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PREDICTING SURFACE ROUGHNESS IN THE MILLING OF BIOCOMPATIBLE ALLOY TI–6AL–4V

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Abstract: Mechanical engineering plays an essential role in the development of medical devices, implants, prostheses, and medical equipment, with precise machining of bio–compatible materials being of considerable importance. Among the various traditional and modern machining methods, milling stands out as a widely employed technique. This study is dedicated to optimizing milling parameters to achieve a minimal average surface roughness (Ra) during the milling of the biocompatible alloy Ti–6Al–4V. This paper presents the optimization of machining parameters: cutting speed, feed rate and depth of cut. Each parameter is explored at three distinct levels, resulting in the initial design of 27 experimental runs. The paper further demonstrates how an extensive set of experiments can be streamlined to a more manageable 9 runs through the application of the Taguchi methodology. This paper points out the significant impact that varying levels can exert on the obtained results, highlighting the importance of a comprehensive and systematic approach to experimentation and optimization.
Keywords: Average surface roughness (Ra), difficult–to–cut materials, Ti–6Al–4V, ANOVA, Taguchi method

1. INTRODUCTION

Ti–6Al–4V, also known as Titanium 6–4, holds significant importance in various industries, particularly in biomedical and aerospace applications. The chemical composition of Ti–6Al–4V is detailed in Table 1. Its significance lies in its exceptional combination of properties, including high strength–to–weight ratio, excellent corrosion resistance, and biocompatibility, making it an ideal choice for medical implants, aircraft components, and more.

To successfully machine this alloy, manufacturers often employ techniques such as milling, turning, and grinding, using carefully optimized cutting parameters, tool materials, and cooling/lubricating methods to achieve desired surface finishes while maintaining dimensional accuracy and minimizing tool wear.

Milling is a widely used method for cutting this material. To effectively mill this material, machinists typically adopt strategies that involve selecting appropriate cutting tools and cutting parameters, i.e. cutting speed, feed rate, and depth of cut. This approach helps manage the heat generated during machining, reduce tool wear, and achieve the desired surface quality. Furthermore, optimizing these milling parameters is crucial to attain precise and efficient machining results when working with Ti–6Al–4V, especially in applications where surface roughness is a critical factor.

Despite having three factors, each with three levels, the full factorial design initially entails 27 experimental runs. However, by employing the Taguchi methodology and an orthogonal array, the number of required experimental runs is efficiently reduced to 9.

Table 1. Ti–6Al–4 chemical composition

Ti–6Al–4	V	Al	Sn	Zr	Mo	C	Si
	4,22	5,48	0,0625	0,0028	0,05	369	0,0222

Milling is a widely used conventional machining method. This paper explores the influence of cutting speed, feed rate, and depth of cut on surface quality during the milling of Ti–6Al–4V alloy. Achieving optimal machining parameters is essential for enhancing material removal rates, extending tool life, and achieving surface quality. Numerous research studies have explored the effects of machining parameters on surface roughness.

Kosarac et al. [1] conducted an experiment following the Taguchi methodology, which involved 27 experimental runs. Their research identified feed rate as the most influential factor affecting the average surface roughness in machining Al7075. Using a dataset consisting of these 27 samples, they developed various neural networks to predict surface roughness. Their findings suggested that even with a relatively small dataset, neural networks could be effectively developed for this purpose.

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Tesic et al. [2] used the Taguchi methodology to determine optimal machining parameters and analyze their impact on surface roughness during milling of Ti6Al4V alloys. Their analysis revealed that, when machining the bio–compatible titanium alloy Ti6Al4V, the speed of cutting had the most significant influence on the roughness of the machined surface, followed closely by the feed rate per tooth.

Sun et al. [3] have conducted a series of end milling experiments to comprehensively characterize the surface integrity at various milling conditions. Their experiments have shown that the milled surface shows the anisotropic nature, and the surface roughness increases with feed and radial depth of cut, while the cutting speed has less impact.

Rahman et al. [4] used Taguchi methodology and analysis of variance (ANOVA) to determine the significance of radial depth of cut on on cutting force, tool life and surface roughness compared to that of cutting speed and feed rate during face milling of Ti6Al4V alloy. They used mono and multi objective optimizations of the response characteristics to determine the optimal input parameters, namely, cutting force, feed rate, and radial depth of cut. According to their analysis the most significant factor for surface roughness is the feed rate, while the cutting force and radial depth of cut have the most impact on tool life.

Bai et al. [5] experimented with the lubrication performance of different nanofluids in milling Ti6Al4V alloy. They investigated the lubrication performance in terms of milling force, surface roughness and morphology of the workpiece surface. Experimental results demonstrated that the Al2O3 nanoparticle obtained the minimal milling force, followed by SiO2 nanoparticle. The minimum surface roughness was obtained by the Al2O3 nanofluid followed by Sio2, MoS2, CNTs, graphite and SiC in the given order of significance. Spherical Al2O3 and Sio2 nanoparticles improved the lubrication effect of base oil mostly and were more suitable as environment–friendly additives for the base oil compared with the others.

Shokrani et al. [6] investigated the effect of cryogenic cooling using liquid nitrogen on surface integrity of Ti6Al4V alloy in end milling operations. They experimented with super cold liquid nitrogen at –197 °C as a method of heat dissipation when end milling at various combinations of cutting parameters compared to dry and flood cooling. Surface roughness and microscopic surface integrity were investigated and the analysis indicated that cryogenic cooling has resulted in up to 39% lower surface roughness compared to dry cutting and 31% compared to flood cooling. The investigation indicated that cryogenic cooling considerably improves surface integrity in end milling Ti6Al4V alloy.

Danish et al. [7] experimented with dry milling of Ti6Al4V alloy at constant depth of cut while varying the cutting speed and feed rate to observe the effects of these parameters on tool wear. They used a coated carbide insert end mill as cutting tool to investigate its performance under dry machining conditions and to optimize the cutting parameters to machine Ti6Al4V. The results show that cutting speed has the most impact on tool life. Lower cutting speed increases shocking force and decreases tool life. The results also indicate that for fixed depth of cut, full endmill engagement with the workpiece creates constant chip thickness and evenly distributes the cutting force between the tool and workpiece thus limiting the effect of the feed rate on surface roughness.

Eyup et al. [8] conducted a series of face milling experiments using the Taguchi methodology to determine the optimal cutting parameters for milling cobalt–based alloy "Stellite 6". The evaluated milling parameters are feed rate, cutting speed and depth of cut, while the surface roughness was measured as result data. The settings of face milling parameters were determined using Taguchi experimental design method, while the results were evaluated using signal to noise ratio and analysis of variance (ANOVA) to determine the optimal parameters. Confirmation tests with the optimal levels of cutting parameters were carried out and demonstrated the effectiveness of Taguchi optimization method. The study shows that cutting speed, feed rate and depth of cut have significantly influenced surface roughness with 95% confidence level.

Athreya et al. [9] used the Taguchi method to optimize cutting parameters for face turning on mild steel. Cutting speed, feed rate and depth of cut were evaluated at three levels using an orthogonal L9 Taguchi experiment array. After conducting the experiments the surface roughness was measured and Signal to Noise ratio was calculated. Optimal parameters were calculated and confirmation experiments were carried out, while the results were compared with the full factorial method. They conclude that the

Taguchi method of experimental setup can be used to evaluate and optimize different parameters with high levels of confidence. It is also concluded that on face turning mild steel the most significant factor for surface roughness was the cutting speed, followed by depth of cut and feed rate.

Kumar et al. [10] experimented with hard turning of Ti6Al4V alloy using a carbide insert tool. The experiments were conducted by varying 4 parameters on 3 levels using the Taguchi L9 orthogonal matrix for experimental design. The evaluated parameters were nose radius, depth of cut, feed rate and cutting speed while the surface roughness was measured. Their experiments show that for dry turning of Ti6Al4V the most significant parameter on tool wear and surface roughness is the nose radius of the cutting tool insert, followed by feed rate, depth of cut and cutting speed.

Kumar et al. [11] investigated the effect of cutting parameters on surface roughness when turning AISI 1045 carbon steel. They used Taguchi method for experimental setup and an L27 orthogonal array for three parameters on three levels, cutting speed, feed rate and depth of cut. Using the analysis of variance method (ANOVA) they concluded that the most significant parameter affecting surface roughness when turning AISI 1045 is the feed rate with 95% significance.

2. EXPRERIMENTAL SETUP

In the pursuit of optimizing machining parameters and surface roughness in the milling of the biocompatible alloy Ti–6Al–4V, a comprehensive experimental setup was employed. This setup incorporated several components, each playing a role in the precision and effectiveness of the machining process.

Machine Tool

All experimental runs were performed under identical machining conditions and using the same machine tool. The experiment was carried out using the Emco Concept Mill 250 machining center. With a maximum RPM of 10,000 and a power rating of 7 kW, this machine tool provided the necessary mechanical force and precision for the milling operation.

Cutting Tool

The choice of cutting tool was the Pramet indexable end mill cutter model HF 16E2R030A16–SBN10–C, outfitted with two BNGX 10T308SR–MM: M8345 inserts designed explicitly for alloy cutting.

Measurement Tools

The average surface roughness (Ra) was measured using a Mitutoyo SJ–210 measuring device, ensuring accurate and consistent data collection. For this experiment, measuring parameters are set according to the expected value of the Ra to λf = 2.5 μm, λc = 0.8 mm, ln = 4 mm.

Machining Process

The milling operation was performed on sample parts measuring 30 × 30 × 20, clamped in a general–purpose milling vise. Employing the climb milling method, material was removed from both sides of the sample parts. Notably, the sample parts were fed along the cutter's direction of rotation, a strategic choice to enhance the overall quality of the machined surface.

For the purpose of this research, two experiments were conducted, each comprising 9 experimental runs, planned by Taguchi Design of Experiments (DOE). Two factors, namely cutting speed and radial depth of cut, were set at consistent levels in both experiments, while the level of feed rate varied between the two sets of experiments. The objective was to assess the impact of the range of levels for this factor on the prediction of average surface roughness.

The axial depth of cut (ap) remained constant throughout the experiment, consistently set at half of the cutting edge length. In contrast, the radial depth of cut (ae) was subject to variation during the experimental process. The arithmetic mean roughness was measured on the peripheral side of the workpiece. For all experiments, wet machining was conducted using the semi–synthetic fluid BIOL MIN–E, which conforms to the ISO 6743/7 quality standard. Experimental factors and their levels for both experiments are provided in Table 2 and Table 3.

The rpm used in the experiment (1200 rpm, 1600 rpm, 2000 rpm) were calculated based on adopted upper and lower cutting speed (Table 2 and Table 3). The feed rate per minute is calculated using the determined rpm, feed per tooth value and number of inserts of end mill. The minimum feed rate (fmin = 120 mm/min) corresponds to the smallest number of revolutions (n1 = 1200 rpm) and the lowest value of feed per tooth (f_{z1} = 0.05 mm/tooth – Experiment 1). The maximum feed rate (fmax = 1400 mm/min) corresponds to a maximum rpm (n3 = 2000 rpm) and maximum feed per tooth (f_{z3} = 0.35 mm/tooth – Experiment 2).

Table 2. Experimental factor and their levels for experiment 1

Factor	Level		
	1	2	3
Cutting speed (m/min)	60	80	100
Feed rate per tooth (mm/tooth)	0.05	0.075	0.1
Radial depth of cut (mm)	0.3	0.6	0.9

Table 3. Experimental factor and their levels for experiment 2

Factor	Level		
	1	2	3
Cutting speed (m/min)	60	80	100
Feed rate per tooth (mm/tooth)	0.15	0.25	0.35
Radial depth of cut (mm)	0.3	0.6	0.9

3. TAGUCHI METHOD FOR OPTIMIZATION OF CUTTING PARAMETERS

The influence of different factors on the surface quality was determined by conducting an experiment. Full factorial plan means conducting the maximum number of experimental runs, determined by the factor and levels number. That means much longer time and a higher cost of the experiment. The Taguchi method is one of the most commonly used methods in the designing of the experiments. This method assume fewer experimental runs in compare to the full factorial plan. The main goal of this method is defining a minimum number of the experimental runs, which will contain an optimal combination of the factors and their levels.

Data analysis is subsequently based on statistical methods. It determines the optimal conditions, in order to obtain a minimum of the cost function. The Taguchi optimization method is often used to obtain low surface roughness in various cutting operations. A measure of quality characteristics, the signal–to–noise ratio, is observed. The signal– to–noise ratio represents a deviation from the desired value. For the optimization of static problems, there are three signal–to–noise ratios: smaller is better, bigger is better and nominal is the best. The goal of this experiment was the determination of the arithmetical mean roughness (Ra), and the selected S/N ratio of interest corresponded to the "Smaller is better" criterion. In this case, a full factorial experiment entailed 3^3 = 27 experimental runs.

Table 4. Experimental plan – L_{27} orthogonal array (Taguhci method) – Experiment 1

Number of Trials	Cutting Speed (m/min)	Feed per Tooth (mm/tooth)	Depth of Cut (mm)	Replicate			Average R_a (μm)	S/N ratio (dB)
				R_{a1} (μm)	R_{a2} (μm)	R_{a3} (μm)		
1	60	0.05	0.3	0.437	0.32	0.482	0.413	7.68
2	60	0.075	0.6	0.623	0.53	0.404	0.519	5.696
3	60	0.1	0.9	0.854	1,81	0.709	0.781	2.141
4	80	0.05	0.6	0.466	0.366	0.38	0.404	7.872
5	80	0.075	0.9	0.601	0.616	0.722	0.646	3.790
6	80	0.1	0.3	0.483	0.456	0.52	0.486	6.261
7	100	0.05	0.9	0.387	0.401	0.413	0.413	7.951
8	100	0.075	0.3	0.373	0.516	0.414	0.434	7.243
9	100	0.1	0.6	0.701	0.549	0.589	0.613	4.250

Table 5. Experimental plan – L_{27} orthogonal array (Taguhci method) – Experiment 2

Number of Trials	Cutting Speed (m/min)	Feed per Tooth (mm/tooth)	Depth of Cut (mm)	Replicate			Average R_a (μm)	S/N ratio (dB)
				R_{a1} (μm)	R_{a2} (μm)	R_{a3} (μm)		
1	60	0.05	0.3	0.787	0.697	0.714	0.732	2.701
2	60	0.075	0.6	0.797	0.85	0.777	0.808	1.851
3	60	0.1	0.9	1.012	1.085	1.315	1.137	–1.117
4	80	0.05	0.6	0.716	0.712	0.521	0.649	3.746
5	80	0.075	0.9	0.766	0.953	0.813	0.844	1.473
6	80	0.1	0.3	0.874	1.036	0.859	0.923	0.695
7	100	0.05	0.9	0.445	0.426	0.391	0.420	7.521
8	100	0.075	0.3	0.413	0.51	0.546	0.489	6.201
9	100	0.1	0.6	0.969	0.929	0.875	0.924	0.683

Using the Taguchi method, the experiments were reduced from 27 runs to 9 runs by means of an orthogonal design. The orthogonal matrix shown in Table 4 and Table 5 has 9 rows, representing the number of experimental runs.

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} yi^2\right)$$

The optimization of the studied factors concerning the "Smaller is better" criterion provided the optimal combination, coded as 3–1–1 for the first experiment, and 3–1–3 for the second experiment. Since the 3–1–1 combination does not exist in the orthogonal array, a confirmation experiment needed to be conducted. The experimentally obtained value of Ra for the 3–1–1 combination of input parameters was Ra = 0.389 μm, which confirms the results obtained when applying the presented method, Table 8.
The combination 3–1–3 is present in the orthogonal array in experiment 2, obviating the need for a confirmation experiment.

Table 6. S/N ratio of the arithmetic mean roughness Ra – Experiment 1

Factors	Level			Delta	Rank
	1	2	2		
Cutting speed	5.173	5.975	6.482 *	1.309	3
Feed per tooth	7.835 *	5.577	4.218	3.617	1
Radial depth of cut	7.062 *	5.940	4.628	2.434	2

*Optimal level

Table 7. S/N ratio of the arithmetic mean roughness Experiment 2

Factors	Level			Delta	Rank
	1	2	2		
Cutting speed	1.145	1.972	4.802 *	3.65	2
Feed per tooth	4.656 *	3.176	0.087	4.56	1
Radial depth of cut	0.960	2.094	2.626 *	1.66	3

*Optimal level

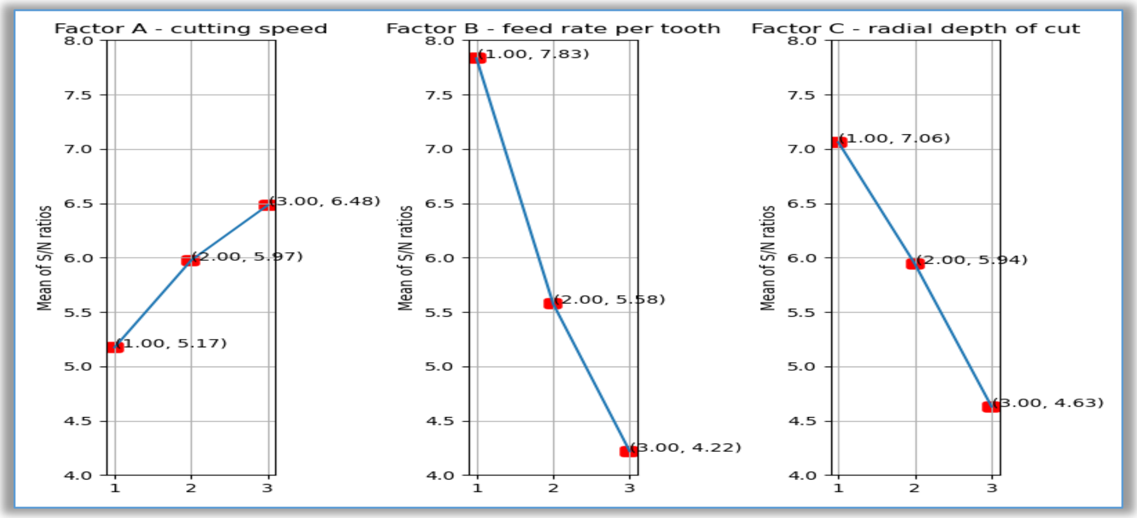

Figure 1. Main effect plot for S/N ratio – experiment 1

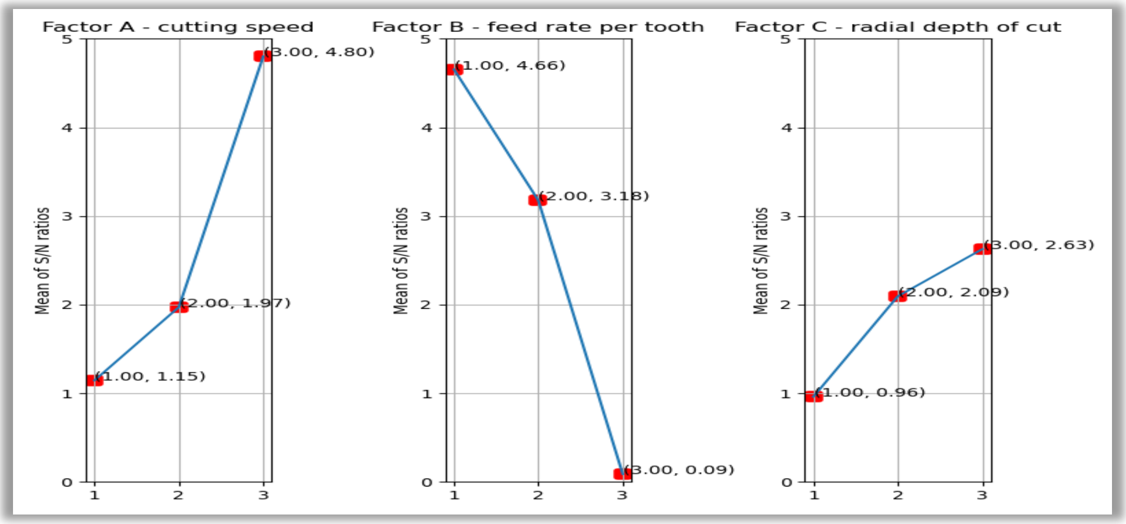

Figure 2. Main effect plot for S/N ratio – experiment 2

Table 8. Confirmation experiment for combination 3–1–1

	Speed	Feed per tooth	Radiao depth of cut	S/N	Ra calculated	Ra test
Level	100	0,05	0,3	7.191	0.436	0.389

The graphical representation of the relationship between input variables, including cutting speed, feed rate, and depth of cut, alongside the output variable, average mean roughness (Ra), is effectively conveyed through Figure 3 in the form of a correlation matrix. Within this figure, the left section represents Experiment 1, while the right section depicts Experiment 2.

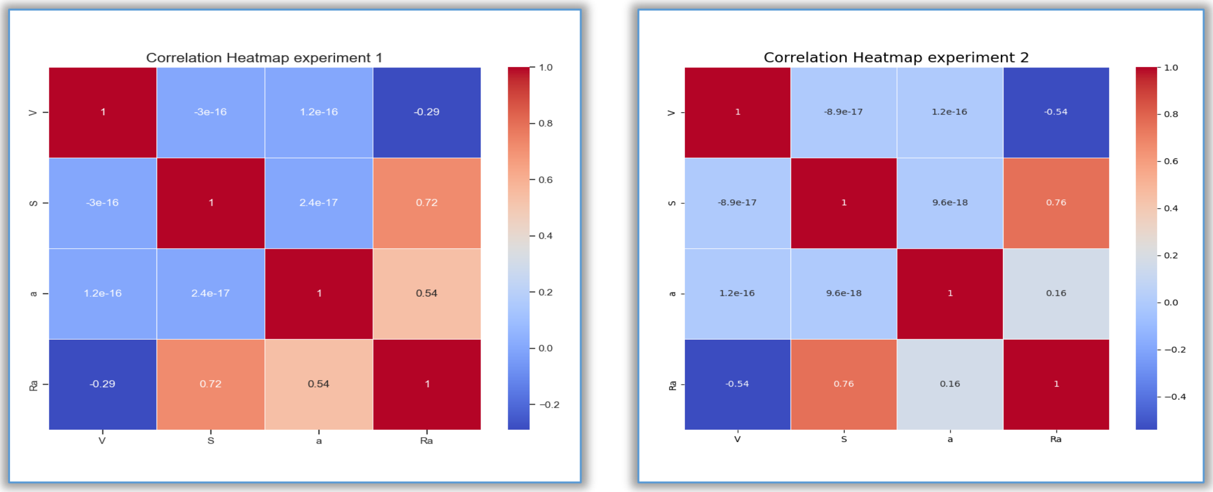

Figure 3. Correlation matrix of cutting speed, feed rate, and depth of cut to mean average roughness Ra for experiment 1 (left) and experiment 2 (right)

To analyze the correlation matrix results, it will be explored the following insights.

- Feed Rate Dominance: In both experiments, the correlation matrix indicates that feed rate has the most significant positive impact, as it has the largest positive value. This suggests that changes in feed rate have a substantial influence on the output variable, Ra.
- Positive Correlation with Feed Rate: The positive correlation between feed rate and Ra is highlighted by the positive value in the correlation matrix. This indicates that as the feed rate increases, the Ra value tends to increase as well. In other words, there is a direct relationship between feed rate and surface roughness (Ra).
- Negative Correlation with Cutting Speed: The negative value in the correlation matrix for cutting speed aligns with expectations. It signifies that cutting speed and Ra are inversely related. As cutting speed increases, Ra tends to decrease. This finding is consistent with the well–known principle that increasing cutting speed often results in a smoother surface finish (lower Ra).

4. ANALYSIS OF VARIANCE (ANOVA)

ANOVA is a statistical technique used to test the significance of the main factors comparing a mean square to an estimate of the experimental error at a certain level of confidence. In this study, the arithmetic mean roughness Ra obtained experimentally was analyzed using ANOVA. Analysis of variance illustrates the degree of importance of each factor that prominently influenced the arithmetic mean roughness Ra. Table 9 and Table 10 show the ANOVA results for the arithmetic mean roughness Ra for both experiments.

Table 9. Results of ANOVA for the arithmetic mean roughness experiment 1

Factor	DoF	Sum of squares	Variation	F–test
Cutting speed	2	0.012	0.006	0.918
Feed rate	2	0.074	0.037	5.558
Depth of cut	2	0.041	0.021	3.097
Error	2	0.01	0.007	
Total	8	0.137		

Table 10. Results of ANOVA for the arithmetic mean roughness experiment 2

Factor	DoF	Sum of squares	Variation	F–test
Cutting speed	2	0.124	0.062	5.94
Feed rate	2	0.246	0.123	11.818
Depth of cut	2	0.013	0.007	0.650
Error	2	0.020	0.010	
Total	8	0.4154		

The magnitude of the F–test for "Factor A" (cutting speed) in Experiment 1 is observed to be less than 1, similarly, the magnitude of the F–test for "Factor C" (depth of cut) in Experiment 2 is also found to be below 1. This suggests that these specific values hold limited statistical significance. As a result, a reevaluation of the inclusion of "Factor A" in Experiment 1 and "Factor C" in Experiment 2 has been conducted. After their exclusion, the F–test values were recalculated, and the results are presented in Table 11 and Table 12.

Table 11. Results of the final ANOVA for the arithmetic mean roughness experiment 1

Factor	DoF	Sum of squares	F–test	Percentage
Feed rate	2	0.0611	5.796	43.50%
Depth of cut	2	0.0284	3.230	20.22%
Error	4	0.0510		36.28%
Total	8			100%

Table 12. Results of the final ANOVA for the arithmetic mean roughness experiment 2

Factor	DoF	Sum of squares	F–test	Percentage
Cutting speed	2	0.107	7.208	26.38%
Feed rate	2	0.229	14.320	56.62%
Error	4	0.068		17.00%
Total	8			100%

Based on the F distribution tables, the ratios corresponding to 95% and 99% confidence levels are $F_{0.05,2.4} = 6.9943$ and $F_{0.01,2.4} = 18.000$.

Both factor in Table 11 show physical and statistical insignificance corresponding to both confidence levels. Furthermore, the error value is notably elevated, standing at 36.28%.

In the same time factors presented in table 12 shows physical and statistical significance corresponding to both confidence level, 95% and 99%.

5. OBSERVATIONS ON FACTOR LEVELS:

Experiment 1:

Experiment 1 investigates cutting speed, feed rate per tooth, and radial depth of cut with the following levels:

— Cutting Speed (m/min): 60, 80, 100;
— Feed Rate per Tooth (mm/tooth): 0.05, 0.075, 0.1;
— Radial Depth of Cut (mm): 0.3, 0.6, 0.9

Notably, all factors in Experiment 1 were found to be statistically insignificant, with physical and statistical insignificance observed at both the 95% and 99% confidence levels. This suggests that, within the range of levels tested, variations in cutting speed, feed rate per tooth, and radial depth of cut did not significantly affect the average surface roughness (Ra) in Experiment 1. Furthermore, the high error rate of 36.28% underscores the complexity of achieving minimal Ra under these conditions.

Experiment 2:

In Experiment 2, the same factors were explored, with one notable difference in the range of feed rate per tooth:

— cutting speed (m/min): 60, 80, 100;
— feed rate per tooth (mm/tooth): 0.15, 0.25, 0.35;
— radial Depth of Cut (mm): 0.3, 0.6, 0.9

Experiment 2 yielded different results. Here, all factors demonstrated both physical and statistical significance at both the 95% and 99% confidence levels. This indicates that, with the altered range of feed rate per tooth, variations in cutting speed, feed rate per tooth, and radial depth of cut had a substantial impact on achieving minimal Ra. Although the error rate decreased to 17%, it remained relatively high, underscoring the challenges in optimizing these parameters.

In summary, this study reveals the critical role that a comprehensive approach to experimentation and optimization plays in understanding and improving machining processes. While Experiment 1 indicated insignificance and a high error rate, Experiment 2 showed significance, particularly due to the altered range of feed rate per tooth. These findings emphasize the importance of carefully selecting factor levels when seeking optimal machining parameters. Further research may explore additional factors and levels to refine the optimization process.

6. CONCLUSIONS

This study was dedicated to optimizing milling parameters for achieving minimal average surface roughness (Ra) during the machining of the biocompatible alloy Ti–6Al–4V. The investigation entailed optimizing cutting speed, feed rate per tooth, and radial depth of cut, where each parameter was examined at three distinct levels. This comprehensive approach resulted in a full factorial design comprising 27 experimental runs.

A significant aspect of this research was the application of the Taguchi methodology, which allowed for the streamlining of the extensive set of experiments from 27 runs to a more manageable 9 runs. The study underscores the profound impact that varying parameter levels can have on obtained results, emphasizing the importance of a comprehensive and systematic approach to experimentation and optimization.

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