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Investigating the influence of machining parameters and tool coatings on surface qualtiy of titanium parts in aerospace industry

Havacılık endüstrisinde titanyum parçaların yüzey kalitesi üzerindeki işleme parametrelerinin ve takım kaplamalarının etkisinin araştırılması

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Abstract

In the aerospace sector, most titanium components are produced through milling, which poses several challenges in achieving superior surface quality. Consequently, optimizing cutting parameters and choosing appropriate cutting tool coatings are critical factors influencing the surface roughness of these parts. This study examines the impact of depth of cut, cutting speed, and feed rate on surface roughness when milling the Ti-6Al-4V alloy. It also provides an in-depth analysis of three different coatings - Aluminum Chromium Nitride (AlCrN), tungsten-based AlCrN, and tungsten-based Aluminum Titanium Nitride (AlTiN) - in terms of surface quality. The findings reveal that cutting speed is the most significant factor affecting surface roughness in experiments conducted using the Taguchi method, with three values assigned to each parameter. Moreover, the tungsten-based AlCrN coating demonstrated the best average surface roughness values. Overall, this study offers valuable insights into factors affecting surface roughness in titanium milling and presents practical recommendations for selecting cutting parameters and tool coatings to improve surface quality in aerospace parts production. In future research, additional factors such as tool geometry and cooling strategies can also be investigated to further improve surface quality in titanium machining.

Keywords: Ti-6Al-4V, Machining parameters, Milling, Surface roughness, Taguchi method

Öz

Havacılık endüstrisinde çoğu titanyum parça frezeleme işlemi kullanılarak üretilir ve yüksek yüzey kalitesinin elde edilmesinde çeşitli zorluklar vardır. Bu nedenle talaşlı imalatta kesme parametrelerinin optimize edilmesi ve kesici takım kaplamalarının seçilmesi parçaların yüzey pürüzlülüğünü etkileyen en önemli faktörlerdir. Bu çalışmada Ti-6A1-4V alaşımının frezelenmesi sırasında kesme derinliği, kesme hızı ve ilerleme parametrelerinin yüzey pürüzlülüğüne etkileri araştırılmıştır. Ayrıca yüzey kalitesine dayalı AlCrN (Alüminyum Krom Nitrür), AlCrN-tungsten bazlı ve AlTiN (Alüminyum Titanyum Nitrür)-tungsten bazlı olmak üzere üç farklı kaplama derinlemesine incelenmektedir. Taguchi yöntemi kullanılarak her parametre için üç değer belirlenerek yapılan deneylerde sonuçlar, yüzey pürüzlülüğünü etkileyen en önemli parametrenin kesme hızı olduğunu göstermektedir. Ayrıca AlCrN-tungsten bazlı Ayrıca tungsten bazlı AlCrN kaplama en iyi ortalama yüzey pürüzlülüğü değerlerini göstermiştir. Genel olarak bu çalışma, titanyum frezelemede yüzey pürüzlülüğünü etkileyen faktörler hakkında değerli bilgiler vermekte ve havacılık parçaları üretiminde yüzey kalitesini iyileştirmek için kesme parametrelerinin ve takım kaplamalarının seçilmesine yönelik pratik öneriler sunmaktadır. Gelecekteki araştırmalarda, titanyum işlemede yüzey kalitesini daha da artırmak için takım geometrisi ve soğutma stratejileri gibi ek faktörler de araştırılabilir.

Anahtar kelimeler: Ti-6Al-4V, İşleme parametreleri, Frezeleme, Yüzey pürüzlülüğü, Taguchi yöntemi

1 Introduction

Titanium alloys are stand out among engineering materials due to their exceptional balance of lightweight properties and resilience against cracking, as well as superior strength and remarkable resistance to corrosion. These materials have recently had surge in interest interest due to their versatility in the aerospace, biomedical, petrochemical, and automotive industries. Over the years, the aerospace industry has been at the forefront of developing and applying new materials. The current need for reduced fuel consumption and high manufacturing standards is pushing aerospace engineering to create materials that can endure extreme conditions, offer significant weight reduction, and possess good machinability. The properties of aerospace materials are meticulously tailored to specific applications. Titanium alloys show exceptional resistance to corrosion and superior strength-to-weight ratio when compared to most steels and aluminum. This explains their growing prevalence in modern aerospace: they can withstand higher temperatures than aluminum alloys while boasting a weight advantage over most steels [1-4]. While titanium alloys boast

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widespread use and impressive properties, their machinability presents a significant challenge. Unlike many other metals, they are notoriously difficult to machine due to inherent material characteristics. These challenges include low thermal conductivity, which traps heat and accelerates tool wear; low modulus of elasticity, leading to vibrations and reduced tool life; and high chemical reactivity, causing adhesion and further wear. Consequently, machining titanium alloys results in high cutting temperatures, rapid tool wear, and significant vibrations.

Over the past few decades, research has focused on developing new cutting tool materials, improving existing tool designs, and conducting extensive machinability studies. These efforts aim to identify the optimal combination of cutting tools, machine tools, and cutting parameters to address the significant challenges in machining titanium alloys. [5-9].

The machining process significantly affects the surface quality properties of titanium alloy workpieces. Various machining phenomena, such as build-up edge formation (BUE), tool shape and geometry, tool wear, temperature, tool coating, feed rate, cutting speed, and depth of cut, greatly influence the surface quality of titanium components. The primary causes of these effects during machining include thermo-mechanical cycling, microstructural alterations, and mechanical and thermal deformations. [5].

Ünal and Karaca [10] examined various cutting parameters, including different feed rates, cutting speeds, and depths of cut, for Ti-6Al-4V on a vertical machining center CNC machine. They investigated the effects of these parameters on chip type, surface roughness, and surface microhardness. Their experiments revealed that surface roughness increased with higher feed rates and cutting speeds. Generally, they observed the formation of continuous spinning and saw tooth cross-section chips. Ezugwu et al. [6] explored the use of cubic boron nitride (CBN) tools, commonly used for machining hard alloys like hardened high chromium steels and nickel alloys, for turning Ti-6Al-4V alloys. The study assessed the machinability performance of the Ti-6Al-4V alloy at various cutting speeds with different grades of CBN tools under diverse cooling applications. They evaluated tool wear, cutting and feed force, tool life, and surface roughness to determine the cutting tools' performance. The study observed excessive shedding and notches on the cutting edges, attributed to the diffusion wear mechanism.

Ensaroğlu and Çakir [11] investigated the influence of various machining parameters, such as feed rate, cutting tool type, depth of cut, cutting speed, and coolants/lubricants, on the machinability of titanium alloys. Their study also analyzed wear mechanisms, surface roughness, and chip formation specific to these alloys. They found that cutting speed has the most significant impact on tool life, although it can improve productivity and surface finish. This finding suggests that prioritizing cutting speed can enhance production efficiency in titanium machining, despite the trade-off of increased tool wear and potentially rougher surfaces compared to using slower speeds and higher feed rates.

Palanisamy et al. [12] investigated the impact of high-pressure coolant on chip formation during the turning of Ti-6Al-4V alloy. Their research revealed significant improvements in both tool life and surface roughness when high-pressure coolant was employed. Additionally, they explored the effect of coolant pressure on chip morphology, observing that varying coolant pressures significantly altered the thickness, shape, and microstructure of the machined chips.

Fierce competition compels manufacturers to prioritize product quality to survive and expand market share. Consequently, they employ various quality improvement methods. However, these methods often involve numerous parameters, leading to high costs and lengthy experimentation times. To address these challenges, Genichi Taguchi pioneered the use of orthogonal arrays in the 1940s. The Taguchi method offers a powerful approach to reduce experiment time and associated costs. It achieves this by strategically dividing the quality system into pre-production and production phases. Notably, the method emphasizes that product quality and customer satisfaction are strongly influenced by a well-designed and developed product, highlighting the importance of upfront planning and engineering [13, 14].

Cutting parameters are critical factors that vary depending on the material being processed and the cutting tool used, and they hold the most significant influence on the final surface finish. Optimizing these parameters is crucial for achieving the desired surface roughness. This study aims to investigate the effect of machining parameters, such as cutting speed, depth of cut, feed rate, and various cutter coating types, on the surface roughness of the titanium alloy Ti-6Al-4V during milling operations, an area not extensively covered in the literature.

A review of existing literature reveals a focus on lathe machining for studying surface roughness in Ti-6Al-4V. However, the aerospace industry relies heavily on milling to manufacture structural parts. This highlights a gap in research – there's a need for more investigations into how milling parameters affect surface roughness in this crucial material. Furthermore, existing milling studies often concentrate on dry or cryogenic cutting conditions. Since surface roughness directly impacts the reliability and lifespan of high-precision aerospace components, exploring a wider range of milling parameters, including cutting fluids and tool coatings, is essential for optimizing surface quality.

2 Material and method

This study utilizes Ti-6Al-4V, an alpha-beta titanium alloy. For reference, the chemical composition and mechanical properties of the alloy are detailed in Tables 1 and 2, respectively.

Table 1. Chemical compositions of Ti-6Al-4V (weight %)

Ti	Al	V	Fe	C	N	H	O
5.5-6.75	3.5-4.5	3.5-4.5	<0.25	<0.08	<0.05	<0.01	<0.2

Experiments were carried out using DMG MORI ecoMill 800V 3-axis CNC machine in Skymark Aviation

Technologies company. The power of the machine is 13 kW, the speed of the machine is 12000 rpm, and dimensions of the machine are 800 x 560 x 510 mm. The CNC vertical machine was used in the experiment as indicated in Figure 1(a). Cutting tool and stock with 35 x 76 x 110 mm dimensions were used as shown in Figure 1(b).

Table 2. Physical and mechanical properties of Ti-6Al-4V

Parameter	Value
Density (kg/m^3)	4430
Melting point (°C)	1668
Thermal conductivity (W/m/°C)	7.3
Ultimate strength (MPa)	950
Specific heat (J/(kg/°C))	526
Yield strength (MPa)	820
Young's modulus (GPa)	113.8
Poisson's ratio	0.342

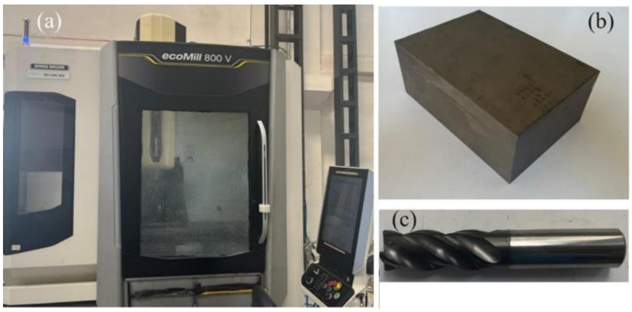
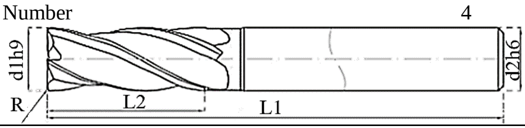


Figure 1. (a) EcoMill 800V 3-axis CNC machine (b) stock used in experiments (c) cutting tool used in experiments

In the experiments, 27 pieces of tools with the code 111416010 and a 16 mm diameter which were supplied from Karcan Cutting Tools, were used under wet condition. They have a coating layer consisting of AICrN (Aluminum Chromium Nitride), AlCrN-tungsten based coating, and AlTiN (Aluminum Titanium Nitride)-tungsten based coating. Brand new tools were used in each experiment to keep everything at same condition. Schematic view of cutting tool shown in Figure 1(c) and the technical specifications are given in Table 3.

Table 3. Tool designation

Parameter	Value
Tool Code	111416010
Cutter Diameter (d1h9)	16 mm
Shank Diameter (d2h6)	16 mm
Overall Length (L1)	93 mm
Length of Cut (L2)	36 mm
Radius (R)	1 mm
Flute Number	4



The surface roughness that occurred as a result of the machining processes was measured with the Mitutoyo SJ-210 surface roughness measuring device. The tip radius of the profilometer needle is 2 µm and 60° tip angle is measured. The force is 0.75 mN and the scanning speeds are chosen 0.25, 0.5, and 0.75 mm/s respectively.

The tool designation, and requirements for the Ti-6Al-4V alloy lead to the investigating parameters given in Table 4.

Table 4. Experimental parameters

Process parameters	Range		
Cutting Speed	60 m/min	70 m/min	75 m/min
Feed Rate	0.02 mm/tooth	0.025 mm/tooth	0.03 mm/tooth
Depth of Cut	3 mm	3.5 mm	4 mm

First, CAM programs were prapared using the Siemens NX program, with the experimental sequences in the Taguchi method. Since tool wear is one of the important factors affect the test results due to surface roughness, a brand-new tool was used for each experiment. Due to the dimensions of the stock and the diameter of the tool used, experiments could not be completed on a single surface of the raw material. Therefore, both surfaces of the stock were used for experiments. While 5 experiments were carried out on one surface of the test sample, the remaining 4 experiments were completed on the other surface. After the first 5 experiments were completed, the CNC machine was stopped for the other 4 experiments and the stock was removed from the clamp used. The stock was turned upside down and placed in the clamp and was tightly tied to the clamp with the help of a plastic hammer. The experiment was completed by restarting the CNC machine and running the remaining 4 CAM programs. Every step is repeated for other experiments. After the completed experiments, the test sample was removed from the CNC machine for surface roughness measurement.

Surface roughness measurements were made through the machining direction of the cutting tool and at the inlet and outlet areas of the cutting tool into the stock which is shown in Figure 2. Measurements were made from the lateral surface of the inlet and outlet areas. The test results were found by averaging the different roughness values measured for each test.

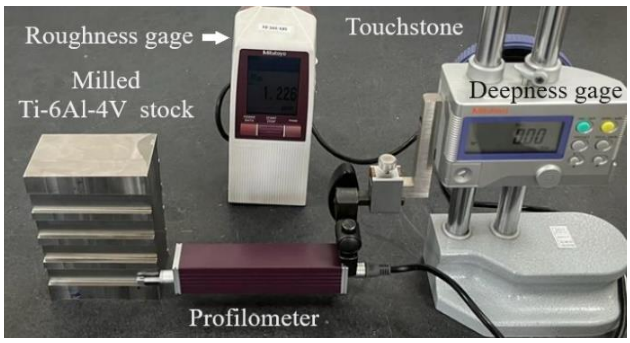


Figure 2. Surface roughness measurement on test specimen

2.1 Taguchi method

The Taguchi method is used as a valuable tool for identifying optimal configurations among various levels of multiple variables. It excels in optimizing design parameters by strategically planning the experimental design. This method offers a significant advantage: it reduces the number of required experiments compared to a traditional approach where every combination of variable levels is tested. The Taguchi method achieves this efficiency by utilizing orthogonal array tables, which allow for the evaluation of a wide range of factors with a minimal number of experiments. [15]. One of the key strengths of the Taguchi method lies in its use of orthogonal arrays. These arrays enable researchers to simultaneously evaluate all levels of each factor within a limited number of experiments. This eliminates the need for time-consuming, one-factor-at-a-time testing. This efficiency is a major reason why the Taguchi method has become widely adopted in the manufacturing sector. [16, 17]. The main purpose of the Taguchi method is to design products or processes that are insensitive to all combinations of uncontrollable factors while controllable variables are time and cost efficient at certain levels. On the other hand, the main purpose of the Taguchi experimental design is to achieve the desired quality values of the products and to complete the process of obtaining this quality with a much lower number of experiments and costs [18]. To evaluate performance within the Taguchi method, researchers utilize a specific set of statistical criteria known as signal-to-noise (S/N) ratios. These ratios are measured in decibels (dB) and provide a metric for assessing the impact of noise factors (uncontrollable variables) on the desired signal (product or process characteristic). Notably, Taguchi categorized practical problems into three types based on the target outcome, and assigned a corresponding S/N ratio formula for each category [19, 20].

A minimization problem is the case where the value of Y is zero is the "smallest is best" case. In this case, the signal-to-noise ratio is defined as in Equation (1).

$$\frac{S}{N} = -10log\left(\frac{1}{n}\sum\nolimits_{u=1}^{n} {Y_i}^2\right) \tag{1}$$

where "Y" indicates the performance characteristic value. i is the experimental number. n is the number of trials for experiment i. u is the trial number. Similarly, a maximization problem, the "biggest is best" case, becomes the inverse of the "smallest best" case. Its S/N ratio is obtained by Equation (2).

$$\frac{S}{N} = -10log\left(\frac{1}{n}\sum\nolimits_{u=1}^{n} \frac{1}{{Y_i}^2}\right) \tag{2}$$

Another situation is that in the "Target value is best" case, the target value is given for Y, such as the product dimensions, and in this case the equation is as in Equation (3).

$$\frac{S}{N} = -10log\left(\frac{Y^2}{\sigma^2}\right) \tag{3}$$

where σ^2 represents the variance where σ is the standard deviation [16-18].

A cornerstone of the Taguchi method is the use of orthogonal arrays, also known as design matrices. These arrays offer a powerful approach for efficiently designing experiments involving multiple factors. Their key advantage lies in enabling the simultaneous evaluation of different factor levels, minimizing the number of required tests. The Taguchi categorized orthogonal arrays into various types based on the number of levels involved (typically 2 or 3), as indicated in Equation (4).

$$L_d(a)^k \tag{4}$$

where L is orthogonal arrays, d is total experiment numbers, a is stage numbers of factors, and k is the factor number. Generally used 2-level arrays are L_4, L_8, L_{16} while 3-level arrays are L_9, L_{18}, L_{27} arrays. When selecting the arrays, the number of levels and total degrees of freedom are considered. The $L_9(3)^3$design matrix is given in the Table 5.

Table 5. Orthogonal arrays in L_9 type

Experiment Number	Parameter 1	Parameter 2	Parameter 3
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

Thanks to orthogonal arrays, the number of experiments that need to be done as required by the full factorial design is greatly reduced. According to the full factorial design, $(3)^3(27)$ different experiments are required for this example, while 9 experiments are sufficient by help of the orthogonal arrays.

The Taguchi L_9 orthogonal array was chosen as the most suitable design for the experiment to examine the effect of process parameters on surface roughness, considering the variables. Table 6 shows the placement of the determined experimental factors and levels in the Taguchi L_9orthogonal array.

Table 6. Control factors and levels

Control factors and levels				
Symbols	Parameters	Levels		
		Level 1	Level 2	Level 3
A	Cutting speed (m/min)	60	70	75
B	Feed rate (mm/tooth)	0.02	0.025	0.03
C	Depth of cut (mm)	3	3.5	4

The Taguchi L_9 orthogonal arrays was chosen as the most suitable design for the experiment to be conducted to examine the effect of process parameters on the surface roughness, considering the variables. Table 6 shows the placement of the determined experimental factors and levels in the Taguchi L_9 orthogonal array. The selected experimental conditions were repeated 2 times and get avereged to increase the relaiblity of the results.

The 9 experiments are designed as in Table 7.

Table 7. The placement of the determined experimental factors and levels

Experiment Number	Variables	Parameter 1	Parameter 2	Parameter 3
1	A1B1C1	1	1	1
2	A1B2C2	1	2	2
3	A1B3C3	1	3	3
4	A2B1C2	2	1	2
5	A2B2C3	2	2	3
6	A2B3C1	2	3	1
7	A3B1C3	3	1	3
8	A3B2C1	3	2	1
9	A3B3C2	3	3	2

The parameters corresponding to Table 7 is shown explicitly in Table 8.

Table 8. Experiment factors and L_9 orthogonal arrays

Experiment No	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Depth of Cut (mm)
1	60	0.02	3
2	60	0.025	3.5
3	60	0.03	4
4	70	0.02	3.5
5	70	0.025	4
6	70	0.03	3
7	75	0.02	4
8	75	0.025	3
9	75	0.03	3.5

3 Results and discussion

This study examines the impact of milling parameters on the surface roughness of Ti-6Al-4V alloy. The research uses the Taguchi L_9 orthogonal array to optimize cutting speed, depth of cut, and feed rate, while evaluating three different cutting tool coatings. Each parameter was assessed at three levels. Milling experiments were performed according to the Taguchi design, and the resulting surface roughness was measured.

Subsequently, Taguchi optimization techniques were applied to the experimental data to identify the parameter combination yielding the minimal surface roughness. Additionally, an Analysis of Variance (ANOVA) was performed to determine the relative impact of each parameter on the surface roughness of milled titanium. Minitab 20 and MATLAB software were utilized for data analysis.

Building on the average surface roughness values measured from the experiments, the signal-to-noise (S/N) ratios were calculated using Equation (1) – presented earlier – following a "smaller-the-better" approach (as explained previously). For instance, the average surface roughness for the AlCrN coated tools was 1.01 micrometers, resulting in an S/N ratio of 0.35 dB. Table 9 presents all calculated S/N ratios.

The average value of the surface roughness for the AlCrN-tungsten based coating obtained as a result of the milling experiments was calculated as 0.831 µm. Similarly, the average value of S/N ratios was calculated as 1.66 dB.

The average value of the surface roughness for AlTiN-tungsten based coating obtained as a result of the milling experiments was calculated as 0.866 µm. Similarly, the average value of S/N ratios was calculated as 1.33 dB.

The Taguchi S/N response tables, detailed in Tables 9-11, were analyzed to assess the influence of each milling parameter on surface roughness. These tables reveal the optimal parameter settings that achieve minimal surface roughness. Notably, cutting speed emerged as the most significant parameter impacting surface quality, followed by feeding rate and cutting depth, in that order. ANOVA confirmed these findings.

Table 9. Experiment results and S/N ratios for the AlCrN coating

Experiment No	A	B	C	Ra (µm)	*S/N* ratio (dB)
1	60	0.02	3	0.565	4.959031
2	60	0.025	3.5	0.586	4.642048
3	60	0.03	4	0.974	0.228821
4	70	0.02	3.5	1.130	-1.06157
5	70	0.025	4	0.862	1.289855
6	70	0.03	3	0.887	1.041528
7	75	0.02	4	1.203	-1.60531
8	75	0.025	3	1.299	-2.27218
9	75	0.03	3.5	1.591	-4.0334

Table 10. Experiment results and S/N ratios for the AlCrN-tungsten based coating

Experiment No	A	B	C	Ra (µm)	*S/N* ratio (dB)
1	60	0.02	3	0.720	2.85335
2	60	0.025	3.5	0.680	3.349822
3	60	0.03	4	0.753	2.4641
4	70	0.02	3.5	0.913	0.790584
5	70	0.025	4	0.840	1.51441
6	70	0.03	3	0.816	1.76620
7	75	0.02	4	0.916	0.762091
8	75	0.025	3	0.825	1.670921
9	75	0.03	3.5	1.023	-0.19751

Table 11. Experiment results and S/N ratios for the AlTiN-tungsten based coating

Experiment No	A	B	C	Ra (µm)	S/N ratio (dB)
1	60	0.02	3	0.831	1.60798
2	60	0.025	3.5	0.764	2.33813
3	60	0.03	4	0.853	1.38102
4	70	0.02	3.5	0.813	1.79819
5	70	0.025	4	0.713	2.93821
6	70	0.03	3	0.756	2.42956
7	75	0.02	4	0.989	0.09607
8	75	0.025	3	0.923	0.69597
9	75	0.03	3.5	1.158	-1.27417

On the other hand, the graphics showing the level values of the parameter factors for the surface roughness values are given in Figure 3-5, respectively, where "smaller is the best" was aimed.

The optima are given in Table 12-14.

The optimal levels for each control factor are identified by analyzing the signal-to-noise (S/N) ratio across all levels of that factor. For milling Ti-6Al-4V alloy, the best levels and their corresponding S/N ratios were determined as follows: cutting speed at level 1 with an S/N ratio of 3.27663, feed rate at level 2 with an S/N ratio of 1.21991, and depth of cut at level 1 with an S/N ratio of 1.24279. In other words, the optimal surface roughness for Ti-6Al-4V was achieved with a cutting speed of 60 m/min, a feed rate of 0.025 mm/tooth, and a cutting depth of 3 mm.

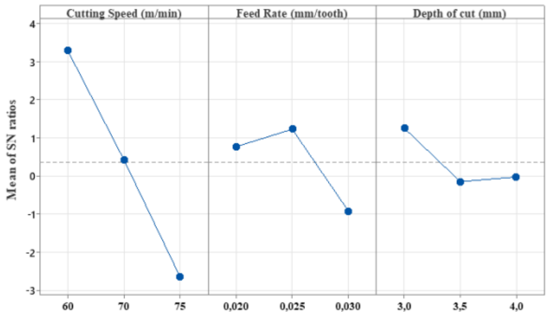


Figure 3. Local sensitivities in the parameters in the case of the AlCrN coating

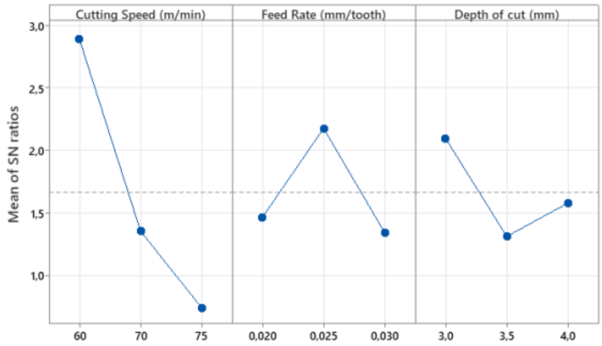


Figure 4. Local sensitivities in the parameters in the case of the AlCrN-tungsten based coating

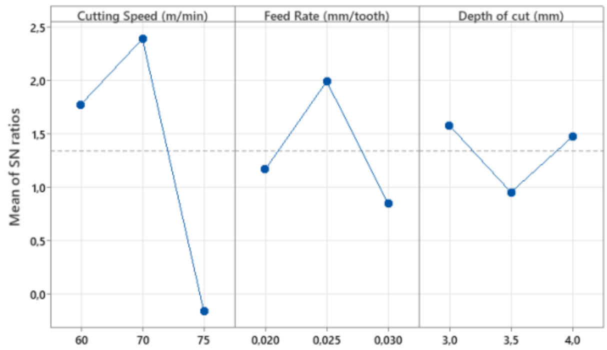


Figure 5. Local sensitivities in the parameters in the case of the AlTiN-tungsten based coating

Table 12. Response table for signal to noise ratios for the AlCrN coating

Level	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Depth of Cut (mm)
1	**3.27663**	0.76405	**1.24279**
2	0.42327	**1.21991**	-0.15097
3	-2.63697	-0.92102	-0.02888
Delta	5.91360	2.14092	1.39377
Rank	1	2	3

The optimal level for each control factor is determined by analyzing the signal-to-noise (S/N) ratio for all levels of that factor. For milling Ti-6Al-4V alloy, the best levels and their corresponding S/N ratios were found to be: cutting speed at level 1 with an S/N ratio of 2.8891, feed rate at level 2 with an S/N ratio of 2.1784, and depth of cut at level 1 with an S/N ratio of 2.0968. This means that the optimum surface roughness for Ti-6Al-4V was achieved with a cutting speed of 60 m/min, a feed rate of 0.025 mm/tooth, and a cutting depth of 3 mm. This result aligns with the findings for the first tool coating.

Table 13. Response table for signal to noise ratios for the AlCrN-tungsten based coating

Level	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Depth of Cut (mm)
1	**2.8891**	1.4687	**2.0968**
2	1.3571	**2.1784**	1.3143
3	0.7452	1.3443	1.5802
Delta	2.1439	0.8341	0.7825
Rank	1	2	3

Table 14. Response table for signal to noise ratios for the AlTiN-tungsten based coating

Level	Cutting Speed (m/min)	Feed Rate (mm/tooth)	Depth of Cut (mm)
1	1.7757	1.1674	**1.5778**
2	**2.3887**	**1.9908**	0.9541
3	-0.1607	0.8455	1.4718
Delta	2.5494	1.1453	0.6238
Rank	1	2	3

The optimal level for each control factor is identified by examining the signal-to-noise (S/N) ratio for all levels of that factor. For milling Ti-6Al-4V alloy, the best levels and their corresponding S/N ratios were found to be: cutting speed at level 2 with an S/N ratio of 2.3887, feed rate at level 2 with an S/N ratio of 1.9908, and depth of cut at level 1 with an S/N ratio of 1.5778. Thus, the optimum surface roughness for Ti-6Al-4V was achieved with a cutting speed of 70 m/min, a feed rate of 0.025 mm/tooth, and a cutting depth of 3 mm. Additionally, compared to the results from the first two experiments, the third coating performed better at higher cutting speeds. An Analysis of Variance (ANOVA) was conducted to assess the influence of control factors and their interactions on surface roughness during Ti-6Al-4V alloy milling. The results, presented in Table 15, were obtained at a 95% confidence level. F-values and percentage impact rates within the table indicate the relative importance of each factor, with the factor having the highest F-value exerting the strongest effect on surface roughness.

Table 15. The ANOVA results for surface roughness

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value
Feed Rate (mm/tooth)	2	0.09186	10.33%	0.09186	0.04593	1.04
Cutting Speed (m/min)	2	0.65726	73.94%	0.65726	0.32863	7.45
Depth of cut (mm)	2	0.05154	5.80%	0.05154	0.02577	0.58
Error	2	0.08819	9.92%	0.08819	0.04410	
Total	8	0.88886	100.00%			

The ANOVA analysis of the first experiment revealed cutting speed as the most dominant factor affecting surface roughness, contributing 73.94% to the variation. Feed rate followed in significance with a 10.94% impact, while depth of cut had the least influence (5.8%). Given the primacy of cutting speed, further analysis focused on its interaction with feed and depth of cut, visualized through graphs. Notably, similar trends were observed in experiments with different tool coatings. These coatings, while not altering the relative importance of cutting speed, feed rate, and depth of cut, did influence the overall surface roughness and optimal parameter values. This study aligns with findings from Yusuf et al. [21] who identified cutting speed as the primary factor impacting surface roughness in titanium alloys, followed by feed rate. However, contrasting results were reported by Riberio et al. [22] where radial depth of cut emerged as the most influential parameter. Krishnaraj, V. et al. [23] investigating high-speed end milling of titanium observed minimal influence of feed rate on surface roughness, aligning with the dominance of cutting speed observed here. Their findings, however, suggest depth of cut might hold a greater significance compared to this study.

Figure 6(a, b) illustrates the impact of cutting speed and feed rate on surface roughness. The graph shows that as cutting speed increases, surface roughness also rises. Ünal and Karaca. [10] stated according to their experiments with increasing cutting speed, surface roughness also tends to increase. As the cutting speed increases, scratches with larger pitch occur on the surface. The size of these scratches significantly increases the surface roughness. Since increasing cutting speed and increasing cutting forces and cutting temperatures can be considered as factors that accelerate tool wear, increasing cutting speed can be associated with increasing surface roughness.

The analysis indicates a positive correlation between feed rate and surface roughness. As feed rate increases, the chip cross-sectional area grows proportionally. This translates to a larger slip plane area within the primary deformation zone, demanding more energy for chip removal. Higher feed rates also lead to elevated cutting temperatures due to the increased volume of material being machined per unit time. The additional energy required to overcome these factors manifests as increased surface roughness. Furthermore, increased feed rates necessitate greater cutting forces, which themselves contribute to a rougher surface finish. Ramesh et al. [24], employed different machining parameters for a titanium alloy and utilized ANOVA to analyze their findings. While they anticipated an influence of feed rate on the results, it is well-established within machining literature that conventional surface roughness, for a specific tool tip radius, is inherently linked to feed rate.

Figure 6(a, b) reveals an interesting interaction between cutting speed and feed rate in their influence on surface roughness. As cutting speed increases, the sensitivity of surface roughness to variations in feed rate also intensifies. Conversely, at moderate cutting speeds, changes in feed rate have a less pronounced effect on surface roughness. When selecting cutting parameters based on these two factors, prioritizing the values that yielded the minimal surface roughness, as identified in the graphs, is recommended.

Figure 6(c, d) depicts the effect of cutting depth on surface roughness in conjunction with cutting speed. The data indicate that increasing the depth of cut results in a rise in surface roughness. This increase can be attributed to the well-documented influence of machining vibrations or chatter on surface finish. [22]. A greater depth of cut translates to increased cutting forces, which can induce vibrations in the cutting tool. Consequently, the rise in surface roughness observed with increasing depth of cut is likely linked to these amplified cutting forces.

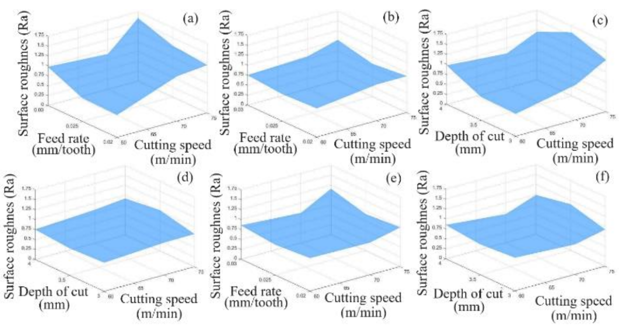


Figure 6. The effects of the parameters on surface roughness for (a) the AlCrN coating, (b) the AlCrN-tungsten based coating, (c) the AlCrN coating, (d) the AlCrN-tungsten based coating, (e) AlTiN-tungsten based coating, (f) AlTiN-tungsten based coating

Figure 6(c, d) unveils a complex interaction between cutting speed and depth of cut regarding their influence on surface roughness. Contrary to a monotonic rise, the impact of increasing depth of cut on surface roughness intensifies at higher cutting speeds. Here, an interesting trend emerges: while surface roughness initially increases with depth of cut, it can exhibit a decline beyond a specific threshold. This improvement in surface quality can be attributed to the interplay between cutting forces and temperature. High cutting forces, associated with larger depths of cut, also elevate temperatures within the cutting zone. This thermal increase may induce softening of the machined material, facilitating easier machining. This phenomenon likely explains the observed reduction in surface roughness at high cutting speeds and significant depth of cut values. When selecting cutting parameters based on these factors, prioritizing the values that yielded the minimal surface roughness, as identified in the graphs, remains crucial.

In Kara's study [25] conducted, the experimental results with values such as cutting speed, feed rate, and depth of cut were analysed with the help of the ANOVA, and it was revealed that the most used parameter that affected the experimental results the least was the depth of cut. It can be said that the reason why depth of cut is the least affecting parameter in this study is that the depth of cut values used in both studies are low enough to be used in finish surface operations. This result matches many studies in the literature [20,24].

Figure 6(e) shows that the increase in cutting speed increased the surface roughness at high cutting speeds, while it was close to each other at low and average cutting speeds. This shows that the coating is durable up to a certain cutting speed, but after that tool wear occurs and influences surface roughness. At high feed rates, the surface roughness decreased while the cutting speed was average. According to the result in the graph, it can be said that the third coating is relatively resistant to cutting temperatures, but the surface roughness increases at high cutting and high feed values due to the further increase in temperature. The values should not be chosen too high to reach low values in surface quality.

According to the conclusion drawn from the graph in Figure 6(e); as the effect of feed rate on surface roughness increases with increasing cutting speed, especially at high cutting speed. At average cutting speed values with using the AlTiN-tungsten based coating, the effect of feed rate on surface roughness does not change very much. Liang et al. [26] found that in their study, the lowest surface roughness value was found by using the AlTiN-tungsten based coating and this coating is suitable for micro machining of titanium.

Figure 6(f) shows that the cutting speed increases, the effect of cutting depth on surface roughness also increases. It is concluded from the graph that the decrease in surface roughness at high depth of cut, average and high cutting speed values may be due to thermal softening with increasing temperature value. The effect of depth of cut increases with increasing cutting speed. The high surface roughness value due to the depth of cut can be attributed to the forces and vibration on the tool. Compared to the AlCrN coating, the AlTiN-tungsten based coating seems to be more suitable for deep cutting at average cutting speeds. However, it would be better to choose lower depths of cut as the vibration of the tool mentioned earlier is one of the factors affecting tool life.

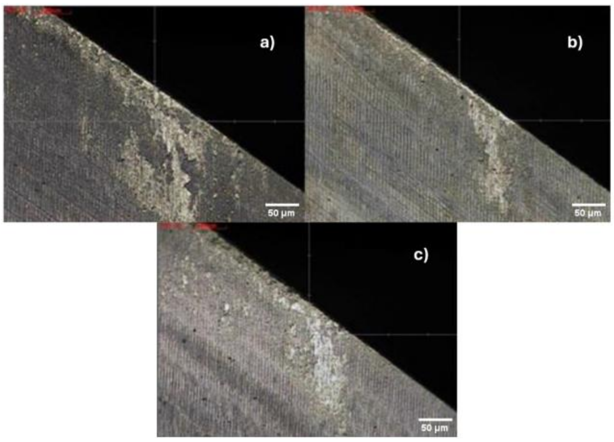


Figure 7. Coating wear at different coating types a) AlCrN (Aluminum Chromium Nitride), b) AlCrN-tungsten based, c) AlTiN (Aluminum Titanium Nitride)-tungsten based

Figure 7 shows the coating wear in the cutting zone for different coatings. The tools in the images are taken from experiments with high surface roughness for each experimental setup. When the images are examined, it seems that the coating adhesion can be attributed to the temperature increase at high cutting speed values and insufficient cooling. Coating adhesion and wear were observed on the tool surface. Since the experiments in which the tool samples were taken were all carried out at high cutting speed, the result is consistent with the experiments. It is necessary to reduce the temperature in the cutting zone to reduce coating wear. Therefore, the temperature in the cutting zone is reduced, the coating adhesion becomes lover, the higher the tool life can be achieved. It is challenging subject that the lower the costs and the lower the surface roughness value, which should not be ignored when machining titanium materials.

4 Conclusion

In this study, the effects of various cutting parameters and various coating types on surface roughness were investigated using the Taguchi orthogonal array. The following results were drawn:

- The most important parameter affecting surface roughness was found to be cutting speed based on the Taguchi test results. The second important parameter was the feed rate, and the less affecting parameter was the depth of cut.
- The lowest surface roughness was obtained from the experiment number 1 with a value of 0.565 µm. The highest surface roughness was obtained from the experiment number 9 with a value of 1.591 µm.
- The AlCrN-tungsten based coating has the best average of all surface roughness's.
- Optimum values were found for the AlTiN-tungsten based coating with slightly higher cutting speed. It can be said that it is more durable than the other coatings tested.
- According to ANOVA results for the AlCrN, the contribution of cutting speed, which is the most important parameter affecting surface roughness, was found to be 73.94%. The result is similar for the other coatings.

Conflict of interest

The authors declare that they have no conflict of interest.

Similarity rate (iThenticate): %16

References

[1] M. Peters, J. Hemptenmacher, J. Kumpfert and C. Leyens, Structure and properties of titanium and titanium alloys, Titanium and Titanium Alloys: Fundamentals and Applications, 1-36, 2003. https://doi.org/10.1002/3527602119.ch1

[2] I. Inagaki, T. Takechi, Y. Shirai and N. Ariyasu, Application and features of titanium for the aerospace industry, Nippon Steel & Sumitomo Metal Technical Report, 106, 22-27, 2014.

[3] R.R. Boyer, An overview on the use of titanium in the aerospace industry, Materials Science and Engineering: A, 213(1-2), 103-114, 1996. https://doi.org/10.1016/0921-5093(96)10233-1

[4] A. Gomez-Gallegos, P. Mandal, D. Gonzalez, N. Zuelli and P. Blackwell, Studies on titanium alloys for

aerospace application, Defect and Diffusion Forum, Trans Tech Publications, 419-423, 2018. https://doi.org/10.4028/www.scientific.net/DDF.385.419

[5] J.P. Davim, Machining of hard materials, Springer Science & Business Media, 2011.

[6] E. Ezugwu and Z. Wang, Titanium alloys and their machinability—a review, Journal of Materials Processing Technology, 68(3), 262-274, 1997. https://doi.org/10.1016/S0924-0136(96)00030-1

[7] H. Hong, A. Riga, J. Gahoon and C. Scott, Machinability of steels and titanium alloys under lubrication, Wear, 162, 34-39, 1993. https://doi.org/10.1016/0043-1648(93)90481-Z.

[8] C. Ohkubo, I. Watanabe, J. Ford, H. Nakajima, T. Hosoi and T. Okabe, The machinability of cast titanium and Ti–6Al–4V, Biomaterials, 21(4), 421-428, 2000. https://doi.org/10.1016/S0142-9612(99)00206-9.

[9] M. Rahman, Y. San WONG, A.R. Zareena, Machinability of titanium alloys, JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, 46(1), 107-115, 2003. https://doi.org/10.1299/jsmec.46.107.

[10] C. Ensarioğlu, M.C. Çakır, Titanyum ve alaşımlarının işlenebilirlik etüdü-Bölüm I, Mühendis ve Makina, 46(546), 36-46, 2005.

[11] S. Palanisamy, S.D. McDonald and M.S. Dargusch, Effects of coolant pressure on chip formation while turning Ti6Al4V alloy, International Journal of Machine Tools and Manufacture, 49(9), 739-743, 2009. https://doi.org/10.1016/j.ijmachtools.2009.02.010

[12] R.K. Roy, A primer on the Taguchi method, Society of Manufacturing Engineers, 2010.

[13] I. Tlhabadira, I.A. Daniyan, L. Masu and L.R. VanStaden, Process design and optimization of surface roughness during M200 TS milling process using the Taguchi method, Procedia Cirp, 84, 868-873, 2019. https://doi.org/10.1016/j.procir.2019.03.200

[14] A. Freddi, M. Salmon, A. Freddi and M. Salmon, Introduction to the Taguchi method, Design Principles and Methodologies: from Conceptualization to First Prototyping with Examples and Case Studies, 159-180, 2019. https://doi.org/10.1007/978-3-319-95342-7_7

[15] S.K. Karna and R. Sahai, An overview on Taguchi method, International Journal of Engineering And Mathematical Sciences, 1(1), 1-7, 2012.

[16] M. Saravi, L.B. Newnes, A.R. Mileham, Y.M. Goh and K. Morton, Using Taguchi method to optimise performance and product cost at the conceptual stage of design, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 227(9), 1360-1372, 2013. https://doi.org/10.1177/0954405413488361

[17] J.J. Pignatiello Jr, An overview of the strategy and tactics of Taguchi, IIE transactions, 20(3), 47-254, 1988. https://doi.org/10.1080/07408178808966177

[18] T.B. Barker, Engineering quality by design: interpreting the Taguchi approach, CRC Press, 1990.

[19] T.R. Bement, Taguchi techniques for quality engineering, Taylor & Francis, 1989. https://doi.org/10.1080/00401706.1989.10488519

[20] K. Yusuf, Y. Nukman, T. Yusof, S. Dawal, H. Qin Yang, T. Mahlia and K. Tamrin, Effect of cutting parameters on the surface roughness of titanium alloys using end milling process, Scientific Research and Essays, 5(11), 1284-1293, 2010.

[21] J. Ribeiro, H. Lopes, L. Queijo and D. Figueiredo, Optimization of cutting parameters to minimize the surface roughness in the end milling process using the Taguchi method, Periodica Polytechnica Mechanical Engineering, 61(1), 30-35, 2017. https://doi.org/10.3311/PPme.9114

[22] V. Krishnaraj, S. Samsudeensadham, R. Sindhumathi and P. Kuppan, A study on high speed end milling of titanium alloy, Procedia Engineering, 97, 251-257, 2014. https://doi.org/10.1016/j.proeng.2014.12.248

[23] E. Ünal ve F. Karaca, Ti–6Al–4V alaşımının dik işlem merkezli CNC tezgahında işlenebilirliğinin araştırılması, Fırat Üniversitesi Doğu Araştırmaları Dergisi, 6(1), 135-139, 2007.

[24] S. Ramesh, L. Karunamoorthy and K. Palanikumar, Surface roughness analysis in machining of titanium alloy, Materials and Manufacturing Processes, 23(2), 174-181, 2008. https://doi.org/10.1080/10426910701774700

[25] V. Kara, Taguchi metodu yardımıyla, GS 24Mn5 N malzemenin frezeleme operasyonunda, işleme parametrelerinin yüzey kalitesine etkisinin optimizasyonu, Yüksek Lisans Tezi, Mersin Üniversitesi, Fen Bilimleri Enstitüsü, Mersin, 2012.

[26] Z. Liang, P. Gao, X. Wang, S. Li, T. Zhou and J. Xiang, Cutting performance of different coated micro end mills in machining of Ti-6Al-4V, Micromachines, 9(11), 568, 2018. https://doi.org/10.3390/mi9110568