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Taguchi-based experimental study on surface roughness of EN31 steel in turning operations

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Abstract - This work investigates the influence of turning process parameters feed rate, cutting speed, and depth of cut on the surface roughness of EN31 steel, a high-carbon alloy commonly used in automotive components and precision bearings. Hard-turning experiments, designed using the Taguchi L16 orthogonal array, were conducted with a Cubic Boron Nitride tool to evaluate process parameter variations. Analysis revealed that feed rate had the greatest influence on surface roughness (55.22%), followed by cutting speed (22.72%) and depth of cut (22.06%). Increased feed rates and cutting depths resulted in higher surface roughness, emphasizing the importance of parameter optimization. The optimal conditions produced a smoother surface, reduced variability, and minimized tool wear. The study highlights the combined effects of machining parameters and valuable guidance for improving hard-turning processes, supporting the development of predictive models for precise and economical manufacturing in industries such as aerospace and automotive.

Keywords - Design of Experiments, Taguchi, Optimization, ANOVA.

I. INTRODUCTION

Modern manufacturing industries such as automotive, aerospace, and precision engineering require superior surface quality. However, achieving optimal surface roughness (SR) remains challenging due to the interaction of machining parameters. Controlling SR enhances durability, reduces wear, improves assembly fit, and extends tool life, making it crucial for performance and product quality [1-2]. SR is essential to the aesthetics and performance of machined components, directly affecting fatigue resistance, friction, and wear. For hardened materials like EN31 steel, used in bearings, tools, and automotive parts, precise control of machining process parameters is critical due to its hardness and toughness. Turning is a crucial machining process for rotational parts, feed rate (FR), cutting speed (CS), and depth of cut (DOC) to achieve precise finishes, tolerances, and shapes [3-5].

Mehdi employed hybrid algorithms and the Taguchi method to optimize the FR, DOC, and noise radius (Rn), reducing surface roughness. Experiments with L9 orthogonal arrays have optimized cutting parameters for materials like stainless steel, cast iron, and AISI4140 steel in turning operations [6]. Vasikerappa et al. optimized critical parameters for TiC-coated carbide inserts in hard turning using an L27 orthogonal design and the technique of Taguchi to analyze SR and tool wear.

The study highlights hard turning as a sustainable process that minimizes tool usage and produces eco-friendly chips [7]. Umamaheswarrao et al., focus on cutting parameters to optimize SR. It was observed that SR varied with FR and that cutting forces increased with hardness and machining time [8]. Sai Ravi Kiran et al. optimized turning parameters for AA 6063 T6 aluminum using the Taguchi L9 array, enhancing SR and surface machining rate [9]. Modi used the Taguchi technique and ANOVA to analyze the effects of DOC, FR, and CS on mild steel, highlighting their impact on machining [10]. Kumar et al. applied Response Surface Methodology (RSM) to study SR in AISI H13 die steel, identifying CS, FR, Rn, and hardness as key factors, with minimal effect from DOC. Higher CS reduced SR, while increased FR worsened it [11]. Yaka et al. used the Taguchi technique on a CNC lathe to minimize average surface roughness (Ra). An L9 experiment showed that optimal conditions had the highest S/N value, with FR > DOC > CS in significance. SR rose with higher FR and DOC but dropped with increased CS [12]. Jacob et al. analyzed the CBN hard turning of EN31 steel, using Taguchi and regression analysis to study SR and chip morphology, identifying FR as the key factor [13,22]. Varma and Kaladhar achieved <0.618 μm surface roughness using cryo-treated PVD inserts and hybrid optimization, with feed rate and cutting speed as key factors [14].

Sharma and Kumar used high-modulus coated carbide tools for efficient turning. SR rose with FR, influenced by DOC and CS [15]. Tauseef and Verma used SN ratios and ANN to study cutting parameters, with a 3-2-1 model achieving strong predictive accuracy (R = 0.9923) [16]. Singh and Kumar analyzed cutting parameters using the Taguchi technique L9 array and ANOVA. FR greatly influenced SR, while the DOC impacted the surface machining rate [17]. Santosh Kumar et al. optimized EN-45 steel turning using Taguchi L16 and regression analysis, finding FR influenced SR while CS affected surface machining rate and tool wear [18]. Rajaparthiban et al. used Taguchi's DOE to optimize EN31 steel turning with carbide inserts. CS significantly influenced SR and tool wear [19]. Kumar et al. found ceramic tools, despite shorter tool life than CBN, significantly lowered tooling costs, with FR impacting tool life more than cutting speed [20,21].

Key machining parameters influencing SR in hard-turning are CS, FR, DOC, tool geometry, and material hardness, with secondary factors like tool wear and vibrations. Optimizing these parameters is essential for achieving a perfect balance between surface quality, productivity, and tool life. The Taguchi method predicts surface roughness and optimizes those parameters using regression analysis for a predictive model. This study applies the Taguchi technique to evaluate the effect of key parameters on SR in the hard-turning of EN31 material. Response surface methodology is used to carry out the optimization of PTAW process parameters [23]. Taguchi analysis is performed to optimise of process parameters and select the best range of each parameter. From ANOVA the optimised value of each process parameter for minimisation of defects are evaluated and validated by conducting experiments [24]. The findings aim to enhance process understanding, optimize machining parameters, and develop a predictive model for improved surface finish, reduced tool wear, and consistent machining quality.

II. MATERIALS AND METHODS

A high-carbon, chromium steel (AISI 52100) EN31 alloy steel known for its exceptional hardness and durability. This makes it an ideal material for producing precision anti-friction bearings, such as ball and roller bearings. Commonly referred to as "bearing steel," it offers excellent performance at room temperature and can withstand continuous operation up to 1200°C. Its cost-effectiveness and long service life further enhance its appeal. Widely used across various engineering applications, EN31 is a preferred material for aircraft bearings, CV joints, ball screws, gauges, knives, spinning tools, punches, and dies. In the industrial sector, it is particularly valued for manufacturing roller-bearing components, including brakes, cylinders, bearing bush, and conical needle rollers, due to its outstanding mechanical properties and reliability.

Table. 2.1. EN31 Steel: Elemental Composition and Percentages

C	Mn	Si	P	S	Cr
0.989	0.572	0.218	0.026	0.031	1.379

This study examines the hard-turning of EN31 steel with a CBN cutting tool, analyzing the impact of

DOC, CS, and FR on SR. The Taguchi technique with an L16 array is used to optimize parameters and minimize trials.

Surface roughness (SR) is evaluated using ANOVA to identify significant parameters. S/N ratio analysis in MINITAB 21.2 develops predictive models for optimizing machining parameters and improving surface finish.

Experimentation

In this experiment, we focus on three essential cutting parameters—cutting speed (CS), feed rate (FR), and depth of cut (DOC)—each examined at four distinct levels. Table 3.1 presents the carefully chosen input-cutting parameters along with their various levels, providing a structured framework for our analysis. This approach will help us gain valuable insights into the effects of these parameters on cutting performance.

Experimental Design for Machining Optimization Using the Taguchi Method: A Taguchi techniques L16 orthogonal array method was strategically employed to design experiments focused on optimizing cutting conditions. This approach aims to identify the best cutting parameters for minimizing surface roughness on bearing bush components. The details of this experiment's design for the input cutting parameters are presented in Table 3.2.

Table. 3.1. Process parameters for the experiments

Parameters	Level			
	A	B	C	D
CS	70	110	150	190
FR	0.04	0.08	0.12	0.16
DOC	0.1	0.2	0.3	0.4

Table. 3.2. Design of experiments run chart

S. N.	DOC (mm)	FR (mm/rev)	CS (m/min)
1	0.1	0.04	70
2	0.1	0.08	110
3	0.1	0.12	150
4	0.1	0.16	190
5	0.2	0.04	110
6	0.2	0.08	70
7	0.2	0.12	190
8	0.2	0.16	150
9	0.3	0.04	150
10	0.3	0.08	190
11	0.3	0.12	70
12	0.3	0.16	110
13	0.4	0.04	190
14	0.4	0.08	150
15	0.4	0.12	110
16	0.4	0.16	70

Experimental Workflow: The experiments were conducted on a hard-turning machine with linear guideways and a robust spindle, embodying precision and dynamic stiffness essential for machining materials at 60 HRC hardness.

EN31 steel, a high-carbon alloy respected for its exceptional hardness and wear resistance in bearing applications, was chosen to lead the way. The raw steel, originally 50 mm in diameter and 23 mm in length, was transformed to 43 mm using a Schaublin

CNC lathe, showcasing the power of innovation. Sixteen workpiece samples were prepared for this ground-breaking study. A CBN insert (CNGA 120408GN2 MBC020) with a 0.8 mm nose radius was employed, demonstrating superior performance for machining hardened materials, and paving the path for future advancements.

Precision was demonstrated by experimenting with all sixteen combinations of cutting parameters. The SR of the hard-turned-bearing bush components was meticulously measured using a profilometer, underscoring our commitment to excellence. Each measurement, taken before and after the hard turning of the bearing steel, reflects the pursuit of perfection in engineering craftsmanship.

Results and Discussion

Experimental result: Surface roughness was measured using a profilometer, and the results are summarized in Table 4.1.

Table. 4.1. Design of experiments run chart with Ra value

S. N.	DOC (mm)	FR (mm/rev)	CS (m/min)	Ra (µm)
1	0.1	0.04	70	1.291
2	0.1	0.08	110	2.059
3	0.1	0.12	150	2.369
4	0.1	0.16	190	3.0567
5	0.2	0.04	110	1.381
6	0.2	0.08	70	2.129
7	0.2	0.12	190	2.921
8	0.2	0.16	150	2.6891
9	0.3	0.04	150	1.597
10	0.3	0.08	190	2.842
11	0.3	0.12	70	2.357
12	0.3	0.16	110	2.516
13	0.4	0.04	190	2.611
14	0.4	0.08	150	2.9647
15	0.4	0.12	110	2.87
16	0.4	0.16	70	3.0926

Response table and main effect plots for S/N Ratios: The "smaller-is-better" criterion was chosen to determine optimal surface roughness conditions. Table 4.2 presents the response table for S/N ratios.

Table. 4.2. Response of S/N ratio

Level	DOC (mm)	FR (mm/rev)	CS (m/min)
A	-6.457	-4.111	-6.408
B	-6.549	-7.851	-6.298
C	-7.022	-8.17	-7.378
D	-9.102	-8.997	-9.046
Delta	2.645	4.886	2.748
Rank	3	1	2

Table 4.2 presents the average S/N ratio values, showing the range between maximum and minimum for each parameter, highlighting their impact on SR. Feed exhibits the highest range (4.886), followed by CS (2.748) and DOC (2.645), making FR the most significant factor. Higher S/N ratio values indicate optimal parameter settings for minimal surface roughness. From the response table and main effect plot (Fig. 4.1), the optimum parameters for minimum SR are CS (110 m/min), FR (0.04 mm/rev), and DOC (0.1 mm). ANOVA results in Table 4.3 detail each

parameter's percentage contribution to surface roughness.

Table. 4.3. ANOVA results for surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	C%
DOC	3	1.1098	1.1098	0.36994	8.72	0.013	22.06
FR	3	2.7765	2.7765	0.92551	21.83	0.001	55.22
CS	3	1.1419	1.1419	0.38065	8.98	0.012	22.72
Residual Error	6	0.2544	0.2544	0.0424			4.82
Total	15	5.2827					100
	S=0.2059	R^2=95.18 %	R^2(adj) =87.96%				

Fig. 4.1 Main effect plots for SN Ratios of SR

Fig. 4.1 depicts the Main Effects Plot for Signal-to-Noise (S/N) Ratios, assessing the influence of Depth of Cut (DOC), Feed Rate (FR), and Cutting Speed (CS) on process performance. The SN ratio is used to optimize the system by minimizing variation, with the goal in this case being smaller-is-better. In the DOC panel, the SN ratio steadily decreases as the DOC increases, indicating that larger depths result in worse performance. Thus, lower DOC levels, such as 0.1 or 0.2, are preferable. For the FR, a sharp drop in the SN ratio occurs between 0.04 and 0.08, followed by a gradual decline at higher levels. This indicates that the lowest feed rate (0.04) is optimal for reducing noise and variation. Lastly, the CS panel reveals relatively stable SN ratios between 70 and 110, followed by a sharp decline at higher CS. This suggests that lower CS, particularly 70 or 110, are more favorable to achieving better results.

Fig. 4.2 shows the Interaction Plot for Surface Roughness, highlighting the combined effects of Depth of Cut (DOC), Feed Rate (FR), and Cutting Speed (CS) on surface roughness (SR). Each panel of the graph highlights the interactions between two factors, while the third factor is represented through varying levels and symbols. Non-parallel lines in these panels indicate significant interactions, suggesting that the impact of one factor on SR is influenced by the levels of the other factor.

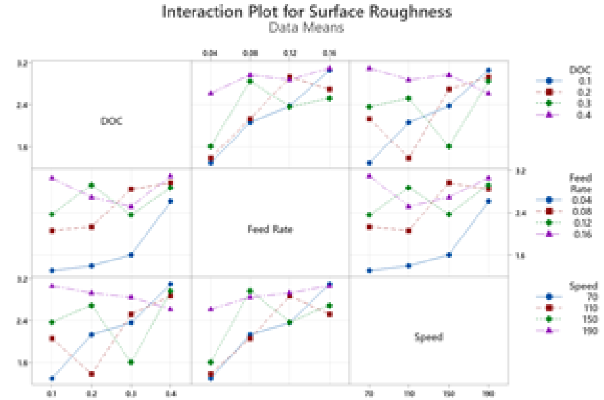

Fig. 4.2 Interaction plot for SR

In the interaction between DOC and FR, SR generally increases with FR, particularly at higher DOC levels (e.g., 0.4), showing a stronger interaction. Lower DOC values, combined with smaller feed rates (e.g., 0.04), result in smoother surfaces. For DOC and CS, surface roughness (SR) remains stable at lower DOC levels but increases sharply at higher CS (e.g., 190) when the DOC is also high. Similarly, the interaction between FR and CS reveals that surface roughness rises significantly at higher FR (e.g., 0.16) and CS (e.g., 150 or 190), whereas lower FR results in smoother surfaces across all speeds. The graph highlights that the factors cannot be optimized in isolation due to their interactions. Lower levels of DOC, FR, and CS (e.g., DOC = 0.1, FR = 0.04, CS = 70) generally lead to reduced surface roughness. This underscores the importance of considering the combined effects of parameters to achieve optimal process performance and minimize surface roughness.

Optimal results are achieved with lower DOC, minimal FR, and slower CS, underscoring the need to balance these factors holistically for consistent and smooth outcomes.

The ANOVA in Table 4.3 indicates that feed plays a critical role, contributing 55.22% to the surface roughness of the bearing bush. In addition, the depth of cut and cutting speed make valuable contributions of 22.06% and 22.72%, respectively. This data underscores the importance of focusing on feed, as it significantly influences the final surface quality of the bearing bush component. By prioritizing the optimization of feed, we can effectively enhance manufacturing outcomes and achieve superior results.

III. CONCLUSIONS

The hard-turning experiments conducted on an EN31 steel-bearing bush using a CBN insert reveal a remarkable journey toward excellence in machining. Through diligent study of the cutting parameters and their impact on surface roughness, we uncovered the optimal conditions that pave the way for superior results. The analysis, grounded in the principles of Taguchi's design of experiments and ANOVA, demonstrates that as we elevate the feed rate, there is a natural increase in surface roughness across various cutting speeds and depths. This discovery underscores feed as the most influential factor in enhancing surface quality.

By leveraging the Taguchi L16 orthogonal array and main effect plots, we were able to identify the ideal cutting parameters that achieve minimal surface roughness. These guiding recommendations of speed between 70-110 m/min, a feed rate of 0.04 mm/rev, and a depth of cut of 0.1 mm serve as benchmarks for excellence in machining.

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