium alloy using a PCD insert. The dry machine was utilised with a length of cut of 30mm and a diameter of 25mm. The results showed that higher cutting speeds reduced surface roughness, primarily due to work material softening and decreased cutting force. However, increases in cutting speed also led to increased surface roughness caused by a phenomenon known as "chatter."

In a separate study by Yilmaz *et al.* (2020), the workpiece material was 7075 aluminium alloy (AA7075) with carbide cutting tools. Three feed rate values (0.05, 0.15, and 0.25 mm/rev), and three cutting speeds (190, 280, and 375 m/min) were tested while maintaining a constant cutting depth of 0.5 mm. The research revealed that rise in the feed rate significantly affected surface roughness, while an increase in cutting speed had minimal impact.

Therefore, most prior research has concentrated on a single cutting tool insert approach to assess the influence of surface roughness on titanium alloy. There is a critical need for further investigation as existing literature lacks a comprehensive analysis of how different cutting tool materials and machining parameters impact the surface roughness of the alloy. This study aims to explore two distinct cutting tool inserts while assessing various machining parameters including feed rate, cutting speed, and cutting depth to investigate their influence on achieving high-quality surface finishes for titanium alloys

intended for biomedical implant applications. The primary objective is to identify the most influential machining parameter and evaluate the surface roughness of titanium alloy, subsequently examining how different turning parameters affect the surface roughness of biomedical-grade titanium alloy through the usage of both tungsten carbide and PCD inserts.

2.0 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Workpiece Material for the Research

The cylindrical workpiece material chosen for this research was Biomedical-grade Titanium alloy (Ti-6Al-4V) with the length of 100mm and diameter of 25 mm. The Ti-6Al-4V's mechanical properties and chemical composition that are used in this experiment, are presented in Tables 1 and 2 as per the American Iron and Steel Institute standard (AISI).

Table 1: Titanium Alloy's (Ti-6Al-4V) physical properties

Mechanical Properties	Values
Ultimate Tensile Strength (MPa)	1170
Tensile Strength, Yield (MPa)	1100
Modulus of Elasticity (GPa)	114
Shear Modulus (GPa)	44
Elongation at break (%)	10
Poisson's Ratio	0.342

Table 2: Titanium Alloy's (Ti-6Al-4V) chemical composition

Elements	Content (%)
Titanium (Ti)	90
Aluminium (Al)	6
Vanadium (V)	4
Iron (Fe)	0.25
Oxygen (O)	0.2

2.2 Cutting Tool

A PCD insert, and Tungsten carbide insert were used in this project. The turning operation is conducted by using a conventional lathe machine. The machine used for this project is the Pinacho SP/165 Conventional lathe machine. The speed of cutting is expressed from m/min to revolutions per minute (RPM) to align with conventional lathe programming commands. Meanwhile, Band Saw Horizontal, HB 280 B machine is used to cut the Titanium alloy into required pieces for the experiment.

2.3 Experiment Set Up

The Band Saw Horizontal, HB 280 B machine was used to cut a 1000mm rod of biomedical-grade Titanium alloy into nine pieces, each 100 mm in length. After cutting, nine pieces are prepared for the experiment. The experiment involved cutting a length of 30 mm from each end of the rod using an external turning operation. One end of the rod was cut by using a Tungsten Carbide insert while the other end of the rod was cut by using a PCD insert. The cutting speeds used on a lathe machine were 68, 110, and 125 m/min, combined with feed

rates of 0.05, 0.1, and 0.15 mm/rev, and cutting depths of 0.5, 1.0, and 1.5mm. A total of 18 experiments were conducted using the Taguchi method on both ends of the titanium alloy. Each titanium alloy rod was labelled with plastic tape for easy identification during the analysis phase to measure surface roughness.

Next, the Mitutoyo Surface Roughness Measuring Tester, model SJ-410 (SURFTEST SJ-410), was utilised to measure the surface roughness of the alloy. Before the measurement, the surface of the samples was cleaned and free of debris to make sure the data obtained was precise. Then, a Vee-block was used to support the Titanium alloy sample to free it from any unnecessary movement while taking the measurement. The standard parameter for surface roughness in this experiment was the average surface roughness, Ra. The tester was positioned on the titanium alloy's surface to conduct the measurement, with the device probe traversing the surface for 20 mm and recording the height variations that comprise the surface texture. After measurement, the device displayed the results, which were recorded for further analysis. The average surface roughness measurements (Ra) were plotted on the y-axis, while different machining parameters—such as cutting speed (m/min), feed rate (mm/rev), and depth of cut (mm)—were plotted on the x-axis for both inserts to study their influence on surface roughness.

Additionally, an Optical Microscope, model XST60 was used to observe the surface of sample that has the highest and lowest surface roughness obtained for both inserts. First, the interpupillary distance was adjusted by moving the eyepieces closer or further apart until a single circular field was visible. Then, the selected four samples were placed on the specimen slide one by one and secured with the Vee-block. The lens magnification used to examine the sample surfaces was 20x. For optimal clarity, the diaphragm was adjusted to control the light on the titanium alloy samples. Finally, the images obtained from the microscope were saved in PDF format.

2.4 Taguchi Method

The Taguchi method was employed in the experiment to identify the optimal machining performance characteristics of the titanium alloy (Ti-6Al-4V). This approach ensures consistent results throughout the turning experiment. Table 3 shows that there are three acceptable factors, each with three levels. A crucial aspect of a parametric analysis is the selection of controlled parameters. The primary parameters considered for the experiment include cutting speed, feed rate, and depth of cut.

Table 3: The considered parameters and levels for the experiment

Factor	Cutting Parameters	Level			Unit
		1	2	3	
1	Cutting speed	68	110	125	m/min
2	Feed rate	0.05	0.1	0.15	mm/rev
3	Depth of Cut	0.5	1.0	1.5	mm

Additionally, the orthogonal array L9 is used to execute the experiment. As a result, Table 4 displays the orthogonal array type L9 with a variety of parameters.

Table 4: Table of Taguchi design for the experiment (Orthogonal Arrays L9)

Experiment Number	Cutting Parameter Level		
	A	B	C
	Cutting Speed	Feed Rate	Depth of Cut
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The parameter selection in Table 5 using the Taguchi technique was conducted in the machining process to identify the impact of cutting tool materials with machining parameters on performance of machining for the workpiece. A total of 18 experiments were conducted on both end sides of the workpiece using the presented cutting parameter level in Table 5.

Table 5: The layout of the experiment is based on an L9 orthogonal array for the research

Number of Experiment	Cutting Parameter Level			Diameter (mm)
	A	B	C	
PCD Insert	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	
	68	0.05	0.5	25
	68	0.1	1.0	25
	68	0.15	1.5	25
	110	0.05	1.0	25
	110	0.1	1.5	25
	110	0.15	0.5	25
	125	0.05	1.5	25
	125	0.1	0.5	25
	125	0.15	1.0	25
Tungsten carbide insert				
	68	0.05	0.5	25
	68	0.1	1.0	25
	68	0.15	1.5	25
	110	0.05	1.0	25
	110	0.1	1.5	25
	110	0.15	0.5	25
	125	0.05	1.5	25
	125	0.1	0.5	25
	125	0.15	1.0	25

3.0 RESULTS AND DISCUSSION

3.1 Results

3.2 The Impact of Machining Parameters on the Surface Roughness of Biomedical-Grade Titanium Alloy Utilising a Tungsten Carbide Insert

The surface roughness of biomedical-grade titanium alloy is significantly influenced by machining parameters, which vary based on the cutting inserts used. When employing a tungsten carbide insert, higher cutting speeds and depths of cut result in a notable increase in surface roughness. The lowest recorded surface roughness is 0.366 μm , while the maximum is 0.954 μm , achieved during experiments 1 and 7, respectively. It was observed that increasing the depth of cut strongly affects the surface roughness of the titanium alloy, leading to visible deterioration in surface quality.

In addition to machining parameters, it is noteworthy that tungsten carbide inserts have weaker wear properties compared to PCD inserts. PCD inserts provide superior wear resistance, even at high cutting speeds. During the machining of titanium alloy, generated heat is effectively dissipated from the cutting area, helping to prevent thermal workpiece deformation, and minimising heat-induced surface irregularities.

Figure 1 shows the relationship between surface roughness against the influence of feed rate on cutting speed using tungsten carbide method. As the feed rate increases, surface

roughness gradually rises. Initially, there is a linear increase in surface roughness for feed rates of 0.05 mm/rev and 0.10 mm/rev with cutting speeds ranging from 68 m/min to 110 m/min. However, at feed rates of 0.05 mm/rev and 0.15 mm/rev, a significant change in surface roughness occurs when cutting speeds increase from 110 m/min to 125 m/min. This is due to the crucial role of depth of cut in determining surface roughness at these feed rates. Specifically, a depth of cut of 1.5 mm at a feed rate of 0.05 mm/rev increases the tool and workpiece contact area, exerting more strain on the tungsten carbide insert.

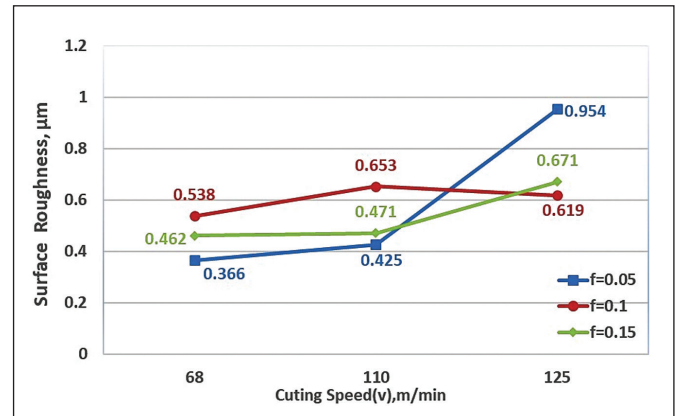


Figure 1: Graph of surface roughness against the influence of feed rate on cutting speed using Tungsten Carbide inserts

Table 6: Result of average surface roughness during machining process on Polycrystalline diamond and Tungsten carbide inserts

Number of Experiment	Cutting Parameter Level			Diameter (mm)	Spindle Speed (RPM)	Average Surface Roughness (μm)
	A	B	C			
Polycrystalline Diamond insert (PCD)	Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)			
1	68	0.05	0.5	25	860	0.347
2	68	0.1	1.0	25	860	0.310
3	68	0.15	1.5	25	860	0.615
4	110	0.05	1.0	25	1400	0.424
5	110	0.1	1.5	25	1400	0.425
6	110	0.15	0.5	25	1400	0.531
7	125	0.05	1.5	25	2000	0.429
8	125	0.1	0.5	25	2000	0.516
9	125	0.15	1.0	25	2000	0.582
Tungsten carbide insert						
1	68	0.05	0.5	25	860	0.366
2	68	0.1	1.0	25	860	0.538
3	68	0.15	1.5	25	860	0.462
4	110	0.05	1.0	25	1400	0.524
5	110	0.1	1.5	25	1400	0.653
6	110	0.15	0.5	25	1400	0.471
7	125	0.05	1.5	25	2000	0.954
8	125	0.1	0.5	25	2000	0.619
9	125	0.15	1.0	25	2000	0.671

Conversely, a feed rate of 0.15 mm/rev with a depth of cut of 1 mm results in less heat generation, leading to less impact on surface roughness compared to a feed rate of 0.05 mm/rev. Consequently, the tool's cutting edge distorts and wears down, resulting in a rougher workpiece surface during the turning operation. Further evidence of this is seen in the fluctuation of surface roughness values at a feed rate of 0.10 m/rev, where an initial increase is followed by a slight decrease. The significant role of depth of cut in determining the surface roughness of titanium alloy is underscored by the observed variations. These variations arise from differences in depth of cut values, with a setting of 1.5 mm at a cutting speed of 110 m/min compared to 0.5 mm at a cutting speed of 125 m/min.

Figure 2 illustrates the relationship between surface roughness against the influence of cutting speed on depth of cut using Tungsten Carbide inserts. The graph shows that surface roughness initially increases as the depth of cut rises across all cutting speed levels, except at a cutting speed of 68 m/min. At 68 m/min, surface roughness increased from 0.366 μm to 0.538 μm but then decreased back to 0.462 μm . This phenomenon is attributed to the relatively low cutting speed, which results in less heat generation, thus having a minimal effect on the surface roughness of titanium alloy. Given that titanium alloy has low thermal conductivity, this property has been safe from this heat generation.

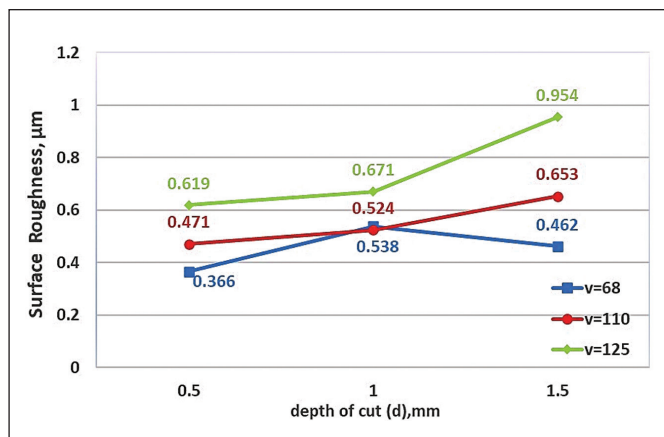


Figure 2: Graph of surface roughness against the influence of cutting speed on depth of cut using Tungsten Carbide inserts

Furthermore, a correlation exists where an increase in cutting depth leads to higher surface roughness across various cutting speeds, although the rate of increase varies. For example, at a cutting speed of 110 m/min, the difference in surface roughness between a 1 mm and a 1.5 mm increases to 0.283 μm . This comparison underscores the varying impact of cutting depth on surface roughness at different cutting speeds. Clearly, increased cutting speeds combined with greater cutting depths lead to elevated temperatures when machining titanium alloys with tungsten carbide inserts. The rise in temperature results from increased friction between the cutting tool and the workpiece at higher speeds and depths, leading to greater heat generation. Consequently, this thermal effect facilitates the formation of burrs and built-up edges (BUE) on the workpiece surface under such high-temperature conditions.

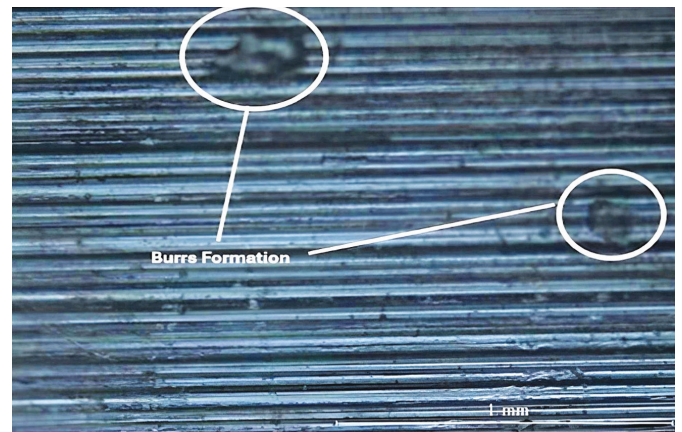


Figure 3: Diagram of Titanium alloy with highest surface roughness using Tungsten Carbide insert

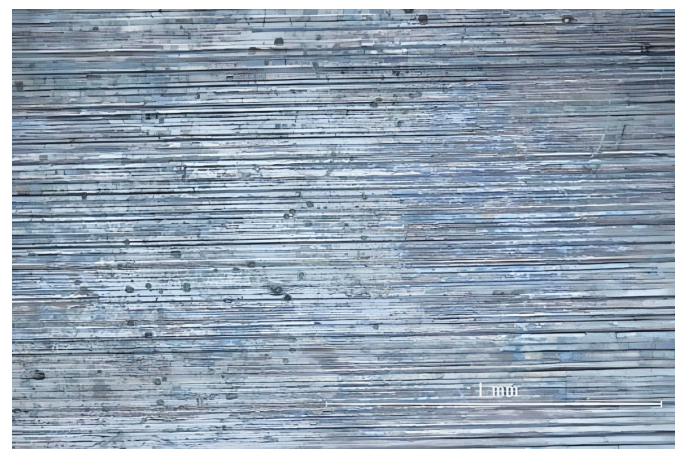


Figure 4: Diagram of Titanium alloy with lowest surface roughness using Tungsten Carbide insert

As evident, figures 3 and 4 show the diagram of Titanium alloy surface with the highest surface roughness and lowest surface roughness using the Tungsten Carbide insert which was observed through optical microscope at a magnification of 20x, respectively.

The highest surface roughness value obtained was 0.954 μm with the parameter setting of 125m/min, 0.05mm/rev and 1.5mm. It's obvious to see that the Titanium alloy surface has developed some burrs, an imperfection in the shape of deformed material that sticks out from the surface. It is usually linked to aggressive machining conditions or poor cutting parameters that fail to control the material flow.

There are no apparent imperfections or burrs in the surface, suggesting a smoother and more regular surface texture. The lowest surface roughness recorded was 0.366 μm with the machining parameter of 68m/min, 0.05mm/rev and 0.5mm. This suggests that the machining parameters were fine-tuned for this sample, leading to a superior finish.

3.3 The Impact of Machining Parameters on the Surface Roughness of Biomedical-Grade Titanium Alloy Utilising Polycrystalline Diamond Insert

The utilisation of PCD inserts resulted in achieving a minimum surface roughness of 0.310 μm , while the maximum surface roughness of 0.615 μm was attained during experiments 2 and 3.

Figure 5 shows the relationship between surface roughness against the influence of feed rate on cutting speed using PCD insert. Initially, surface roughness increases for all feed rates except for the rate of 0.15 mm/rev as cutting speed varies from 68 m/min to 110 m/min. There is an approximate twofold increase in surface roughness, rising from 0.31 μm to 0.615 μm when the feed rate increases from 0.10 mm/rev to 0.15 mm/rev at a cutting speed of 68 m/min. The primary factor contributing to the spike in surface roughness is the cutting depth chosen for the experiment, where the feed rate of 0.15 mm/rev corresponds to a depth of 1.5 mm, higher than the other depths of cut, which are 0.5 mm and 1 mm. Consequently, cutting temperatures increased directly in proportion to the cutting depth, significantly affecting the final surface roughness of the titanium alloy.

The conducted research clearly indicates that surface roughness progressively increases with both rising feed rate and cutting speed when employing a PCD insert. In Experiment 1, the recorded surface roughness value was 0.347 μm at a feed rate of 0.05 mm/rev. This was succeeded by a higher surface roughness value of 0.425 μm in Experiment 5, where the feed rate was 0.10 mm/rev. Ultimately, during Experiment 9, using a feed rate of 0.15 mm/rev, the surface roughness value further increased to 0.582 μm . Utilising PCD tools for titanium machining notably reduces tool wear due to the formation of a protective titanium carbide coating on the tool's rake face during the machining process. This titanium carbide forms when titanium from the workpiece reacts with carbon from the cutting tool at elevated temperatures. The chemical reaction between

titanium and carbon leads to titanium carbide formation, which then bonds with the surface of the cutting tool. Therefore, PCD maintains its sharp cutting edge at high temperatures without deteriorating and produces less surface roughness on titanium alloy compared to tungsten carbide.

Figure 6 illustrates the relationship between surface roughness against the influence of cutting speed on depth of cut using PCD inserts. At a cutting speed of 68 m/min, the surface roughness initially decreases as the depth of cut increases from 0.5 mm to 1 mm, but then rises significantly when the depth of cut reaches 1.5 mm. In contrast, at a cutting speed of 110 m/min, surface roughness decreases from 0.5 mm to 1 mm, and remaining constant when the depth of cut increases to 1.5 mm. Lastly, at a cutting speed of 125 m/min, surface roughness increases from 0.5 mm to 1 mm, but decreases when the depth of cut reaches 1.5 mm.

The increase in surface roughness at lower depths of cut is primarily attributed to ploughing rather than chip formation. Additionally, surface roughness was slightly influenced by cutting speed at shallow depths. Specifically, at the slowest cutting speed of 68 m/min, a depth of cut of 0.5 mm resulted in the smoothest surface, measuring 0.347 μm . Conversely, at the highest cutting speed of 125 m/min, the roughest surface recorded was 0.516 μm . At a cutting speed of 68 m/min and a depth of cut of 1.5 mm, the roughest surface roughness observed on titanium alloy using a PCD insert was 0.615 μm , representing the highest surface roughness recorded in this experiment. It was determined that cutting speed and depth of cut significantly influence surface roughness more than feed rate, with depth of cut showing the strongest effect on overall surface roughness when using PCD inserts.

Figures 7 and 8 show the diagram of Titanium alloy surface with the highest surface roughness and lowest surface roughness using the PCD insert which was observed through optical microscope at a magnification of 20x, respectively.

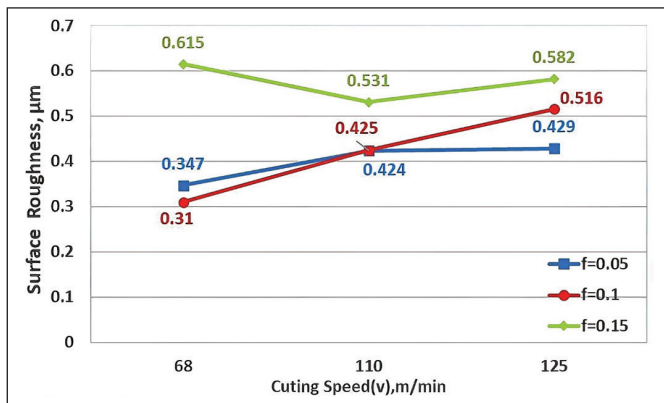


Figure 5: Graph of surface roughness against the influence of cutting speed on depth of cut using PCD insert

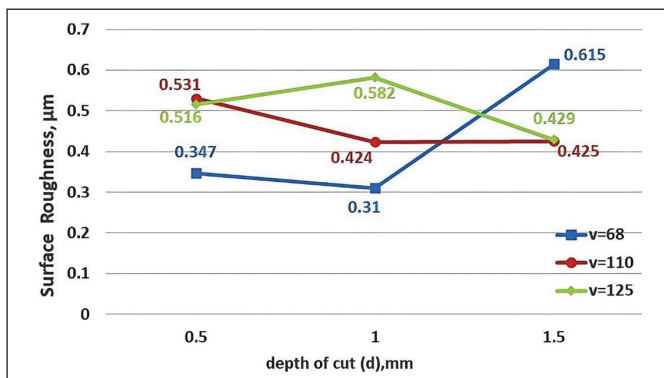


Figure 6: Graph of surface roughness against the influence of cutting speed on depth of cut using PCD insert

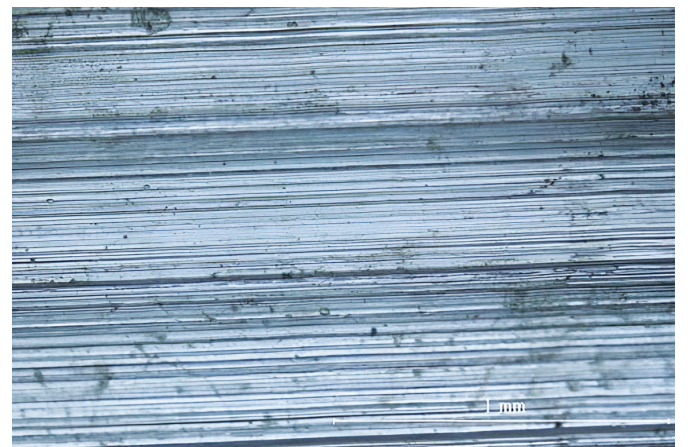


Figure 7: Diagram of Titanium alloy with highest surface roughness using PCD insert

The surface roughness value obtained was 0.615 μm which is the highest recorded using PCD insert using machining parameter of 68m/min, 0.15mm/rev and 1.5 mm. From the diagram, it clear that the finishing surface is much better as there is no significant burrs formations compared with Tungsten Carbide insert.

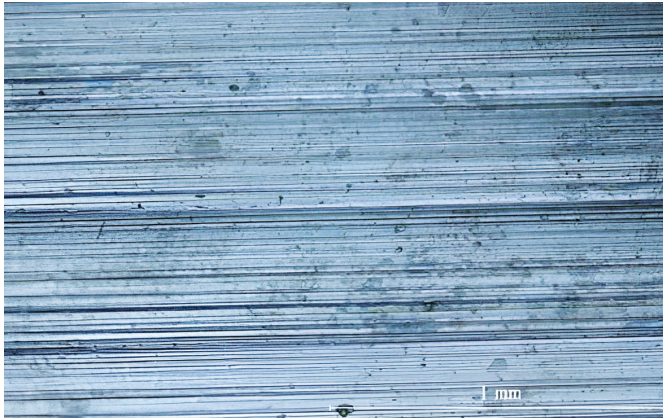


Figure 8: Diagram of Titanium alloy with lowest surface roughness using PCD insert

The lowest surface roughness value obtained was $0.310 \mu\text{m}$ which is overall the lowest surface roughness value with the parameter setting of 68m/min , 0.1mm/rev and 1.0mm obtained by using Tungsten Carbide insert. This clearly proves that PCD insert shows excellent performance in machining biomedical-grade titanium as it produces the best finishing surface. The Titanium alloy machined by using PCD insert could potentially be better suited for use as a medical implant.

4.0 CONCLUSION

The study successfully identified the surface roughness of biomedical-grade titanium alloy using PCD and tungsten carbide inserts. Based on the study's objectives, the results indicated that cutting speed and depth of cut have the most significant influence on surface roughness. Surface roughness increases significantly as cutting speed and depth increase. The maximum surface roughness achieved with a tungsten carbide insert was $0.954 \mu\text{m}$, under machining parameters of 125 m/min , 0.05 mm/rev , and 1.5 mm . Conversely, the minimum surface roughness recorded with a PCD insert was $0.316 \mu\text{m}$, corresponding to machining parameters of 68 m/min , 0.1 mm/rev , and 1.0 mm , representing the lowest cutting speed and depth of cut. This superior performance of the PCD insert is attributed to its low coefficient of friction and excellent heat conductivity, which contribute to finer surface finishes. The average surface roughness from nine experiments for each insert was calculated, showing an average of $0.584 \mu\text{m}$ for the tungsten carbide insert and $0.464 \mu\text{m}$ for the PCD insert. The slight deviations in average roughness values for both inserts stem from their good thermal conductivity, helping dissipate heat generated during machining.

Although both inserts yield similar average roughness, the PCD insert achieves a significantly better overall surface roughness due to its exceptional wear resistance, which allows it to withstand the abrasive wear typical of machining titanium alloys without significant tool wear. This durability keeps the cutting-edge sharp throughout the machining process, ensuring a consistent and smooth cutting action. However, the study has limitations in optimization, as it primarily focuses on surface roughness without thoroughly examining other crucial machining performance factors, such as tool wear, cutting forces, and temperature generation. Further investigation into

the combined effects of these parameters on the machining process is necessary to achieve the best outcomes.

5.0 RECOMMENDATIONS FOR FUTURE WORK

A well-balanced combination of machining parameters including cutting speed, feed rate, and depth cut, along with the appropriate selection of cutting tool materials, plays a crucial role in the efficient machining of biomedical-grade titanium alloy. Several recommendations are proposed to enhance the reliability of the experiment:

1. **Use biocompatible coolants:** Traditional petroleum-based coolants can pose health risks. It is recommended to use water-soluble coolants or vegetable-based oils for medical implants. Exploring lubrication systems such as minimum quantity lubrication (MQL) or cryogenic cooling can significantly improve machining results. For instance, cryogenic cooling with liquid nitrogen can reduce thermal damage and enhance surface quality, thus increasing the biocompatibility of titanium implants.
2. **Compare cutting performance and tissue compatibility with other biomedical alloys:** For instance, cobalt-chromium and stainless steel. Cobalt-chromium is recognized for its wear resistance and is used in joint replacements, while stainless steel is cost-effective and easy to shape. By examining these attributes alongside those of titanium alloys, researchers can identify the optimal material for medical applications such as dental implants and bone fixation plates. This analysis will guide the development of more effective and biocompatible medical devices.
3. **Employ full factorial design:** Instead of the Taguchi method, which focuses on a subset of factors, a complete factorial design approach should be used to assess all potential combinations of factors and levels. For example, when examining the impact of cutting speed, feed rate, and type on the surface roughness of titanium implants, a full factorial design evaluates every possible combination of these variables. This method helps identify interactions among factors that might not be apparent in a partial analysis.
4. **Conduct ANOVA for improved accuracy:** Performing an Analysis of Variance (ANOVA) assesses the statistical significance of each variable and their interactions, ensuring that detected effects are not coincidental. Employing ANOVA to carefully consider the statistical significance of experimental results enhances the integrity and reliability of research conclusions.

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REFERENCES

- [1] Chauhan, D., Makhesana, M. A., Rashid, R. a. R., Joshi, V., & Khanna, N. (2023). Comparison of Machining Performance of ti-6al-4v Under Dry and Cryogenic

- Techniques Based on Tool Wear, Surface Roughness, and Power Consumption. *Lubricants*, 11(11), 493. <https://doi.org/10.3390/lubricants11110493>
- [2] Dadgari, A., Huo, D., & Swailes, D. (2018). Investigation on Tool Wear and Tool Life Prediction in Micro-Milling of Ti-6Al-4V. *Nanotechnology and Precision Engineering*, 1(4), 218–225. <https://doi.org/10.1016/j.npe.2018.12.005>
- [3] Festas, A., Ramos, A., & Davim, J. (2019). Medical Devices Biomaterials – A review. *Proceedings of the Institution of Mechanical Engineers Part L. Journal of Materials Design and Applications*, 234(1), 218–228. <https://doi.org/10.1177/1464420719882458>
- [4] Hwang, Y., Choi, Y., Hwang, Y., Cho, H., & Lee, D. (2020). Biocompatibility and Biological Corrosion Resistance of Ti-39Nb-6Zr+0.45Al Implant Alloy. *Journal of Functional Biomaterials*, 12(1), 2. <https://doi.org/10.3390/jfb12010002>
- [5] Khalik, M. A., Zahiri, S. H., Masood, S. H., Gulizia, S., Faizan-Ur-Rab, M., & Palanisamy, S. (2023). Simultaneous Densification and Improvement of Cold Spray Additively Manufactured Ti-6Al-4 V Properties via Electro-plastic Treatment. *The International Journal of Advanced Manufacturing Technology*, 126(9–10), 4297–4316. <https://doi.org/10.1007/s00170-023-11401-5>
- [6] Khan, A., & Maity, K. (2018). Machinability Assessment of Commercially Pure Titanium (CP-Ti) During Turning Operation: Application Potential of GRA Method. *IOP Conference Series Materials Science and Engineering*, 338, 012005. <https://doi.org/10.1088/1757-899x/338/1/012005>
- [7] Ma, H., Wang, J., Qin, P., Liu, Y., Chen, L., Wang, L., & Zhang, L. (2024). Advances in Additively Manufactured Titanium Alloys by Powder Bed Fusion and Directed Energy Deposition: Microstructure, Defects, and Mechanical Behavior. *Journal of Material Science and Technology*, 183, 32–62. <https://doi.org/10.1016/j.jmst.2023.11.003>
- [8] Masek, P., Maly, J., Zeman, P., Heinrich, P., & Alagan, N. T. (2022). Turning of Titanium Alloy with PCD Tool and High-Pressure Cooling. *Journal of Manufacturing Processes*, 84, 871–885. <https://doi.org/10.1016/j.jmapro.2022.10.034>
- [9] Moran, T. P., Carrion, P. E., Lee, S., Shamsaei, N., Phan, N., & Warner, D. H. (2022). Hot Isostatic Pressing for Fatigue Critical Additively Manufactured Ti-6Al-4V. *Materials*, 15(6), 2051. <https://doi.org/10.3390/ma15062051>
- [10] Nabhani, F. (2001). Machining of Aerospace Titanium Alloys. *Robotics and Computer-Integrated Manufacturing*, 17(1–2), 99–106. [https://doi.org/10.1016/s0736-5845\(00\)00042-9](https://doi.org/10.1016/s0736-5845(00)00042-9)
- [11] Noor, N. D., & Musfirah, A.H., (2022). Optimization of Cutting Parameter for Machining Ti-6Al-4V Titanium Alloy. *Journal of Modern Manufacturing Systems and Technology*, 6(1), 53–57. <https://doi.org/10.15282/jmmst.v6i1.7465>
- [12] Palanikumar, K., Nithyanandam, J., Natarajan, E., Lim, W. H., & Tiang, S. S. (2023). Mitigated Cutting Force and Surface Roughness in Titanium Alloy-Multiple Effective Guided Chaotic Multi Objective Teaching Learning-Based Optimization. *Alexandria Engineering Journal*, 64, 877–905. <https://doi.org/10.1016/j.aej.2022.09.029>
- [13] Rahman, M., Wang, Z., & Wong, Y. (2006). A Review on High-Speed Machining of Titanium Alloys. *JSME International Journal Series C*, 49(1), 11–20. <https://doi.org/10.1299/jsmec.49.11>
- [14] Sadik, M. I., Coronel, E., & Lattemann, M. (2019). Influence of Characteristic Properties of PCD Grades on the Wear Development in Turning of β -titanium Alloy (Ti5Al5V5Mo3Cr). *Wear*, 426–427, 1594–1602. <https://doi.org/10.1016/j.wear.2019.01.012>
- [15] Salikhyanov, D., Veselova, V., & Volkov, V. (2021). Flow Behavior and Microstructure Evolution of Ti-6Al-4V Titanium Alloy Produced by Selective Laser Melting Compared to Wrought. *The International Journal of Advanced Manufacturing Technology*, 119(1–2), 953–967. <https://doi.org/10.1007/s00170-021-08000-7>

LIST OF NOTATIONS

List of Abbreviations

<i>AISI</i>	American Iron and Steel Institute
<i>BUE</i>	Build-Up Edge
<i>PCD</i>	Polycrystalline Diamond
<i>TC</i>	Tungsten Carbide
<i>Ti</i>	Titanium

List of Symbols

<i>MPa</i>	Mega Pascal
<i>Ra</i>	Surface Roughness
%	Percentage
<i>d</i>	Depth of cut
<i>f</i>	Feed rate
<i>v</i>	Cutting speed
<i>mm</i>	Measurement for depth of cut
<i>mm/rev</i>	Measurement for feed rate
<i>m/min</i>	Measurement for Cutting speed
°C	Celsius

PROFILES



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