Vidhyayana - ISSN 2454-8596
An International Multidisciplinary Peer-Reviewed E-Journal
www.vidhyayanaejournal.org
Indexed in: Crossref, ROAD & Google Scholar

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Experimental Research on Surface Roughness and Tool Life for Machining of AISI 4340 ALLOY STEEL

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Abstract

In today's fiercely competitive market landscape, the expectations of customers are shifting towards a strong emphasis on the superior quality and longevity of critical components such as automotive drive shafts, power transmission shafts, and other torque-bearing shafts. The reliability of these components is paramount, especially as they are subjected to rigorous operational stresses. Within the realm of modern CNC milling operations, two key performance indicators that significantly impact the manufacturing process are tool life and surface roughness, commonly denoted as Ra. Both of these factors are essential in determining the overall efficiency and quality of machining processes. To gain a deeper understanding of these factors, a comprehensive experimental analysis was conducted. This study systematically examined various machining parameters, which included the feed rate (f), the cutting speed (N), the depth of cut (d), tool life, and surface roughness (Ra). Each of these parameters plays a critical role in influencing the outcome of the CNC milling process. The experimental

framework was designed using a 3^3 factorial model, which facilitated an in-depth exploration of the relationships between these machining variables and their combined effects on tool life and surface finish quality. To identify the optimal values for the parameters under investigation, advanced statistical tools were employed. Main effects plots and contour plots, derived through the renowned Taguchi method, were utilized to visually represent the impact of the machining conditions on the response variables. These graphical analyses allowed for the precise determination of optimal conditions that maximize tool life while minimizing surface roughness. Furthermore, to enhance the predictive capabilities of the analysis, regression equations were developed based on the empirical data obtained from the experiments. These equations serve as valuable tools for predicting the outcomes of future machining processes, providing a mathematical model to estimate tool wear and surface quality based on the input parameters.

Keywords: CNC milling, AISI 4340 alloy steel, Surface roughness, Tool life, Taguchi method

I. INTRODUCTION

In industrial environments, raw materials typically undergo a series of transformative processes such as casting, machining, forming, and joining before they are shaped into fully finished products. Each of these stages plays a critical role in determining the overall quality, durability, and functionality of the final component. Among these, machining stands out as a widely used material removal technique, where material is selectively taken away from the raw stock to achieve desired shapes and dimensions. In modern manufacturing settings, computer numerical control (CNC) machines have revolutionized machining by enabling precise control, high-quality surface finishes, and reduced production times with minimal manual intervention.

This study primarily focuses on milling, a specific machining operation that involves the use of multi-point cutting tools to efficiently remove material from a work piece. Milling is often favored for its ability to minimize processing time while ensuring tight tolerances and smooth surface finishes. Key performance indicators during the milling process include surface roughness, tool wear, power consumption, and tool life, each of which plays a vital role in assessing the overall efficiency and quality of the operation. These indicators are influenced by a variety of machining parameters, such as spindle speed, lubrication, feed rate, and cutting depth. Fine-tuning these parameters can have a significant impact on the outcomes of the milling process, especially in terms of tool longevity and surface quality.

The experiment at hand delves into the effects of these critical variables, particularly focusing on how they affect surface roughness and tool longevity. Surface roughness, a measure that is often expressed in terms of Ra (average roughness) or Rz (mean peak-to-valley height), is a crucial determinant of the final product's quality and durability. In engineering applications, poor surface finishes can lead to defects or weaknesses in the component, ultimately resulting in part failure under stress. Thus, achieving an optimal surface finish is essential for ensuring the long-term performance and reliability of the part.

Similarly, tool life is another essential metric, typically measured by the volume of material removed per unit of time (mm^3/min). It serves as a key indicator of production efficiency, as extended tool life can reduce downtime, lower costs, and improve overall workflow in industrial settings. A longer tool lifespan enables manufacturers to streamline their processes and meet project timelines more effectively, making it a critical factor in the pursuit of cost-effective, high-quality production outputs. By understanding and optimizing the interactions between spindle speed, lubrication, feed rate, and cutting depth, industries can better control these metrics to enhance both the quality of their products and the efficiency of their manufacturing processes.

II. LITERATURE REVIEW

K. Someswara Rao (2017) [1] A detailed and thorough analysis was conducted to investigate the machining process parameters that influence Niobium C-103 material during dry machining operations, using PVD-coated insert tools. The primary variables evaluated in the study included depth of cut, cutting speed, and feed rate, each of which plays a crucial role in determining the surface roughness of the material. The findings revealed a significant quadratic relationship between surface roughness (Ra) and the range of cutting speeds (80 to 90 m/min), depths of cut (0.3 to 0.6 mm), and feed rates (0.08 to 0.2 mm/rev). It was clearly demonstrated that an increase in feed rate caused a noticeable rise in surface roughness, highlighting feed rate as the most influential parameter in the process. While depth of cut and cutting speed also contributed to variations in surface roughness, their effects were comparatively less pronounced. The study identified the optimal machining parameters for achieving the lowest surface roughness as a cutting speed of 90 m/min and a depth of cut of 0.42 mm. This research offers valuable guidance for enhancing machining performance and surface quality in Niobium C-103 processing, contributing to improved efficiency and product quality in related applications.

Dr. Vijay Kumar (2018) [2] An in-depth analysis of variance (ANOVA) was conducted on turning operations for EN19 stainless steel, employing Taguchi's L18 orthogonal array to examine the effects of various machining parameters. The input variables analyzed in the study included spindle speed, depth of cut, lubrication type, and feed rate, while surface roughness and material removal rate (MRR) were selected as the primary response variables. The results from the analysis of the main plots clearly indicated that MRR exhibited a significant increase with higher feed rates, faster spindle speeds, and greater cutting depths, particularly when wet machining conditions were applied. On the other hand, surface roughness was found to improve, or decrease, as spindle speed and cutting depth were increased, while a reduction in feed rate also contributed to a smoother surface finish under wet conditions. The findings underscored the fact that feed rate and spindle speed emerged as the most critical factors influencing both MRR and surface roughness. In contrast, the depth of cut and the use of lubrication had a relatively smaller, though still relevant, impact on the overall outcomes. This research provides valuable insights for optimizing turning operations on EN19 stainless steel, helping manufacturers to enhance material removal rates, achieve better surface finishes, and ultimately improve machining efficiency and product quality.

M. Nalbant's (2007) [3] A comprehensive study was carried out on CNC turning operations using TiN-coated cutting tools on AISI 1030 carbon steel, applying the Taguchi method to analyze the effects of three critical process variables: nose radius, depth of cut, and feed rate. Following the initial experiments, confirmation tests were conducted to identify the optimal machining parameters for achieving the best surface quality. The analysis of the collected experimental data revealed that both feed rate and nose radius played a significant role in determining surface roughness. The optimal surface roughness value was attained with a nose radius of 1.2 mm, a feed rate of 0.15 mm/rev, and a cutting depth of 0.5 mm.

In a separate analysis, Ilhan Asiltürk (2016) developed a regression model using Statistical 10 software to predict surface roughness during CNC machining. This model was constructed using response surface methodology, based on data from experiments performed with a Taguchi L27 orthogonal array. The primary input variables included depth of cut, spindle speed, tool tip radius, and feed rate. The results indicated that feed rate and tool tip radius were the most influential factors affecting surface roughness, having the most substantial impact on the outcome. This regression model provides valuable insights for improving machining processes by offering a predictive tool that helps manufacturers better control machining parameters to achieve optimal surface finish quality. This combination of experimental findings and regression modeling offers a robust framework for refining CNC machining practices, leading to improved surface finishes and overall process efficiency.

Ilhan Asiltürk (2016) [4] A regression model was developed using Statistical 10 software to predict surface roughness in CNC machining. The model was built using response surface methodology, based on experiments conducted with the Taguchi L27 orthogonal array. The key input variables included depth of cut, spindle speed, tool tip radius, and feed rate. The analysis showed that feed rate and tool tip radius had the most significant impact on surface roughness, influencing the response the most. This regression model offers valuable guidance for optimizing machining processes, enabling better control over parameters to achieve the desired surface finish quality.

S.P. Palaniappan et al. (2020) [5] An experiment was carried out to examine the factors affecting the material removal rate (MRR) and surface roughness (Ra) of aluminum 6082 alloy during CNC turning operations, using a tungsten carbide cutting tool. The study focused on three key input variables: spindle speed (800 to 1600 rpm), depth of cut (0.15 to 0.25 mm), and feed rate (1 to 2 mm/rev). The influence of these parameters was evaluated using the Taguchi method combined with ANOVA analysis to identify their impact on the turning process.

III. METHODOLOGY

Turning is a widely employed machining process wherein a multi-point cutting tool removes material from a rectangular work pieces. To evaluate machine performance, various methods exist, with measuring surface roughness and tool life being the most prevalent. Achieving optimal results entails conducting experiments with different values of selected parameters to determine their effects.

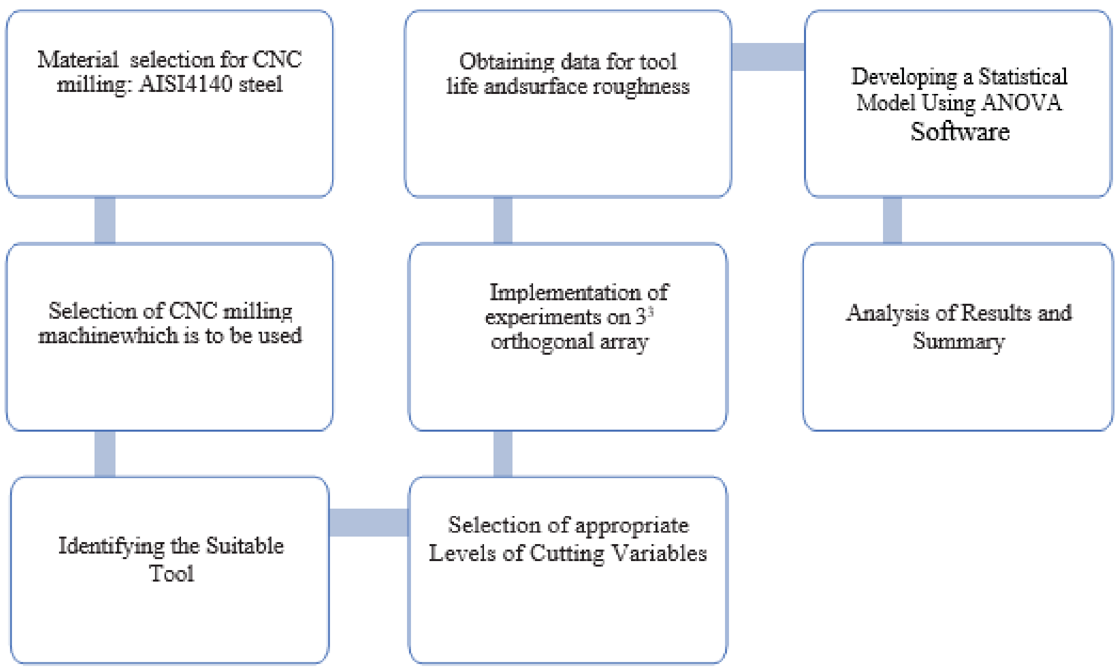

Figure 1: Flow diagram of the research plan

Work piece Material: AISI4140 Steel

In this study, we opted to use high-quality quenched and tempered AISI 4140 medium carbon steel with a hardness of 325 Brinell for our experimental investigations. Rectangular samples measuring 250 × 200 × 20mm were prepared for the experiments. The chemical composition of the material, including the proportions of its various elements, is detailed in Table 1

TABLE 1. AISI4140 Steel Carbon steel chemical composition

Composition	Carbon	Silicon	Manganese	Chromium	Phosphorous	Sulphur
Percentage (%)	0.33	0.93	1.20	0.025	0.031	0.40

The mechanical properties of materials, such as strength, are typically assessed through tests conducted using compression and tensile testing machines. These tests provide valuable data regarding the material's behavior under different loading conditions. Table 2 presents the observed values obtained from these tests, offering insights into the material's strength characteristics

TABLE 2. AISI4140 Steel's Mechanical properties

Properties	Unit	Marked Value
Ultimate Tensile strength	MPa	655
Yield strength	MPa	415
Brinell Hardness	BHN	197
Elongation	(%)	25.70

Computer Numerical Control (CNC) Milling Machine

CNC milling tests were performed on the Macpower Mono MX-250 machine under wet cutting conditions, in accordance with the tool manufacturer's recommendations for the specific material being processed. Wet cutting, which involves the application of coolant or lubricant during machining, is commonly preferred due to its ability to enhance tool life, improve surface finish, and aid in efficient chip removal, particularly with challenging materials. By adhering to the manufacturer's guidelines, the tests ensured that the machining process achieved optimal

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performance while extending the durability of the cutting tools, leading to more consistent results and greater efficiency throughout the operation.

Figure 2: Macpower LX250 milling

Figure 3: Machined Work pieces

Approach by Taguchi

The Taguchi method employs balanced array tests to reduce variations when evaluating control parameters affecting experiments. This technique refines experimental designs to enhance parameters and achieve targeted results. The practical range of cutting parameters, including spindle speed (m/min), cut depth (mm), and feed rate (mm/rev), was determined based on guidelines from the machining handbook.

TABLE 3. Machining Variables and Their Levels

Parameters	Unit	Level I	Level II	Level III
Cutting Speed	rpm	50	75	100
Feed rate	mm/rev	0.10	0.20	0.30
Depth of Cut	mm	0.3	0.4	0.5

Measurement of Responses

Roughness pertains to the fine, closely spaced micro-irregularities found on surfaces, contrasting with waviness, which involves more regularly spaced and larger deviations resulting from factors such as work deflection, vibration, and heat treatment. Roughness typically overlays waviness, adding another layer of surface irregularity. Tool life is defined as the period between two successive grindings of a cutting tool and can be assessed in several ways. These include counting the number of workpieces machined before the tool needs sharpening, measuring the actual operational time (i.e., the duration the tool is in contact with the workpiece), recording the total operational time, evaluating the equivalent cutting speed, and calculating the volume of material removed before the tool requires sharpening.

- Number of work pieces machined before tool sharpening is required.
- Duration of actual machining operation, indicating the time the tool remains in contact with the work pieces
- Total machining time, encompassing all operations from start to finish.
- Equivalent cutting speed, a measure reflecting the combined effect of various cutting parameters on machining efficiency
- Volume of material removed before tool sharpening becomes necessary, indicating the extent of wear on the cutting tool

Taylor Extended Tool life Equation

$V \times T^{n} \times f^{n1} \times d^{n2} = k$

Where, T = Tool Life in min , f = Feed Rate in mm per revolution

d = Depth Of Cut in mm,

n = Tool constant for solid carbide 0.25(from tool manufacturer's data book)

n1= feed exponent constant= 0.5 (from tool manufacturer's data book)

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n2= depth of cut exponent constant = 0.20 (from tool manufacturer's data book)

k = constant= 47 (from tool manufacturer's data book)

Tool life = $\frac{k^{\frac{1}{n}}}{V^{\frac{1}{n}} X\, k^{\frac{n1}{n}} X\, k^{\frac{n2}{n}}}$

IV RESULTS AND DISCUSSIONS

The experimental sets and their corresponding response values with units are detailed in Table 4.

TABLE 4: Experimental Combination for 3^3 Design

Exp. No.	Cutting speed (m/min)-A	Feed (mm/rev)-B	Depth of cut (mm)-C	Tool life (min)	Surface Roughness
1	50	0.10	0.30	204.55	1.9532
2	50	0.10	0.40	162.5	1.9823
3	50	0.10	0.50	135.93	2.053
4	50	0.20	0.30	3.196	1.8821
5	50	0.20	0.40	40.62	1.9031
6	50	0.20	0.50	33.98	1.9232
7	50	0.30	0.30	22.72	1.8502
8	50	0.30	0.40	18.05	1.8621
9	50	0.30	0.50	15.104	1.8727
10	75	0.10	0.30	40.406	1.8023
11	75	0.10	0.40	32.09	1.8300

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12	75	0.10	0.50	26.85	1.8347
13	75	0.20	0.30	10.101	1.6505
14	75	0.20	0.40	8.02	1.6812
15	75	0.20	0.50	6.712	1.7042
16	75	0.30	0.30	4.489	1.3540
17	75	0.30	0.40	3.566	1.4020
18	75	0.30	0.50	2.983	1.4502
19	100	0.10	0.30	12.78	1.2852
20	100	0.10	0.40	10.156	1.2932
21	100	0.10	0.50	8.496	1.3250
22	100	0.20	0.30	3.196	1.1520
23	100	0.20	0.40	2.539	1.2523
24	100	0.20	0.50	2.124	1.2720
25	100	0.30	0.30	1.42	0.9842
26	100	0.30	0.40	1.128	1.0225
27	100	0.30	0.50	0.944	1.1032

Analysis of Variance (ANOVA)

Variance analysis examines how machining variables affect response metrics such as surface roughness and tool life. It determines the importance of these variables by evaluating the p-value at a 95% confidence level ($\alpha = 0.05$). A p-value below 0.05 suggests that the machining variable significantly influences the response, whereas a p-value above 0.05 indicates that the variable has a negligible impact.

V. SURFACE ROUGHNESS IMPACT

The ANOVA results for surface roughness, as shown in Table 5, reveal that cutting speed has a major impact on surface roughness. This is evident from the p-values for cutting speed, which are all below 0.05 at a 95% confidence level. In contrast, the feed rate and depth of cut show minimal influence on surface roughness, as their p-values are above 0.05.

TABLE 5: ANOVA analysis for surface roughness

Source of Variation	Sum of Square	Degree of Freedom	Mean Square	F	p-value	Significant/Insignificant
A	2.45311	2	1.22656	2471.46	0.00001	significant
B	0.34185	2	0.17093	344.41	0.090	Insignificant
C	0.02167	2	0.01083	21.83	0.235	Insignificant
AB	0.07174	4	0.01794	36.14	0.130	Insignificant
AC	0.00143	4	0.00036	10.50	0.432	Insignificant
BC	0.00101	4	0.00025	9.25	0.619	Insignificant
Pure Error	0.00794	8				
Total	2.89632	26				

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Percentage contribution

The percentage contribution for each factor is calculated as follows.

Cutting speed (A) $= \frac{2.45311}{2.89632} \times 100 = 85\ \%$

Feed (B) $= \frac{0.17093}{2.89632} \times 100 = 5\ \%$

Depth of cut (C) $= \frac{0.01083}{2.89632} \times 100 = 0.37\ \%$

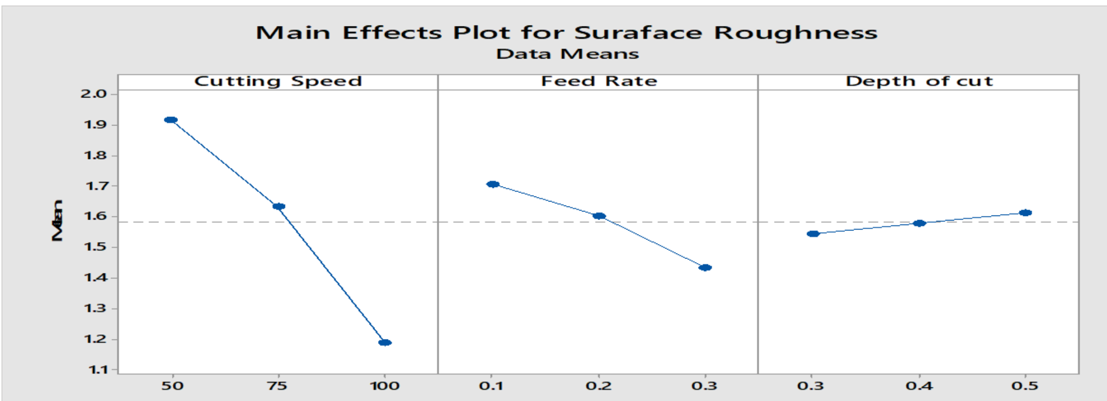

Figure 4: Effect plot for Surface roughness

The main effect plot for surface roughness, shown in Figure 4, indicates that surface roughness is lowest at the high cutting speed of 100 rpm, with roughness values increasing as the cutting speed is reduced. Similarly, for feed rate, surface roughness is minimized at the lower feed rate of 0.10 mm/rev and increases to its highest value at 0.3 mm/rev.

3^3 DESIGN MODEL FOR SURFACE ROUGHNESS

The Surface roughness regression model is given by the equation below

1.58076 + 0.33945 Cutting Speed_50 + 0.05358 Cutting Speed - 0.005261 Speed x Feed rate + 0.003017937 Speed x Depth of cut - 0.00020367 Feed rate x Depth of cut.

VI. EFFECT ON THE TOOL LIFE

The ANOVA results shown in Table 6 reveal that cutting speed and feed rate have a significant impact on tool life, as their p-values are below 0.05 at a 95% confidence level. In contrast, the depth of cut has a negligible effect on tool life, indicated by a p-value greater than 0.05.

TABLE 6: ANOVA Evaluation for Tool Life

Source of Variation	Sum of Square	Degree of Freedom	Mean Square	F	p-value	Significant/ Insignificant
A	22691.0	2	11345.5	74.37	0.00015	significant
B	21955.0	2	10977.5	71.96	0.00016	significant
C	278.6	2	139.3	0.91	0.936	Insignificant
AB	22051.9	4	5513.0	36.14	0.567	Insignificant
AC	1222.5	4	305.6	2.00	0.090	Insignificant
BC	169.3	4	42.3	0.75	0.065	Insignificant
Pure Error	1830.6	8				
Total	70029.6	26				

PERCENTAGE CONTRIBUTION

The percentage contribution for each factor is calculated as follows.

Cutting speed (A) $= \frac{22691}{70029.6} \times 100 = 32\ \%$

Feed (B) $= \frac{21955}{70029.6} \times 100 = 31.35\ \%$

Depth of cut (C) $= \frac{278}{70029.6} \times 100 = 0.37\ \%$

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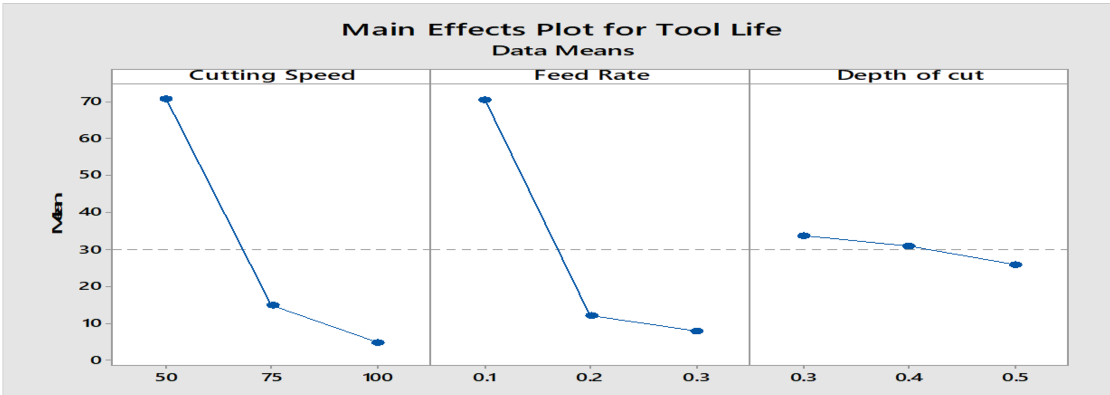

Figure 5: Effects plots for tool life

According to the main effect plot depicted in Figure 5 for tool life, it is evident that for cutting speed, tool life reaches its minimum at a lower level of 50 rpm, with its value increasing as the cutting speed decreases. Similarly, for feed rate, tool life is at its minimum at the lower level of 0.10 mm/rev and reaches its maximum at 0.3 mm/rev.

3^3 DESIGN MODEL FOR SURFACE ROUGHNESS

Tool life regression model is given by the equation below

207.2 - 1.320 Cutting Speed - 313.0 Feed Rate - 38.7 Depth of cut 0.9261 Speed*Feed rate + 0.05017937 Speed *Depth of cut - 0.70367 Feed rate*Depth of cut

VERIFICATION

TABLE 7: Comparison of predicted and experimental values for Surface roughness

	Exp No	Predicted	Experimental
Surface Roughness in Micron	1	1.9823	1.8832
	2	1.2823	1.3095

TABLE 8: Comparison of Predicted and Actual Tool Life Values

	Exp No	Predicted	Experimental
Tool life	1	32.09	35.09
	2	58.09	63.23

VII. CONCLUSION

An analysis of CNC milling operations was performed on AISI 4340 alloy steel to evaluate surface roughness and tool life. The study employed the Taguchi method with a 3^3 orthogonal array to examine how different machining parameters—cutting speed, cut depth, and feed rate—affect these response variables. The effects of each parameter were assessed using ANOVA, and main effect plots were created to analyze how each variable impacts the response and to identify optimal operating conditions. Additionally, regression equations were formulated to predict the response values based on the input parameters.

The main effect plot for surface roughness indicated that the lowest roughness occurs at a cutting speed of 100 rpm, with roughness increasing as the cutting speed is reduced. For feed rate, surface roughness is lowest at 0.10 mm/rev and highest at 0.3 mm/rev. In terms of tool life, the main effect plot showed that tool life is shortest at a cutting speed of 50 rpm and increases as the speed decreases. Tool life also reaches its minimum at a feed rate of 0.10 mm/rev and its maximum at 0.3 mm/rev.

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