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Original Article

Experimental Optimization of Surface Quality in Turning of AISI 1050 Tool Steel

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Abstract

Surface properties significantly influence the compatibility and longevity of machine components. This study analyzed the variations in surface roughness observed during the turning of AISI 1050 tool steel under different machining conditions. Employing the Taguchi L32 experimental design method, optimal machining conditions were determined based on surface roughness variations. The confirmation experiments yielded results within the calculated confidence interval (CI), validating the effectiveness of the Taguchi method in optimizing machining parameters. The optimal machining parameters for achieving the minimum surface roughness were identified as a cutting speed of 225 m/min, a feed rate of 0.3 mm/rev, and a depth of cut of 1 mm under dry machining conditions. Among the parameters, the depth of cut was found to be the most influential factor, accounting for 57.97% of the total effect on surface roughness. The application of the Taguchi method effectively reduced the quality losses associated with surface roughness by 97.1%.

Keywords: AISI 1050, Tool steel, CNC lathe, Turning, Surface roughness, Optimization

AISI 1050 Takım Çeliğinin Tornalanmasında Yüzey Kalitesinin Deneysel Optimizasyonu

Özet

Yüzey özellikleri, makine parçalarının uyumluluğunu ve ömrünü önemli ölçüde etkilemektedir. Bu çalışmada, farklı işleme koşullarında AISI 1050 takım çeliğinin tornalanması sırasında gözlemlenen yüzey pürüzlülüğü değişimleri analiz edilmiştir. Taguchi L32 deney tasarımı yöntemi kullanılarak, yüzey pürüzlülüğü değişimlerine bağlı olarak optimum işleme parametreleri belirlenmiştir. Doğrulama deneyleri, hesaplanan güven aralığı (CI) içerisinde sonuçlar vermiş ve Taguchi yönteminin işleme parametrelerinin optimizasyonundaki etkinliğini doğrulamıştır. Minimum yüzey pürüzlülüğünü elde etmek için belirlenen optimum işleme parametreleri, kuru kesim koşullarında 225 m/dak kesme hızı, 0,3 mm/dev ilerleme ve 1 mm kesme derinliği olarak tespit edilmiştir. Parametreler arasında, toplam yüzey pürüzlülüğü etkisinin %57,97'sini oluşturan en etkili faktörün kesme derinliği olduğu bulunmuştur. Ayrıca, Taguchi yönteminin uygulanması, yüzey pürüzlülüğüne bağlı kalite kayıplarını %97,1 oranında azaltmada etkili olmuştur.

Anahtar Kelimeler: AISI 1050, Takım çeliği, CNC torna, Tornalama, Yüzey pürüzlülüğü, Optimizasyon

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1. INTRODUCTION

Steel is extensively utilized in the manufacturing industry due to its versatility, ease of production, and favorable mechanical properties [1]. The ability of manufactured components to function efficiently depends on maintaining dimensional and surface quality within specified tolerances [2]. Turning is one of the most widely used machining methods, where cutting parameters directly affect surface integrity. Incorrect parameter selection can lead to excessive tool wear, increased material wastage, and poor surface quality [3-4].

The surface quality of parts produced through turning determines their functional characteristics, affecting durability and efficiency. Proper optimization of surface quality can enhance the material's wear resistance, fatigue strength, hardness, and tribological properties. For this reason, measuring and characterizing the material's hardness and surface roughness are crucial for the optimization of machining processes. In the literature, there are various studies related to these optimizations using AISI 1050 cold-worked tool steel.

Avcı et al. (2024) investigated the effects of different machining parameters on surface roughness and hardness during the milling of AISI 1050 steel. Using the Taguchi L18 method, they determined the optimum machining conditions and revealed the changes in surface quality under dry and wet machining conditions. As a result, they found that at high cutting speeds, surface roughness and hardness were higher in operations where coolant was used compared to dry machining conditions [5].

Yağmur (2023) investigated the effects of minimum quantity lubrication (MQL) on cutting forces and surface roughness during the turning of AISI 1050 steel. In the study, experiments were conducted at different cutting speeds, feed rates, and MQL flow rates, and it was determined that the use of MQL reduced both surface roughness and cutting forces [6].

Yılmaz and Güllü (2020) conducted experiments on surface roughness during the turning of AISI 1050 steel using three different cutting speeds, feed rates, and depths of cut. In their study, they identified the most influential cutting parameters affecting surface roughness and expressed the relationship between these parameters and surface roughness through mathematical models and equations. Additionally, they investigated how different cutting parameters alter the chip geometry [7].

In the study conducted by Gurun et al. (2018), AISI 1050 steel was machined on a CNC lathe, and the surface roughness values were recorded to investigate the effects of cutting parameters on surface roughness. According to the results of the variance analysis, the feed rate was identified as the most influential parameter on surface roughness, while the other parameters were found to have no significant effect on surface roughness [8].

Yağmur et al. (2017) investigated the drillability performance of AISI 1050 steel. Using the Taguchi L18 experimental design, they conducted drilling experiments with uncoated and coated (TiN/TiAl/TiCN) tools at different cutting speeds and feed rates. During the drilling operations performed on a CNC vertical machining center, cutting forces were measured, and the Taguchi method was applied to determine the optimal cutting parameters. As a result of the study, it was found that the optimal parameters for the coated tool were a cutting speed of 90 m/min and a feed rate of 0.15 mm/rev [9].

Baday (2016) illustrated the applicability of advanced technologies in machining processes by predicting cutting forces using an Artificial Neural Network (ANN) model [10].

In the study by Çelik and Çaydaş (2016), the effects of feed rate and spindle speed on the surface roughness of workpieces were experimentally determined while keeping the offset distance between tools and depth of cut constant. The results revealed that the surface quality processed by the first tool to contact the workpiece was inferior compared to the others [11].

Gürbüz (2015) investigated the parameters influencing cutting forces through experimental and statistical methods, highlighting the significance of accurate predictive models [12].

Meral et al. (2015) investigated surface roughness, dimensional accuracy, and geometric deviations affecting hole quality in AISI 1050 steel. Experiments were conducted using coated and uncoated HSS drills with different diameters to evaluate the effects of cutting speed and feed rate. The study found that coated drills provided better results, with drill diameter being the most influential factor on surface roughness, while cutting speed had the greatest effect on geometric accuracy [13].

This study investigates the effects of machining parameters on the surface roughness of AISI 1050 steel and determines the optimal conditions using statistical and experimental approaches.

2. MATERIAL AND METHOD

This research aims to assess how machining parameters influence the surface roughness of AISI 1050 steel surfaces that have been turned. To optimize the cutting parameters, Taguchi's orthogonal array Design of Experiments (DoE) technique was employed. A total of 32 experiments were conducted using four factors (cooling method, cutting speed, feed rate, and depth of cut) at two or three levels.

2.1 Workpiece Material

The material used in the experiments was AISI 1050 steel with an approximate hardness of 190 HV. The chemical composition and mechanical properties of the material are presented in Tables 1 and 2, respectively.

Table 1. Chemical composition of AISI 1050 steel (%) [14]

Fe	C	Si	Mn	P	S
Kalan	0,42-0,50	0,15-0,35	0,50-0,80	0,045	0,045

Table 2. Mechanical properties of AISI 1050 steel [15]

Yield S(MPa)	Tensile S(MPa)	Elasticity M(GPa)	Elongation (min. %)	Hardness (HRC)
580	690	205	10	13 (190 HV)

2.2 Experimental Setup

A Goodway GA-3600L CNC turning center with a motor power of 18 kW and a maximum spindle speed of 2,500 rpm was employed. The tool holder used was Takımsaş-MTJNL 2525 M16, with a Kyocera R0.4 cutting insert (Figure 1).

Figure 1. Turning machine, tool holder and cutting tool

2.3 Machining Parameters

The experiments were conducted under both dry and wet conditions. The machining parameters are provided in Table 3. The Taguchi L32 (2^1 4^4) orthogonal array was utilized to design the experiments, incorporating variations in cutting speed (165–250 m/min), feed rate (0.15–0.30 mm/min), and depth of cut (1–2.5 mm). The cutting parameters used in the experiments were selected based on the cutting tool catalog values.

Table 3. Machining parameters and their levels

Parameters	Symbol	Level			
		1	2	3	4
Coolant	A	1 (Wet)	2 (Dry)	-	-
Cutting Speed (m/min)	B	165	190	225	250
Feed rate, (mm/min)	C	0,15	0,20	0,25	0,30
Depth of cut (Ø) (mm)	D	1,0	1,5	2,0	2,5

After the experiments, Signal-to-Noise (S/N) ratios were calculated using the "smaller is better" equation based on the surface roughness values obtained.

$$S/_N = -10\log\frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{1}$$

Surface roughness measurements were performed using a Mitutoyo SJ-210 surface roughness tester (Figure 2), following DIN EN ISO 16610-21 standards.

Figure 2. Surface roughness measurement device

3. RESULT AND DISCUSSION

According to the experimental plan, the first 16 experiments were conducted using a coolant with different cutting speeds, feed rates, and cutting depths. The subsequent experiments, from 17 to 32, were performed under dry conditions. In both the coolant and dry conditions, a new cutting insert was used for each cutting speed.

3.1 Effect of Machining Parameters on Surface Roughness

The experimental results indicate that depth of cut exerts the most significant influence on surface roughness, followed by cutting speed and feed rate. Analysis of Variance (ANOVA) results confirm that cutting depth contributes 57.97% to surface roughness variations, making it the dominant factor in determining surface quality. The surface roughness results obtained from the experiments are presented in Table 4.

3.2 Optimization Using Signal-to-Noise (S/N) Ratios

Signal-to-noise (S/N) ratio analysis was conducted to identify optimal machining parameters. This analysis enabled the ranking of results through delta statistics and evaluated the effects of cutting parameters. According to the mean results presented in Table 5, it was observed that the depth of cut is the most influential factor on surface roughness, ranking first. It is followed by cutting speed, cooling factor, and feed rate, respectively, based on their effects on surface roughness.

Table 5 summarizes the S/N ratio analysis, offering an in-depth examination of how different cutting parameters impact surface roughness. The rankings derived from this analysis highlight the importance of these parameters in attaining optimal cutting performance.

The effects of cutting factors on Ra in the experimental studies are visualized in Figure 3. The factors in the graph were determined through analysis of variance (ANOVA) and represent the two most influential factors on surface roughness (Ra).

The findings suggest that the lowest surface roughness is achieved with dry machining (A2), a cutting speed of 225 m/min (B3), a feed rate of 0.3 mm/min (C4), and a depth of cut of 1 mm (D1). According to the response table (Table 5), the levels of the variables (A_2, B_3, C_4, D_1) are the optimum levels for minimum Ra. This can also be observed from the main effect plot for the S/N ratios presented in Figure 4.

Table 4. The experimental surface roughness results and the calculated S/N ratio

Test Number	A	B	C	D	Surface roughness (μm)	S/N Ratio (dB)	Estimated Ra
1	1	1	1	1	3,00	-9,5482	4,28889
2	1	1	2	2	5,51	-14,8293	5,94434
3	1	1	3	3	8,00	-18,0618	9,05189
4	1	1	4	4	9,38	-19,4459	9,17234
5	1	2	1	1	3,13	-9,9220	4,23189
6	1	2	2	2	4,06	-12,1662	5,88734
7	1	2	3	3	8,24	-18,3207	8,99489
8	1	2	4	4	8,72	-18,8103	9,11534
9	1	3	1	2	4,08	-12,2217	4,23689
10	1	3	2	1	3,33	-10,4593	1,79044
11	1	3	3	4	7,73	-17,7681	8,04644
12	1	3	4	3	7,11	-17,0398	5,97189
13	1	4	1	2	7,03	-16,9366	4,74734
14	1	4	2	1	3,27	-10,3016	2,30089
15	1	4	3	4	8,61	-18,7001	8,55689
16	1	4	4	3	7,59	-17,6071	6,48234
17	2	1	1	4	9,63	-19,6689	8,11461
18	2	1	2	3	7,95	-18,0030	6,62161
19	2	1	3	2	6,37	-16,0773	5,78916
20	**2**	**1**	**4**	**1**	**1,91**	**-5,6116**	**2,76116**
21	2	2	1	4	9,94	-19,9460	8,05761
22	2	2	2	3	7,93	-17,9855	6,56461
23	2	2	3	2	6,53	-16,2983	5,73216
24	2	2	4	1	2,74	-8,7423	2,70416
25	2	3	1	3	3,63	-11,1981	4,91416
26	2	3	2	4	4,62	-13,2853	5,61616
27	2	3	3	1	2,13	-6,5529	1,63526
28	2	3	4	2	2,28	-7,1739	2,70916
29	2	4	1	3	3,57	-11,0631	5,42461
30	2	4	2	4	4,18	-12,4235	6,12661
31	2	4	3	1	2,34	-7,3992	2,14571
32	2	4	4	2	2,40	-7,6115	3,21961

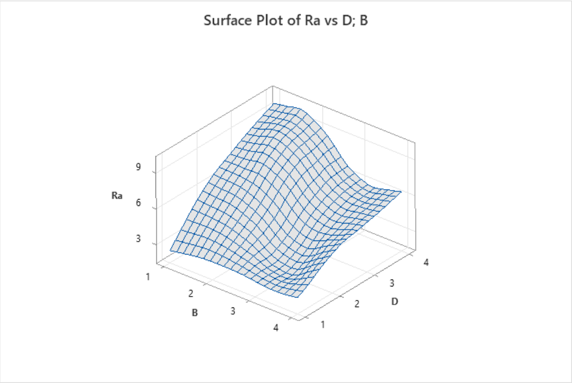

Figure 3. The effect of cutting factors on Ra

Table 5. Response table for Ra

Level	S/N ratio (dB)				Mean (µm)			
	A	B	C	D	A	B	C	D
1	-15,134	-15,156	-13,813	**-8,567**	6,176	6,468	5,502	**2,732**
2	**-12,440**	-15,274	-13,682	-12,914	**4,884**	6,411	**5,106**	4,783
3		**-11,962**	-14,897	-16,160		**4,365**	6,244	6,753
4		-12,755	**-12,755**	-17,506		4,875	5,267	7,851
Delta	2,694	3,312	2,142	8,939	1,293	2,103	1,138	5,118
Rank	3	2	4	1	3	2	4	1

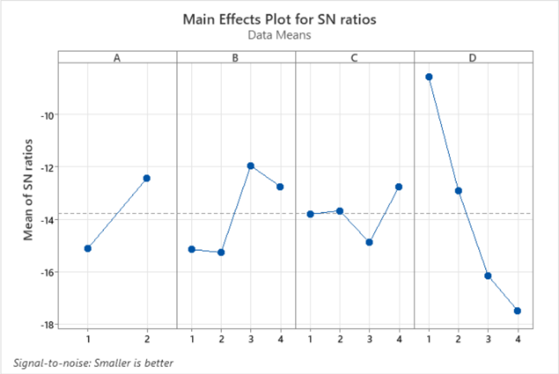

Figure 4. Response graph for S/N ratios of Ra

3.3 Analysis of Variance (ANOVA)

The primary objective of employing Analysis of Variance (ANOVA) in this study was to identify the significant effects of turning parameters on the performance characteristics of machined surfaces [16]. ANOVA was used to analyze the impact of cooling, cutting speed, feed rate, and cutting depth on surface roughness. The analysis was performed at a 5% significance level within a 95% confidence interval. The significance of each control factor was determined by examining the F-values assigned to them. A summary of the ANOVA results for surface roughness is presented in the table. Based on the evaluation of percentage contribution rates, cutting depth (a) emerged as the most significant factor influencing surface roughness, accounting for 57.97% of the total effect.

In summary, this study used ANOVA as a statistical tool to determine the significant effects of various turning parameters on surface roughness. The results presented in Table 6 highlight the significant impact of coolant usage on performance characteristics, emphasizing their dominant role in shaping the properties of the machined surfaces.

Table 6. Analysis of variance (Ra)

Source	**DF**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
A	1	6,35%	13,369	13,369	**6,75**	**0,017**
B	3	13,07%	27,532	9,177	**4,63**	**0,012**
C	3	2,88%	6,073	2,024	1,02	0,403
D	3	57,97%	122,136	40,712	**20,56**	**0,000**
Error	21	19,74%	41,583	1,980		
Total	31	100,00%				

3.4 Regression Analysis and Predictive Modeling

Regression analysis is an effective method for understanding and modeling the relationship between a dependent variable and one or more independent variables. In this study, regression analysis was applied to predict surface roughness, and equations were developed within the framework of a linear model. The linear equations derived for surface roughness are detailed in Table 7.

A linear regression model was developed to predict surface roughness based on machining parameters. These equations, formulated using a linear model, provide a quantitative basis for predicting surface roughness and are summarized in Table 7.

Table 7. Regression equation for Ra

Cooling 1 On/ 2 Off			
1	Ra (µm)	= 3,44 - 0,682 B + 0,043 C + 1,733 D	(2)
2	Ra (µm)	= 2,15 - 0,682 B + 0,043 C + 1,733 D	(3)

3.5 Fitted Plots Assessment

Figure 5 illustrates the goodness-of-fit chart, comparing the predicted Ra response values with the actual measurements. This chart visually depicts the discrepancies between actual and predicted values, with residuals closely aligning to the diagonal line. Such alignment indicates that the model effectively represents the data and demonstrates statistical significance. The calculated R^2 value for Ra responses was 0.80, while the regression P-value from variance analysis was determined to be 0.00, confirming the statistical validity of the model. The model exhibited strong correlation with experimental data, with an R^2 value of 0.80. These results underscore the reliability of predictive modeling in machining optimization.

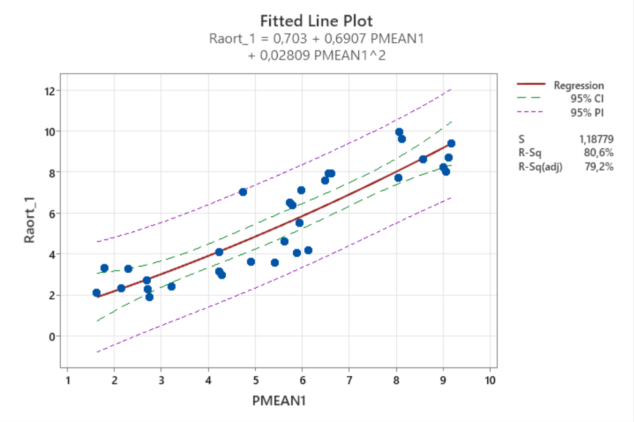

Figure 5. Comparison of the predicted values with the experimental results for the Ra output parameters

3.6 Verification Experiments and Determination of Quality Losses

The final phase of the Taguchi method involves conducting verification experiments and assessing quality losses to analyze quality characteristics [17]. These experiments primarily aim to validate the outcomes derived from the analysis. Verification tests are designed to evaluate specific combinations of factors and their levels, taking into account the cumulative effect of the control factors [18, 19]. Each factor's contribution is integrated into the total observed effect. In the Taguchi optimization process, performing at least one verification experiment is essential to confirm the reliability of the optimized conditions [20]. This rephrased sentence maintains the original meaning but uses a different structure to enhance originality. Therefore, considering the individual effects of the control factors, the minimum surface roughness value (Rac) for the optimal combination $A_2B_3C_4D_1$ (A_2 = dry cutting, B_3 = 225 m/min, C_4 = 0.3 mm/min, D_1 = 1 mm) is calculated using the following equations [21].

$$\eta_g = \overline{\eta_g} + (A_2 - \overline{\eta_g}) + (B_3 - \overline{\eta_g}) + (C_1 - \overline{\eta_g}) + (D_2 - \overline{\eta_g}) \tag{6}$$

$$Ra_C = 10^{-\eta_g/20} \tag{7}$$

Here, A_2, B_3, C_4, and D_1 represent the optimal levels of the factors and their corresponding S/N ratios $\bar{\eta}_g$, denotes the average of the S/N ratios for all factors, while η_g is the S/N ratio calculated for the optimal levels. Based on these measurements, the minimum surface roughness value (Ra_c) is determined to be 1.76 µm. In order to verify the accuracy of this quality characteristic, a confidence interval (CI) is employed during the verification experiments. This interval indicates the range within which the true mean likely resides, given a particular level of confidence. The CI used for predicting the optimal values is calculated using the following equation [22-23].

$$CI = \sqrt{F_{\alpha;1;v_e} x V_{ep} x \left(\frac{1}{n_{eff}} + \frac{1}{r}\right)} \tag{8}$$

In this context, $F_{\alpha:1}$, V_{ep} represents the F ratio of the significance level α, where α denotes the significance level, 1-α defines the confidence interval. Additionally, V_e refers to the error's degree of freedom, V_{ep} indicates the error variance, r stands for the number of validation experiments conducted, and n_{eff} is the count of results measured effectively [22].

$$n_{eff} = \frac{N}{1+[V_t]} \tag{9}$$

In this context, N represents the total number of experiments (32), and Vt calculated based on Table 5, is the total degrees of freedom for the processing parameters (10). Accordingly, neff is calculated as 2.909 [24]. In the 95% confidence interval assessment for surface roughness, considering α = 0.05 and Ve = 21, the value of Fα:1, Ve = 4.32 is obtained from the table. Using Equations (8) and (9), the confidence interval (CI) is calculated as 2.430. The result of the verification experiments for surface roughness, with a 95% confidence interval, is expected to fall between (1.76 ± 2.43) µm, or between -0.670 and 4.189 µm. To assess the performance of the experimental studies conducted in this research, three verification tests were performed under the optimal conditions. These tests, carried out at the optimal parameter levels (A2B3C4D1), yielded surface roughness values of 1.86, 1.86, and 1.92 µm, resulting in an average value of 1.88 µm.

Table 8. Comparison of surface roughness and S/N ratio combinations

	Level	Ra (µm)	S/N (dB)
Initial combination	$A_2B_1C_4D_1$	1,91	-5,61
Optimal combination (experimental)	$A_2B_3C_4D_1$	1,88	-5,48
Optimal combination (prediction)	$A_2B_3C_4D_1$	1,76	-4,91

Table 8 presents a comparison of surface roughness values derived from both experimental and predicted optimal combinations. From a total of 32 experiments, the $A_2B_1C_4D_1$ combination was chosen as the baseline. According to Table 8, the roughness value improved from 1.91 µm to 1.88 µm, reflecting a 1.6% enhancement in accuracy due to the optimal combination ((1.91-1.88)/1.91). Table 9 showcases the performance differences between the initial and refined conditions. The validation experiments yielded an average ranging from -0.670 to 4.189 µm, placing the 1.88 µm value within the anticipated scope. This indicates the substantial accuracy and significance of the control factors in this study.

Table 9. Performance comparison between the initial and optimal combinations

	Initial combination	Optimal combination	
		Prediction	Verification
Level	$A_2B_1C_4D_1$	$A_2B_3C_4D_1$	$A_2B_3C_4D_1$
Ram (µm)	1,91	1,76 ± 2,43	1,88
Quality loss			%2,56

As indicated in Table 9, the quality characteristic of this experiment has seen an enhancement from 1.91 µm ($A_2B_1C_4D_1$, the initial combination) to 1.88 µm ($A_2B_3C_4D_1$, the revised optimal combination). The decrease in quality losses for surface roughness between these combinations is quantifiable through a quality loss ratio. This ratio is based on a function stating that a 3 dB improvement in quality halves the loss. The specifics of this quality loss function are derived from the formula outlined in reference [25].

$$\frac{L_{opt}(y)}{L_{ini}(y)} \approx \left(\frac{1}{2}\right)^{\Delta\eta/3} \tag{10}$$

In this analysis, $L_{opt(y)}$ and $L_{ini(y)}$ denote the optimal and initial combinations, respectively. Δη signifies the difference in the S/N ratios between these combinations. Specifically, the change in the S/N ratios observed in the validation experiments, used to assess the quality loss of the optimal combination, is identified as 0.13 [Δη = 0.13 (= -5.48 – (-5.61))]. The quality loss for the validation test is computed as 0.029 according to Equation (10). Consequently, the quality loss associated with the optimal combination constitutes only 2.9% of that recorded for the initial combination. Thus, through optimization using the Taguchi method, the quality loss concerning surface roughness has been decreased by 97.1%.

4. CONCLUSION

This study successfully optimized the surface roughness of AISI 1050 steel during CNC turning using the Taguchi method. The key findings are as follows:

According to the experimental results, the optimum combination of surface turning parameters was found to be $A_2B_3C_4D_1$ (A_2 = dry machining, B_3 = 225 m/min, C_2 = 0.3 mm/rev, D_1 = 1 mm).

The optimal machining combination for minimum surface roughness is dry machining at 225 m/min cutting speed, 0.3 mm/min feed rate, and 1 mm depth of cut.

Consistent with Avcı et al. (2024), this study also found that depth of cut was the most influential factor affecting surface roughness, accounting for 57.97% of the total effect.

The Taguchi method effectively reduced quality losses associated with surface roughness by 97.1%.

As a result of the conducted experiments, the initially selected surface roughness value of 1.91 µm was reduced to 1.88 µm through confirmation tests carried out under optimum conditions.

When all experiments were examined, it was observed that the highest surface roughness (Ra = 9.94 µm) was obtained under dry machining conditions at a cutting speed of 190 m/min, a feed rate of 0.15 mm/rev, and a depth of cut of 2.5 mm.

Future research may explore advanced cooling strategies and their impact on machining performance to further enhance surface quality.

These findings have practical significance for machine manufacturers using AISI 1050 steel in their production processes. Determining the optimum surface machining parameters to improve the surface roughness of AISI 1050 material used in manufactured machines reduces the need for secondary operations such as grinding or polishing, thereby decreasing production time and costs. These parameters are directly applicable, particularly in the manufacturing of shafts and mold parts where surface quality is critical. In conclusion, the optimum machining parameters identified in this study enhance surface quality, contribute to production efficiency, and support achieving sustainable quality targets in machine manufacturing processes.

5. ACKNOWLEDGEMENT

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