

OPTIMIZING CUTTING PARAMETERS FOR HIGH-SPEED DRY MILLING OF Ti6Al4V BASED ON CUTTING FORCE AND SURFACE ROUGHNESS

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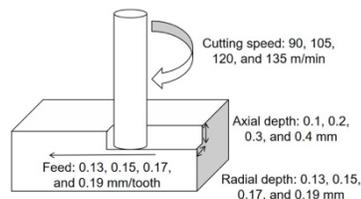
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Graphical abstract



Abstract

Due to their excellent comprehensive characteristics, titanium alloys have found widespread applications. Nonetheless, they are considered to be challenging for machines. The aims of manufacturing and processing are high efficiency, minimal cost, and high quality, while cutting parameters are crucial factors that influence the machining process. This manuscript focuses on optimizing cutting parameters for machining titanium alloys. High-speed dry milling was carried out on Ti6Al4V titanium alloy using coated carbide tools on a HASSVF3SS machining center. An orthogonal experiment featuring four factors, each with four levels, was designed to analyze surface roughness and cutting forces under varied milling parameters. The regression analysis results show that the main factors influencing milling force are axial cutting depth, cutting speed, and feed, with $R^2 = 0.9883$, 0.9757 , and 0.8854 , respectively. Meanwhile, radial cut depth significantly influences surface roughness, with $R^2 = 0.6559$. Using one-way Analysis of Variance to control the two aspects of cutting force and surface roughness, the optimal milling parameter is as follows: 0.1 mm axial cut depth, 90 m/min milling speed, 0.13 mm feed, and 6 mm radial cut depth.

Keywords: Axial cut depth, dry milling speed, feed, radial cut depth, cutting force, surface roughness

Abstrak

Disebabkan oleh ciri-ciri komprehensifnya yang sangat baik, aloi titanium telah menemui aplikasi yang meluas. Walau bagaimanapun, ia dianggap mencabar untuk dimesin. Matlamat pembuatan dan pemrosesan adalah kecekapan tinggi, kos minimum, dan kualiti tinggi manakala parameter pemotongan adalah faktor penting yang mempengaruhi proses pemesinan. Manuskrip ini memberi tumpuan kepada mengoptimalkan parameter pemotongan untuk pemesinan aloi titanium. Pengilangan kering berkelajuan tinggi telah dijalankan pada aloi titanium Ti6Al4V menggunakan alat karbida bersalut pada pusat pemesinan HASSVF3SS. Percubaan ortogonal yang menampilkan empat faktor, setiap satu dengan empat tahap, telah

direka untuk mengukur menganalisis kekasaran permukaan dan daya pemotongan di bawah parameter pemotongan yg berbeza-beza. Keputusan analisis regresi menunjukkan bahawa faktor utama yang mempengaruhi daya pengilangan ialah kedalaman pemotongan paksi, kelajuan pemotongan, dan suapan, dengan R^2 0.9883, 0.9757, dan 0.8854, masing-masing. Sementara itu, kedalaman potong jejeri secara signifikan mempengaruhi kekasaran permukaan, dengan $R^2 = 0.6559$. Menggunakan analisis varian sehala (ANOVA) untuk mengawal dua aspek daya pemotongan dan kekasaran permukaan, parameter pengilangan optimum adalah seperti berikut: kedalaman potong paksi 0.1 mm, kelajuan pengilangan 90 m/min, suapan 0.13 mm dan kedalaman potong jejeri 6 mm.

Kata kunci: Kedalaman potong paksi, kelajuan pengilangan kering, suapan, kedalaman potong jejeri, daya pemotongan, kekasaran permukaan

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1.0 INTRODUCTION

Titanium alloys represent a vital material with abundant development potential and broad application prospects. They are extensively utilized in the automotive, aerospace, and medical industries due to their exceptional properties, which include high specific strength, corrosion resistance, and lightweight [1], [2]. Nonetheless, machining titanium alloys is regarded as a challenging task [3]. Surface roughness and cutting force are significant physical quantities that reflect the machining quality [4].

Cutting force has significant practical implications in production, such as guiding the selection of cutting parameters, optimizing tool parameters, researching cutting mechanisms, designing tools and machines, calculating cutting power, and monitoring cutting force to assess tool wear [5], [6]. Ilesanmi *et al.* [7] conducted milling experiments on Ti6Al4V titanium alloy to evaluate how cutting parameters influence cutting force. The cutting parameters included cutting speeds ranging from 25 and 30 m/min, feed from 0.10 to 0.28 mm, and maximum chip thickness varying from 0.10 to 0.20 mm. The study discovered that the optimal milling parameters to obtain the optimal cutting force at 37.6831 N are at 27.5 m/min milling speed, 0.19 mm feed, and 0.14 mm chip thickness.

Surface roughness in milling reflects crucial machining information, including processing quality, tool wear, cutting parameter optimization, surface treatment requirements, and process improvements, significantly impacting production efficiency and product quality [8]. Surface roughness plays a critical role in determining the quality of a machined surface [9]. Using carbide tools, Daniyan *et al.* [10] explored how milling parameters influence the surface roughness of Ti6Al4V. The examined parameters included a feed range of 0.05 to 0.30 mm, a depth of 0.10 and 3.00 mm, and speeds of 250 to 275 m/min. Their study revealed that the best milling parameters for attaining the lowest surface roughness with air cooling are 0.05 mm feed, 0.5 mm depth, and 265 m/min speed, respectively.

Additionally, Kiswanto *et al.* [11] investigated the influence of high-speed cutting parameters on the

surface roughness of the Ti6Al4V during micro-milling. They varied the feed rate and spindle speed while keeping the same cutting depth. The process parameters range is 30,000 to 80,000 rpm spindle speed, 1 to 3 mm/s for feed rate, and a cutting depth of 10 μ m. Their findings revealed that higher spindle speeds and feed rates produced improved surface roughness.

Researchers used simulation software in some studies to examine how cutting parameters affected cutting qualities. For instance, Özlü *et al.* [12] used Third Wave AdvantEdge software for turning simulation, modeling, analyzing cutting forces, and examining the impact of cutting parameters on those forces. Besides, Zhuang *et al.* [13] used Abaqus software to evaluate the effect of cutting-edge radius on the Ti6Al4V's surface roughness during machining. According to the study, a rougher machined surface and a higher feed force can be obtained with a larger cutting-edge radius.

Furthermore, some researchers have investigated how different cutting settings affect surface roughness, cutting force, and other variables. In their turning experiments on Ti6Al4V, Shah *et al.* [14] analyzed how four cutting parameters—depth of cut, speed, feed, and nose radius—affect force, temperature, and surface roughness. Samsudeensadham *et al.* [15] also examined how cutting depth and feed rate affect force, temperature, and surface roughness while dry-milling Ti6Al4V using coated carbide tools. Their experiments utilized feed rates ranging from 0.03 to 0.12 mm/rev and depths between 0.5 and 1.25 mm while keeping the speed constant at 40 m/min. The findings indicated that feed rate influences temperature and cutting forces more than cutting depth.

Zha *et al.* [16] examined how the cutting feed rate impacts the microstructure, residual stress, surface roughness, and hardness of the Ti6Al4V and analyzed the temperature and cutting force during the experiments. For each cutting experiment, the speed was consistently set at 60 m/min, the cutting depth at 1 mm, and the distance at 30 m. Feed speeds established ranged from 0.05 to 0.2 mm/rev. It was discovered that the surface integrity of the machined

workpiece deteriorated when the feed rate surpassed 0.1 mm/rev. The research discovered that the optimal feed rate for Ti-6Al-4V processing is near 0.1 mm/rev. Suhaimi *et al.* [17] examined the different feed rates, cutting speeds, and cooling/lubrication techniques on the surface roughness, cutting force, and flank wear for compacted graphite iron. The machining parameters include three speeds (400, 600 and 800 m/min), two feed rates (0.1 and 0.2 mm/tooth), an axial cut depth of 2 mm, and a radial cut depth of 5 mm. They discovered an inverse relationship between cutting speed and force. Furthermore, when higher feeds are used, the cutting forces increase significantly. Additionally, it was discovered that surface roughness is unaffected by variations in feed or speed. The lubrication technique and cooling application significantly influenced surface roughness.

Polishetty *et al.* [18] explored how processing variables impact force and surface roughness while turning forged and additively manufactured Ti6Al4V. Their study emphasized the importance of elements such as speed and feed rate. The findings suggest that elevated feed rate and speed result in a deterioration in surface finish and a rise in cutting forces.

The existing literature on surface roughness and force during Ti6Al4V milling reveals significant inconsistencies in findings, particularly concerning the influence of machining parameters such as cutting depth, feed, and speed. For instance, while Kiswanto *et al.* [11] reported that increased spindle speeds and feed rates can improve surface roughness, others indicate that optimal surface quality is reached at a low feed of 0.05 mm with a mid-range speed of 265 m/min [10]. This disparity highlights the complexities of the milling process and suggests that the interplay between these parameters is not fully understood. Furthermore, while certain studies have explored the relationship between axial cut depth and forces, comprehensive research that includes radial depth of cut in conjunction with other machining parameters remains lacking. This oversight limits our understanding of how variations in radial depth can influence milling performance metrics like forces and surface roughness. Moreover, while Ilesanmi *et al.* [7] identified optimal cutting forces, their study did not address surface roughness, leaving a gap in a holistic understanding of the workpiece's surface quality. A recent study found that as the axial cut depth increases, the resultant force rises until it reaches a certain threshold, after which it levels off [19]. Thus, it is essential to determine the optimal machining parameters through experimentation.

Therefore, the purpose of this study is to fill these gaps by evaluating the effects of axial cut depth (a_p) ranging from 0.1 to 0.4 mm, milling speed (v) from 90 to 135 m/min for high-speed milling, feed (F_z) from 0.13 to 0.19 mm, and radial cutting depth (a_e) from 6 to 12 mm on surface roughness and cutting forces during high-speed dry milling of titanium alloys. Additionally, this research aims to identify the optimal combination of milling parameters to improve the workpiece's surface quality.

2.0 METHODOLOGY

2.1 Material Preparation

A rectangular block of Ti6Al4V titanium alloy was prepared to the following specifications: the block's dimensions were precisely cut to 16 mm in thickness, 120 mm in length, and 80 mm in width. The cutting process was performed using a waterjet cutting machine.

2.2 Equipment

Figure 1 depicts the experiments performed on a HASSVF3SS machining center, with a maximum spindle speed of 12,000 rpm and a power output of 22 kW. The tool used was an indexable end mill with a 63 mm diameter and four teeth. The inserts were KORLOY carbide-coated inserts APMT1604.

The surface roughness and cutting force under each set of parameters were measured and recorded using the SDC-C4M force measuring instrument and the TIME3202 handheld roughness tester, as shown in Figures 2 and 3, respectively.

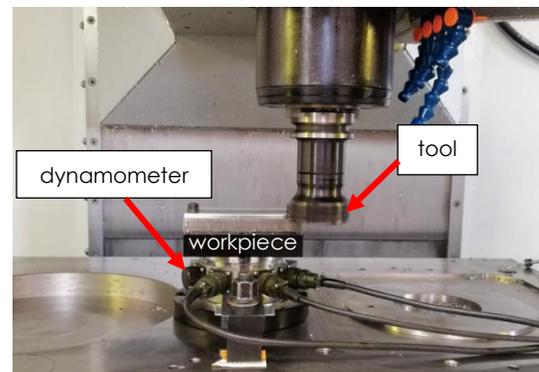


Figure 1 Experimental setup on a HASSVF3SS machining center

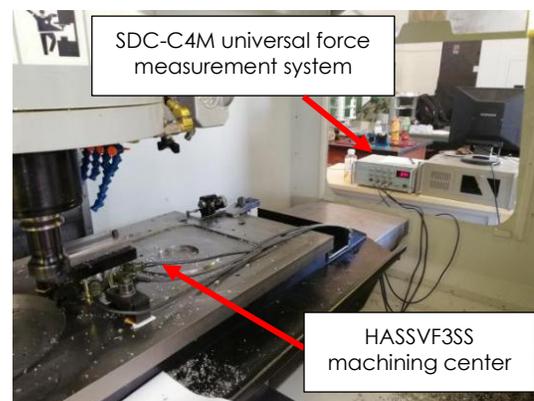


Figure 2 SDC-C4M universal force measurement system

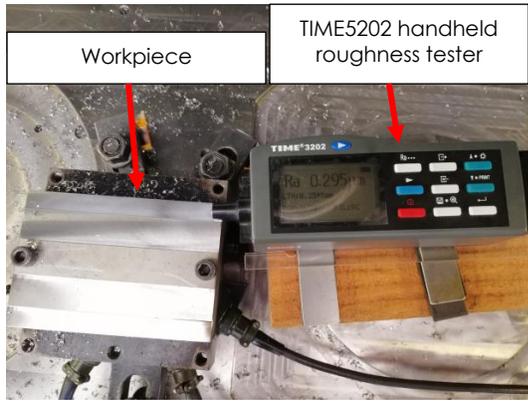


Figure 3 TIME5202 handheld roughness tester

2.3 Experimental Design

This experiment is designed as an orthogonal study, with four factors, each having four levels. Each experimental factor has four levels: axial cut depth (a_p), radial cut depth (a_e), feed (F_z), and speed (v), which are denoted by the numbers 1, 2, 3, and 4, respectively. The settings for the experimental factors and levels can be found in Table 1. Each combination of milling parameters was executed in triplicate to enhance the reliability of the data.

Table 1 Orthogonal test factors and level settings

	a_p (mm)	v (m/min)	F_z (mm)	a_e (mm)
1	0.1	90	0.13	6
2	0.2	105	0.15	8
3	0.3	120	0.17	10
4	0.4	135	0.19	12

2.4 Experimental Procedures

As illustrated in Figure 1, the workpiece and milling tool was securely installed on the HASSVF3SS machining center. A dynamometer was connected to the force measuring device to assess the cutting forces generated during the milling operation, facilitating precise force data collection. A dial indicator was used to verify the leveling of the machine tool, as proper alignment is critical for reliable results. The milling parameters were established based on an orthogonal experimental table, which provided a structured approach to assess various combinations of milling conditions. Throughout the milling process, the workpiece, cutting tool, and force measuring system were continuously monitored for smooth operation, ensuring no external factors could interfere with the results. After completing each milling operation, the cutting forces recorded by the dynamometer were collected for further analysis. Surface roughness measurements were taken using a TIME5202 handheld roughness tester. All combinations of milling parameters outlined in the experimental table were systematically performed, allowing for comprehensive

recording of both cutting force and surface roughness.

2.5 Force Measurement

Cutting force was measured online during the milling of Ti6Al4V at each combination of milling parameters with a dynamometer connected to the SDC-C4M universal force measurement system. The dynamometer installed on the HASSVF3SS machining center was connected to the strain amplifier and data processing system. The amplification factor of the strain amplifier was adjusted to ensure the measured milling force curve was more intuitive and easy to observe. After the strain amplifier is debugged, before data collection, the data collection system software needs to be calibrated, and related data collection work needs to be performed. After completing the above steps, the milling experiment and the corresponding data collection work were started.

The milling force generated by the tool, as it cuts the workpiece, causes the strain gauge in the dynamometer to produce the corresponding deformation. The measured deformation is converted into an electrical signal by the dynamometer, and the electrical signal is amplified by the DC strain amplifier connected to the dynamometer. The amplified electrical signal is transmitted to the computer connected to the DC strain amplifier. Then, the electrical signal is converted into data that can be recognized by the computer by the AD conversion system software in the computer. Finally, the data collecting system software in the computer converts the data into a precise milling force value, which can be represented as an intuitive milling force waveform. Figure 4 clearly shows that the strain amplifier has four interfaces, which monitor force and torque in the X, Y, and Z axes (from right to left). Five readings of average cutting force values were taken for each combination of milling parameters, and the average of these readings was used to calculate the cutting force value for the corresponding milling parameter.

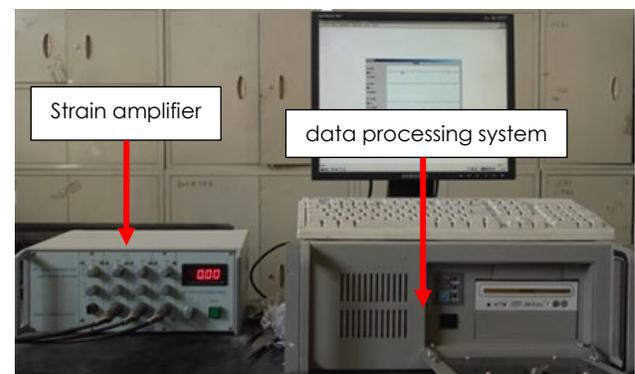


Figure 4 Force measuring device

2.6 Surface Roughness Measurement

Surface roughness measurements were conducted with a TIME5202 handheld roughness tester, which facilitated a thorough assessment of the quality of the milled surfaces. The average surface roughness (R_a) value was calculated for each set of milling parameters. After every milling experiment, the machined surface along a 120 mm cut length was measured for its roughness. Five individual R_a readings were recorded for each machined surface sample. The average of these values was then determined and used as the representative surface roughness value for the corresponding milling parameters.

2.7 Statistical Analysis

2.7.1 One-Way Analysis of Variance

A one-way analysis of variance was performed using the Statistical Package for the Social Sciences (SPSS) to analyze how a_p , v , F_z , and a_e influence surface roughness and force during machining. The calculated F-value was contrasted with the tabular F-value at 95% confidence. Tukey's test was also employed to investigate the differences between group means and identify the optimal milling parameters.

2.7.2 Regression Analysis

The effects of a_p , v , F_z , and a_e on surface roughness and machining forces were investigated using regression analysis. One statistical technique for figuring out whether there is a relationship between variables is a correlation. The correlation coefficient, sometimes called R squared, is a statistical tool to evaluate the direction and strength of a linear correlation between two variables [20].

- (a) When $0.0 < R^2 < 0.3$, it indicates a weak positive linear relationship.
- (b) When $0.3 < R^2 < 0.7$, it signifies a moderate positive linear relationship.
- (c) When $0.7 < R^2 < 1.0$, it denotes a strong positive linear relationship.

3.0 RESULTS AND DISCUSSION

Table 2 analyzes the impact of surface roughness and force on a_p , v , F_z , and a_e through a one-way analysis of variance. The interaction of a_p , V , F_z , and a_e was discovered to affect machining force and workpiece surface roughness. Table 3 shows the average interaction values between the machining force and the workpiece's surface roughness across various parameters, including a_p , v , F_z , and a_e .

Table 2 Overview of the one-way ANOVA analyzing the impacts of a_p , v , F_z , and a_e on the workpiece's surface roughness and cutting force during machining

Responses	Source	SS	df	MS	F	Pr>F
Ra	BG	0.362	15	0.024	91.00	**
	WG	0.008	32	0.000		
Force	BG	826443.07	15	55096.20	2591.34	**
	WG	680.37	32	21.26		

BG refers to between groups; WG indicates within groups; SS stands for sum of squares; df represents degrees of freedom; MS denotes mean square; and F is the F-test used in ANOVA; Ra indicates surface roughness

Number of observations = 48; Number of specimens = 16

** significant at $p \leq 0.01$

Table 3 Mean values of the interaction between the force and the workpiece's surface roughness during machining as a function of the a_p , v , F_z , and a_e

a_p (mm)	v (m/min)	F_z (mm)	a_e (mm)	Ra (μm)	Force (N)
0.1	90	0.13	6	0.213 ^a	97.620 ^a
	105	0.15	8	0.450 ^{ghi}	104.393 ^a
	120	0.17	10	0.494 ⁱ	126.977 ^b
	135	0.19	12	0.578 ^j	132.720 ^b
0.2	90	0.15	10	0.404 ^{cdefg}	259.703 ^e
	105	0.13	12	0.432 ^{efgh}	156.380 ^c
	120	0.19	6	0.379 ^{cd}	242.170 ^d
	135	0.17	8	0.386 ^{cde}	267.100 ^e
0.3	90	0.17	12	0.479 ^{hi}	389.533 ^h
	105	0.19	10	0.409 ^{defg}	428.310 ⁱ
	120	0.13	8	0.396 ^{cdef}	311.270 ^f
	135	0.15	6	0.441 ^{fgh}	320.397 ^g
0.4	90	0.19	8	0.358 ^c	486.773 ^k
	105	0.17	6	0.548 ⁱ	475.213 ^k
	120	0.15	12	0.369 ^{cd}	452.040 ^j
	135	0.13	10	0.293 ^b	330.570 ^g

Tukey's test indicates no significant difference between means with the same letters in the same column ($p \leq 0.05$)

According to the findings reported in Table 3, at an a_p of 0.1 mm, v of 90 m/min, F_z of 0.13 mm, and a_e of 6 mm, the surface roughness is notably lower at 0.213 μm compared to the other parameter combinations. The second lowest surface roughness of 0.293 μm is achieved with parameters of a_p 0.4 mm, v 135 m/min, F_z 0.13 mm, and a_e 10 mm. Conversely, the highest surface roughness values of 0.548 and 0.578 μm are observed at a_p 0.4 mm, v 105 m/min, F_z 0.17 mm, and a_e 6 mm, as well as at a_p 0.1 mm, v 135 m/min, F_z 0.19 mm, and a_e 12 mm. Regarding cutting force, the workpieces processed with an a_p 0.1 mm, v 90 m/min, F_z 0.13 mm, and a_e 6 mm, as well as a_p 0.1 mm, v 105 m/min, F_z 0.15 mm, and a_e 8 mm, exhibit significantly lower cutting forces of 97.620 N and 104.393 N, respectively. In contrast, the maximum cutting forces are observed in the workpieces processed at a_p 0.4 mm, v 105 m/min, F_z 0.17 mm, and a_e 6 mm, along with a_p 0.4 mm, v 90 m/min, F_z 0.19 mm, and a_e 8 mm, registering at 475.213 N and 486.773 N, respectively.

The cutting force rose as the axial cut depth increased from 0.1 mm to 0.4 mm. For example, at an ap of 0.1 mm, the cutting force records at 97.62 N but increases significantly to 486.77 N as the axial cutting depth increases. This trend is consistent across the various axial cutting depths evaluated, indicating that deeper cuts engage more material with each revolution or run of the tool [21]. Consequently, greater axial depths of cut demand increased cutting force, which requires a higher load on the cutting tool due to the elevated energy needed to deform and shear the machined material. The axial cut depth increases the chip cross-section and the shear area, ultimately contributing to the higher forces observed [22]. The variations in surface roughness suggest that improvements are not solely dependent on a single factor but rather influenced by a complex interaction of several machining parameters, including v , F_z , and a_e . Maintaining a constant ap of 0.1 mm resulted in an ideal surface roughness of 0.213 μm at 90 m/min, with an F_z of 0.13 mm and a radial depth of 6 mm. Conversely, the highest surface roughness values of 0.578 μm were recorded at the highest v of 135 m/min, combined with a higher F_z of 0.19 mm and an increased a_e of 12 mm. Interestingly, when the ap was increased to 0.4 mm, there was a notable enhancement in surface roughness, reaching a smoother roughness of 0.293 μm attained at a maximum v of 135 m/min. This illustrates the significant impact of ap in conjunction with other milling parameters, especially v , highlighting the critical role of cutting depth in conjunction with other milling parameters, significantly cutting speed, in achieving optimal surface quality during milling operations.

Cutting speed influences surface roughness and force, particularly at the lower axial cut depth of 0.1 mm. For instance, increasing speed from 90 m/min to 135 m/min at this depth considerably increases surface roughness and force. The surface roughness increases from 0.213 μm to 0.578 μm , while the cutting force goes from 97.62 N to 132.72 N. Nonetheless, this relationship does not hold consistently at deeper axial depths of cut. Surface roughness is higher at a lower speed of 90 m/min for axial cutting depths of 0.2, 0.3, and 0.4 mm. For instance, at an ap of 0.2 mm and a v of 90 m/min, the surface roughness reaches 0.404 μm , whereas an increase to 135 m/min improves it to 0.386 μm . Similarly, at 0.3 mm and 0.4 mm ap, surface roughness improves from 0.479 μm to 0.441 μm and from 0.358 μm to 0.293 μm , respectively, when the v is increased. This reveals that higher cutting speeds can produce smoother finishes due to increased shear rates and reduced contact time between the workpiece and tool, lowering cutting resistance [23]. Nonetheless, excessively high speeds at low depths can induce chatter or vibration, adversely affecting surface quality. Higher cutting speeds also correlate with reduced cutting forces at increased axial depths. For example, at ap values of 0.3 mm and 0.4 mm, when the speed is increased from 90 m/min to 135 m/min, cutting forces fall from 389.533 N to 320.397 N and 486.773 N to 330.570 N, respectively.

Feed is another important parameter influencing cutting dynamics; as it increases, the primary cutting force tends to rise, necessitating the removal of a larger volume of material per time unit, particularly with hard-to-machine materials [23]. At an ap of 0.1 mm, surface roughness and force increase with rising F_z from 0.13 mm to 0.19 mm. As F_z approaches 0.19 mm, cutting forces reach 486.733 N at an ap of 0.4 mm, while maximum surface roughness reaches 0.578 μm at 0.1 mm. This illustrates the direct relationship between F_z and cutting dynamics; higher F_z leads to increased material displacement, resulting in greater cutting forces and potentially rougher surfaces. The cutting force rises as F_z increases, owing to the increased contact area between the workpiece and tool. Additionally, forces increase with greater axial cut depths as a deeper tool penetration heightens resistance along the cutting path [24]. Furthermore, higher F_z values can lead to uncut chips and increased friction between the workpiece and tool, ultimately deteriorating surface roughness [25].

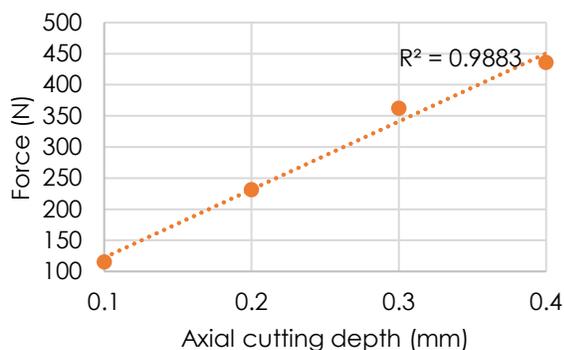
Surface roughness increases as a_e rises from 6 mm to 12 mm, particularly at lower ap of 0.1 mm and 0.2 mm, with surface roughness increasing from 0.213 to 0.578 μm and 0.379 to 0.432 μm , respectively. The increase in a_e correlates with increased forces, which increase vibration in the machine tool [26]. Specifically, as a_e increases from 6 to 12 mm, cutting force rises from 97.62 N to 132.72 N at an ap of 0.1 mm. This increase in cutting force is necessitated by the additional material that must be removed at a more considerable radial cutting depth [27]. However, the relation between force and surface roughness does not consistently trend as a_e increases at higher ap values. This suggests that a_e 's influence on cutting forces is less pronounced than other parameters like ap, v , and F_z . A comparison of mean values across different milling parameter combinations shows variability in cutting forces as a_e changes, with generally lower forces noted at reduced ap levels for the same a_e . This indicates that ap substantially influences cutting force more than a_e .

3.1 Impact of Axial Cutting Depth on the Surface Roughness and Cutting Force

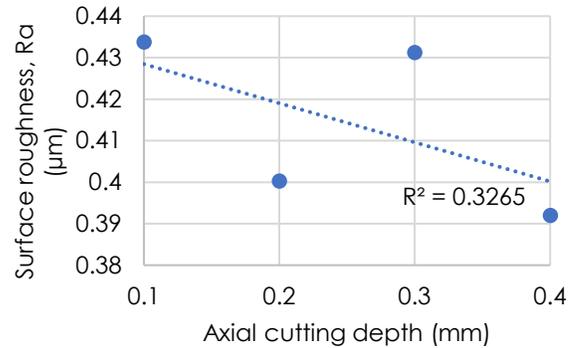
The relationship between cutting force and axial cutting depth is depicted in Figure 5(a). A highly significant positive linear relationship ($R^2 = 0.9883$) between axial cutting depth and force indicates that a rise in the axial cutting depth leads to a corresponding rise in cutting force. This phenomenon occurs because a deeper axial cut produces thicker chips during machining. The increased chip thickness imposes a heavier load on the cutting tool, necessitating a greater cutting force. Furthermore, friction and cutting resistance increase as the tool's surface area comes into contact with the workpiece. Thus, the amount of material removed per pass increases with the axial cutting depth, increasing the workpiece-tool contact area and, consequently, the quantity of cutting forces needed [28], [29]. In a

comparable study, Samsudeensadham *et al.* [15] found that while the axial force was largely unaffected by the cutting depth, it considerably impacted the feed and tangential forces directly related to material removal. A similar summary was also summarized by Guo *et al.* [30]. The axial cutting depth of TC4 resulted in a considerable increment in cutting force during the milling experiment.

Figure 5(b) indicates a moderately negative linear correlation ($R^2 = 0.3265$) between surface roughness and axial cutting depth. This shows that increasing axial cutting depth results in smoother surface roughness, owing to less tool deflection and vibration during cutting. As the axial cutting depth rises, the tool makes more material contact, fostering a more stable cutting environment. A deeper cut generally allows the tool to maintain a firmer position, thereby minimizing deflection and enhancing the consistency of the cutting edge's position relative to the workpiece. This stability leads to a more uniform cut and a smoother surface finish. Research conducted by Casuso *et al.* [31] supports this assertion, indicating that raising the axial depth of the cut to 50% of the sample thickness results in more stable machining than shallower cuts. The improved stability is attributed to the larger lead edge angles associated with deeper depths, which help to prevent chatter. Furthermore, deeper cuts enhance machining stability and productivity, yielding surface roughness that complies with industry quality standards. Conversely, shallower depths may fail to achieve sufficient surface finishing, especially in cases of significant tool wear. Nonetheless, the enhancement in surface roughness observed in this study is not uniform, highlighting the importance of considering other machining parameters, such as v , F_z , and a_e . Research by Ginta *et al.* [32] indicates that the interplay between feed rate and speed significantly influences surface roughness values. Additionally, this study suggests that by finding an appropriate balance between the cutting depth and other milling parameters, including cutting speed, feed, and radial cut depth, a greater axial cut depth of 0.4 mm can also yield a smooth surface finish.



(a)



(b)

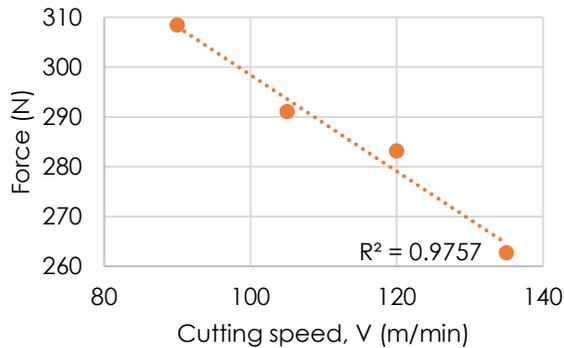
Figure 5 Impact of the axial cutting depth on the (a) cutting force and (b) surface roughness

3.2 Impact of Cutting Speed on Surface Roughness and Cutting Force

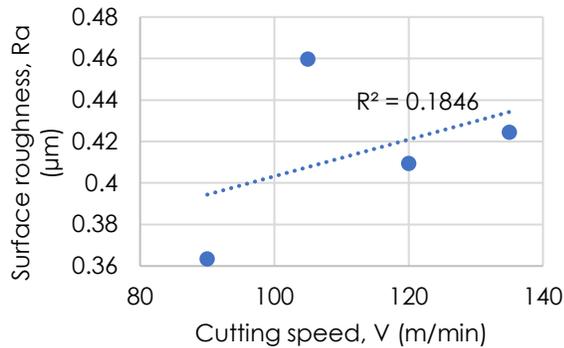
In machining, cutting speed significantly impacts cutting forces and surface roughness. In Figure 6(a), a strong negative linear relationship was observed between cutting speed and force, $R^2 = 0.9757$, indicating that higher cutting speeds substantially decrease the force. The primary cause of this drop is the thermal softening of the workpiece material, as corroborated by previous research [29]. Supporting this finding, Saglam *et al.* [33] also reported an inverse relationship between cutting speed and forces, highlighting that increasing cutting speed lowers cutting forces and elevates the temperature around the tool tip. The rise in temperature within the cutting zone enhances the thermal softening effect, diminishing the forces needed to cut through the material [34], [35]. Besides, the drop in cutting forces can also be explained by a reduction in chip thickness [36]. As the speed rises, reduced chip thickness and lowered material flow stress—resulting from thermal softening—further contribute to the overall decrease in cutting forces [37].

Typically, faster cutting speeds are connected with improved surface finishes. However, as Figure 6(b) illustrates, surface roughness increases with rising cutting speeds. The data reveals only a slight positive linear correlation ($R^2 = 0.1846$), indicating that increased cutting speeds have a minimal effect on surface roughness. Notably, at a cutting speed of 105 m/min, surface roughness increased significantly, which was observed likely attributed to excessive heat generation and subsequent tool wear, which can detrimentally impact surface quality [38]. While beneficial for chip formation, elevated temperatures in the cutting zone pose risks of excessive surface deformation [39]. Higher temperatures can increase friction between the workpiece and the tool, leading to faster wear [40]. Moreover, increased temperatures accelerate cutting tool wear, resulting in a degradation in the tool tip's radius and changes in chip formation. This dynamic interplay of tool wear

and surface roughness is further complicated by developing a built-up edge on the cutting tool, which exacerbates the workpiece's wear and surface roughness [41]. While increasing cutting speed typically reduces cutting forces, an optimal threshold exists; surpassing this speed can result in excessive heat generation, leading to tool wear that may offset the advantages gained [39].



(a)



(b)

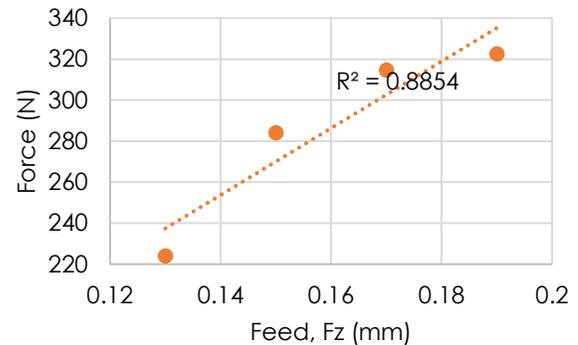
Figure 6 Impact of the cutting speed on the (a) cutting force and (b) surface roughness

3.3 Impact of Feed on Surface Roughness and Cutting Force

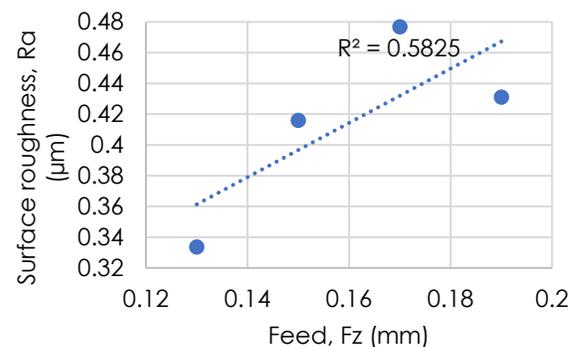
The feed is important in determining surface roughness and milling forces [42]. Figures 7(a-b) illustrate the relationship between feed, surface roughness, and cutting forces. Specifically, Figure 7(a) shows a strong positive correlation between feed and force, with an R^2 value of 0.8854, indicating that higher feed rates significantly increase cutting forces. This increase can be attributed to a larger chip cross-section that results from higher feed rates, leading to greater friction between the workpiece and tool, thus requiring more cutting force to shear the material [29], [43], [44]. In contrast, cutting forces are decreased with a lower feed [18]. In their studies, Shah and Bhavsar [45] and Guo *et al.* [30] reported that the force increases gradually as feed increases.

Figure 7(b) shows a moderate positive linear correlation between feed and surface roughness, with

an R^2 value of 0.5825, indicating that increasing feed leads to increased surface roughness. A strong feed force during the machining process might cause chips to accumulate, increasing the workpiece's surface roughness [46]. Most chips tend to be pushed to the slot's edges, where they stack up individually. This accumulation of chips on both sides of the slot impedes their flow, increasing by cutting temperature because of the inability to dissipate the heat generated [47]. Consequently, the temperature at the chip contact and the cutting forces increase rapidly [48]. The high temperatures produced during machining can create burrs on metal surfaces, complicating the achievement of precise tolerance levels. The materials involved have different elastic moduli and thermal expansion rates, which is difficult [46]. Furthermore, tool vibration and wear substantially impact the machined workpiece's surface roughness; severe tool wear can produce tearing of the workpiece surface and debris collection, which increases surface roughness [44]. Increased cutting force and vibration can disrupt normal machining operations, forming chatter marks on the machined surfaces and ultimately degrading the surface quality of the finished parts. Additionally, these factors can accelerate tool wear and weaken the connections between components such as machine tools and fixtures, reducing the stiffness and precision of the machining process and shortening the equipment's service life [49].



(a)

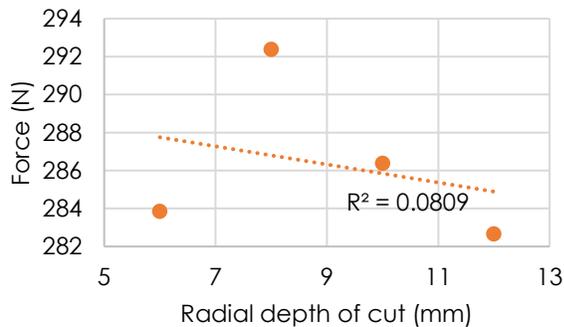


(b)

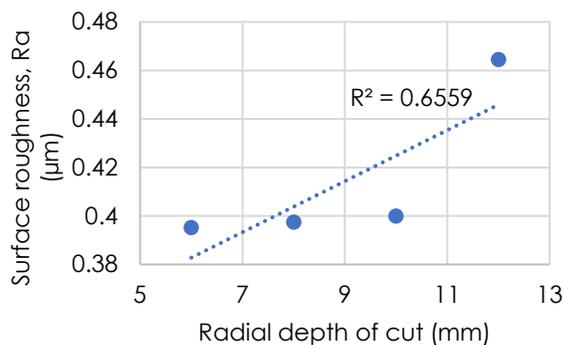
Figure 7 Effect of the feed on (a) cutting force and (b) surface roughness

3.4 Impact of Radial Cutting Depth on Surface Roughness and Cutting Force

Figures 8(a) and 8(b) illustrate the relationship between radial cutting depth, surface roughness, and cutting force. In this research, radial cutting depth does not affect cutting force. A weak negative linear relationship ($R^2 = 0.0809$) was identified between the cutting force and the radial cutting depth, as illustrated in Figure 8(a), indicating that variations in radial cutting depth have a negligible effect on cutting force. The other machining parameters, such as a_p , v , and F_z , are more important in determining cutting forces. Contrary to the findings of Guo et al. [30], who reported that the milling force gradually increased with increasing radial cutting depth, although the change was small. This study noted a sudden rise in cutting force at a radial cut depth of 8 mm, particularly combined with the highest a_p of 0.4 mm, lowest v of 90 m/min, and highest F_z of 0.19 mm. This increase can be explained by the fact that as the radial cut depth grows, so does the size of the cut per tooth. The rise in cutting force is further explained by the narrower entry angle associated with more expansive radial depths, which leads to higher tangential forces [47]. Additionally, the increased friction at the highest a_p and F_z and the lowest v resulted in the need for greater force to remove the material. Conversely, a narrower radial depth produces a wider entry angle, producing lower tangential forces [47]. Consequently, the need for greater force to remove additional material at more considerable radial depths results in elevated cutting forces [27].



(a)



(b)

Figure 8 Effect of the radial cutting depth on (a) cutting force and (b) surface roughness

Regarding surface roughness, an R^2 value of 0.6559 indicates a moderately positive linear correlation between radial cutting depth and surface roughness, as illustrated in Figure 8(b). This implies that a greater radial cutting depth is associated with increased surface roughness, particularly at a 12 mm radial cutting depth. A greater radial cutting depth often produces a rougher surface finish since the heightened material removal can cause increased vibrations and deflections in the cutting tool. This can cause increased surface roughness due to irregularities in the machined surface [50]. Supporting this, Mersni et al. [51] employed the Taguchi technique to optimize milling parameters for the Ti-6Al-4V titanium alloy, focusing on how these parameters affect surface roughness. They observed that an increase in radial depth was consistently linked to an increase in average surface roughness. This relationship emphasizes that as the radial cutting depth increases, so do the resultant cutting forces, further heightening vibrations of the machine tool and consequently affecting surface finish quality [26].

To summarize, the factors that impact milling force, listed in importance, are a_p , v , F_z , and a_e , with R^2 values of 0.9883, 0.9757, 0.8854, and 0.0809, respectively. Regarding surface roughness, the main contributors are a_e , F_z , a_p , and v , which are also of this order of importance, with R^2 values of 0.6559, 0.5825, 0.3265, and 0.1846, respectively. A comparable conclusion was made by Ginta et al. [32]. The F_z significantly impacts surface roughness, followed by v and a_p .

4.0 CONCLUSION

The findings of this study highlight the complex relationship between various milling settings and their effects on cutting forces and surface roughness. The cutting forces increased significantly from 97.62 N to 486.77 N when the axial cutting depth was raised from 0.1 mm to 0.4 mm. Cutting speed rose from 90 m/min to 135 m/min while maintaining an axial depth of 0.1 mm, resulting in considerable increases in surface roughness and cutting force, with cutting force rising from 97.62 N to 132.72 N and surface roughness increasing from 0.213 μm to 0.578 μm . Higher cutting speeds were associated with reduced cutting forces at greater axial depths, with forces decreasing from 389.533 N to 320.397 N and from 486.773 N to 330.570 N for axial depths of 0.3 mm and 0.4 mm, respectively, as the speed increased from 90 m/min to 135 m/min. Surface roughness variations demonstrate that various factors influence machining quality improvements, including axial depth, speed, feed, and radial depth of cut. Surface roughness was consistently higher at a lower speed of 90 m/min for axial depths of 0.2, 0.3, and 0.4 mm. An increase in axial depth to 0.4 mm led to a marked improvement in surface roughness, resulting in a minimum value of 0.293 μm at the highest speed of 135 m/min and the lowest F_z of 0.13 mm. This

demonstrates the significant impact of axial depth in conjunction with cutting speed and feed on achieving superior surface quality during milling operations. This suggests that by finding an appropriate balance between the cutting depth and other milling parameters, including speed, feed, and radial cut depth, a greater axial cut depth of 0.4 mm can also yield a smooth surface finish. Increasing the feed resulted in higher cutting forces and potentially rougher surfaces. The increased feed and greater axial depths, leading to deeper tool penetration, significantly raised resistance along the cutting path. Additionally, as radial cutting depth increased from 6 mm to 12 mm, surface roughness also tended to rise, particularly at lower axial depths of 0.1 mm and 0.2 mm, where roughness increased from 0.213 to 0.578 μm and 0.379 to 0.432 μm , respectively. At 0.1 mm ap, the increase in radial cutting depth corresponded with increased cutting forces. A comparison of mean values across various milling parameter combinations revealed variability in cutting forces with changes in radial cutting depth, showing lower forces at reduced axial depths for the same radial cutting depth. This suggests that axial depth substantially influences cutting forces more than radial depth. The regression analysis results show that the main factors influencing milling force are axial cutting depth, cutting speed, and feed, with $R^2 = 0.9883$, 0.9757 , and 0.8854 , respectively. Meanwhile, radial cut depth significantly influences surface roughness, with $R^2 = 0.6559$. Based on one-way ANOVA analysis, the optimal milling settings for balancing machining force and surface roughness are an axial cut depth of 0.1 mm, a speed of 90 m/min, a feed of 0.13 mm, and a radial cut depth of 6 mm.

Future research should explore a broader range of cutting factors and their interactions to enhance understanding of their impact on machining outcomes. Specifically, investigating the impacts of varying speeds and feeds on different materials could yield insights into optimizing performance across diverse applications. Additionally, it would be beneficial to investigate the effect of tool geometry and material properties on machining force and surface roughness, as these factors may significantly affect machining efficiency and quality. Implementing advanced monitoring techniques, such as real-time sensors and data analytics, could provide valuable information on the cutting process, enabling adaptive control strategies that adjust parameters dynamically for improved results. Moreover, a comparative study of different lubrication techniques and cooling applications could be conducted to evaluate their effects on the same parameters. This would contribute to a better knowledge of the milling process and help develop best practices for various industrial applications. Lastly, extending the research to include long-term wear analysis of cutting tools under different machining conditions would provide essential data for predicting tool life and optimizing maintenance schedules, thus enhancing overall production efficiency.

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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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