Investigation of the Effect of Cutting Parameters on Surface Roughness in Dry Turning of Hardened Steel Using the Taguchi Method

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Abstract

In this experimental work, focuses on the investigation of the effect of cutting parameters on surface Roughness and to minimize surface roughness. A CNC lathe machine has conducted the experiments. Dry turning tests are carried out on hardened steel with coated carbide cutting tools. This study sought to give systematic and trustworthy techniques for manufacturers and engineers to efficiently optimize machining parameters, tool selection, and process conditions by using Taguchi Design Optimization. The experiments revealed that the most favorable combination of cutting parameters, which resulted in a minimum surface roughness of 2.6 μm, corresponded to a cutting speed (V) of 120 m/min, a feed rate (F) of 0.2 mm/rev, and a depth of cut (D) of 0.08 mm, yielding an S/N ratio of -8.29947. The utilization of coated tools has been identified as beneficial for enhancing the machining of hard materials when employing higher speeds and reduced feed rates. The findings from this research reveal that the feed rate plays a paramount role in influencing both Ra and Rz. Furthermore, it is noteworthy that the interplay between two factors, namely the feed rate and cutting speed, as well as the depth of cut and cutting speed, exerts notable effects.

Keywords
CNC Turning, Taguchi Method, ANOVA, Optimization, Surface Roughness

1. Introduction
A variety of difficult issues have evolved in modern manufacturing methods, notably with regard to the wear characteristics and performance of lathe tool inserts. Achieving superior surface quality is a critical objective within manufacturing industries as it significantly impacts the performance and functionality of mechanical components. Surface roughness, a crucial indicator of machined surface quality, holds relevance in engineering applications. Among the variety of materials employed in manufacturing, hardened steel is a popular choice due to its outstanding mechanical properties, durability, and widespread use across industries. Hence, the quest for optimizing surface roughness in the machining of hardened steel poses a significant challenge. This research holds particular importance due to the imperative to advance machining technology, especially when dealing with hard materials. As industries increasingly require components with elevated precision and superior surface characteristics, machining processes must adapt and improve accordingly.

The motivation for this study lies in the aspiration to enhance the surface quality of hardened steel components through the utilization of the Taguchi method in dry turning operations. The driving force behind this investigation stems from the pressing need to enhance machining methods, especially when dealing with demanding materials. The scientific community acknowledges that attaining the ideal surface roughness is a multifaceted task demanding meticulous examination and inventive methodologies. This research is driven by the prospect of offering a methodical and dependable strategy for improving the surface characteristics of hardened steel components. Employing Taguchi Design Optimization as a tool, this investigation aspires to furnish

manufacturers and engineers with valuable knowledge for efficiently and cost-effectively optimizing machining parameters, selecting suitable tools, and setting process conditions to attain the desired surface finish.

The machine of hardened steel holds a pivotal role in manufacturing, where the attainment of supreme surface quality is essential to ensure the functionality and durability of components. In this context, surface roughness stands out as a critical quality metric. This study seeks to explore the impact of cutting parameters, including cutting speed, feed rate, and depth of cut, on surface roughness during the process of dry turning. To facilitate this investigation, the Taguchi Design Optimization method is employed, offering a structured and efficient methodology for experimental design and optimization. Through this research, our objective extends beyond mere comprehension of the complex relationship between cutting parameters and surface roughness. We aim to provide pragmatic guidance for industrial utilization, thereby advancing machining processes and elevating product quality. Critical performance metrics are undeniably influenced by a spectrum of turning parameters, encompassing cutting speed, feed rate, depth of cut, material composition of the tool and workpiece, tool geometry, and factors linked to coolant conditions (Asiltürk and Akkuş 2011). Even with notable progress in machining technology, attaining the targeted surface roughness in the dry turning of hardened steel continues to pose a substantial challenge. The examination included the measurement of surface roughness and tool wear to assess the impact of different cutting parameters (Debnath et al. 2016).

The challenges arising from material characteristics, tool wear, cutting variables, and cooling requirements call for an all-encompassing strategy. This study delves into the following inquiry: "How can we utilize the Taguchi Design Optimization method to optimize surface roughness in the dry turning of hardened steel, aligning with the industry's call for heightened quality, efficiency, and cost-effectiveness?" This research aims to explore viable resolutions to this challenge by assessing the effectiveness of the Taguchi Design Optimization as a potent instrument to enhance surface quality during the processing of hardened steel.

1.1 Objectives

The primary goal of this experimental work is to perform a systematic and complete investigation of the optimization of surface roughness in the context of hardened steel dry-turning processes. To begin, it aims to improve the quality of machined surfaces, particularly on hardened steel workpieces, by systematically identifying and optimizing critical machining parameters, tool geometries, and process conditions. Concurrently, the research aims to reduce the negative impacts of tool wear, a significant issue in machining, by optimizing cutting parameters. The study tries to untangle the deep interdependencies among many parameters impacting surface roughness by leveraging the rigorous statistical techniques given by the Taguchi approach. The research's ultimate goal is to increase the competitiveness of manufacturing companies by promoting effective, long-lasting, and affordable methods of achieving superior surface finishes during dry-turning operations.

2. Literature Review

This research paper fulfills a critical role by providing a structured framework to contextualize and underscore the importance of this study. It navigates the intricate terrain of machining, specifically the dry turning of hardened steel, with a focused lens on surface roughness enhancement. In this review, we embark on a journey through historical developments, theoretical foundations, prior research insights, and the application of Taguchi design methodology, all of which collectively contribute to the foundation upon which this research is built. Machining techniques have evolved significantly as a result of the quest of ideal surface finishes (Yadav et al. 2012). The pursuit of such remarkable precision is a demanding undertaking, and when dealing with the machining of hardened steel, it presents an especially intricate challenge. It requires a profound understanding of the historical progression of machining practices. By revisiting the historical evolution of these methods, the review not only offers a historical context for the research but also underscores the vital role of improving surface quality in shaping contemporary machining techniques. To attain decreased surface roughness, a combination of a reduced feed rate and elevated cutting speed is necessary (Sahu and Choudhury 2015).

To gain a more profound understanding of the study's basis, the review moves on to explain the theoretical fundamentals of both machining and surface roughness. This theoretical clarification aims to furnish the reader with the necessary insights for better comprehension of the research's complexities. It underscores the significance of theoretical mastery in the quest to optimize surface roughness, particularly in the demanding context of hardened steel (Osman et al. 2018). By assimilating the collective wisdom from past scholarly endeavors in the realm of turning hardened steel and surface roughness improvement, this synthesis offers a panoramic view of the methodologies employed and the consequential findings achieved. Taguchi's orthogonal arrays are efficient fractional designs, enabling the estimation of main effects with a minimal number of experimental trials. They are versatile and not limited to two-level factorial experiments; they can effectively explore main effects even when factors have multiple levels. Moreover, these designs offer a solution for investigating the main effects in mixed-

level experiments where the factors exhibit varying levels (Manivel and Gandhinathan 2016). They employed the Taguchi method to enhance surface quality and increase material removal rates during the hard turning of hardened steel by optimizing cutting parameters. Our findings indicate that elevating the tool's feed rate results in a corresponding rise in component surface roughness. Additionally, when operating at high cutting speeds and increased feed rates, we observed improvements in material removal rates (Karthik et al. 2020).

The literature review culminates by succinctly articulating the specific research objectives and hypotheses that serve as guiding stars for this study. In doing so, it underscores the research's weighty significance and accentuates its findings' transformative potential. In sum, this section assumes the role of a scholarly compass, guiding the reader through the labyrinthine landscape of machining, turning processes, surface roughness intricacies, and the judicious application of Taguchi design optimization, thereby priming the intellectual canvas for the ensuing research endeavor (Selvaraj et al. 2014). Getting precise surface finishes is crucial in the world of machining, especially when tackling the difficulties of turning hardened steel. In the turning process, a single-point cutting tool, commonly referred to as an insert, can efficiently complete the entire machining process in a single fixture, resulting in reduced setup times and lower costs (Selvam and Senthil, 2016). This approach offers several advantages over other methods, such as grinding. One significant challenge faced by industrialists today is the need to produce high-quality products with increased productivity within shorter machining times. Surface roughness during the turning of hardened steel is a critical factor affecting product quality (Selvaraj and Chandramohan 2010). Rough surfaces tend to wear more quickly and exhibit higher friction coefficients than smooth surfaces, which can diminish product quality. Therefore, bridging the gap between quality and productivity is essential. Achieving optimality in machining entails minimizing wear rates while maximizing productivity (Das et al. 2013).

Surface roughness serves as an indicator of the technical excellence of a product and significantly impacts production expenses. It characterizes the configuration of machined surfaces and is closely associated with surface texture (Nalbant et al. 2007). In response to these challenges, dry machining and minimal fluid application have gained prominence. Dry machines have garnered significant interest due to their potential benefits, including environmentally friendly manufacturing practices. Hard turning, a machining process involving the use of single-point cutting tools on hardened materials, has become increasingly feasible with the advent of new cutting tool materials. This approach enables the consolidation or elimination of multiple machining operations, reducing product cycle times and enhancing productivity (Motorcu 2010). The influence of various factors, including workpiece grade, cutting tool coating top layer, and cutting speed, has been the subject of investigation in numerous studies related to turning and surface roughness (Borse 2014). Researchers have investigated the influence of these factors on cutting forces and the quality of machined surfaces. Findings indicate that elevating the cutting speed can enhance the surface finish initially, yet beyond a certain threshold, it may lead to heightened roughness. The optimization of machining variables, as illustrated in research employing the Taguchi method, has emerged as a valuable strategy for enhancing surface quality in turning processes (Do Kim et al. 2007). These studies concentrate on determining the ideal parameter combination to minimize wear rates and maximize efficiency.

3. Methodology

The Taguchi Design Optimization method offers a systematic and methodical approach for enhancing processes and products, rendering it a valuable methodology for research articles. It employs factorial experiments with the aid of orthogonal arrays, streamlining the examination of the influence of numerous variables on a sought-after result, be it product quality or process effectiveness (Yang and Tarng 1998). A unique attribute is its utilization of signal-to-noise ratios to measure the impact of variables on the outcome, facilitating the discovery of optimal parameter configurations. A critical component, Robust Parameter Design, seeks to fortify the process or product against fluctuations and external factors, assuring consistent quality. Statistical analysis is employed to pinpoint the best combination of factors to attain the intended objective. The method's real-world applications are extensive, offering practical insights for industrial scenarios, rendering it an essential instrument for enhancing processes and elevating quality in research and beyond.

The process design phase encompasses various activities such as analyzing processing sequences, selecting production equipment, and estimating process parameter values. At this stage, system design is an initial functional concept, and its quality and cost might not be optimal. Parameter design, on the other hand, aims to determine the product parameter values under ideal process parameters and optimize these process parameters to enhance performance characteristics. It is expected that the optimized process parameters identified through parameter design will be robust against variations in environmental conditions and other sources of noise. Consequently, the Taguchi method places significant importance on parameter design as a key stage for achieving high quality without increasing costs. To achieve this, the Taguchi technique employs special orthogonal arrays,

allowing for a comprehensive exploration of the parameter space with a minimal number of experiments. The difference between the experimental value and the intended value is then determined using a loss function. To gauge how a performance attribute deviates from the intended target, Taguchi recommends employing a loss function. The outcome of the loss function is then transformed into a signal-to-noise (S/N) ratio. In the evaluation of the S/N ratio, three typical categories for performance attributes are usually considered: "the lower-the-better," "the higher-the-better," and "the nominal-the-better." Using S/N analysis, the S/N ratio is computed for each level of the process parameters.

The bigger S/N ratio equates to the better performance characteristic, regardless of the category of the performance characteristic. As a result, the level with the largest S/N ratio g is the one where the process parameters are optimal. In addition, an analysis of variance (ANOVA) in statistics is carried out to determine whether process variables are statistically significant. The ideal arrangement of the process parameters may be predicted using S/N and ANOVA studies. The best process parameters discovered through parameter design are then confirmed by an experiment. To achieve the best turning machining performance, the Taguchi approach of cutting parameter design is used in this study. Take note of the decibel scale used to express these S/N ratios. S/NL is used when the system is optimized when the response is as large as possible, S/NS is used when the system is optimized when the response is as little as feasible, and S/NT is used when the goal is to reduce variability around a particular target. The best factor levels are those that optimize the necessary S/N ratio. The objective of this study was to convert materials with the least amount of surface roughness (Ra). Surface roughness that is better or more improved has a smaller Ra value. As a result, a smaller-is-better quality characteristic was used in this investigation.

3.1 Experimental Workpiece
The hardened steel rod with the composition listed in Table 1 is the workpiece material chosen for study. The experimental workpiece is a circular rod with dimensions of 60 mm in diameter and 250 mm in length, as shown in figure 1.

Table 1. Chemical composition of experimental workpiece material

Element	Fe	C	Cr	Mn	V	Mo	Ni	Si
Weight (%)	95	0.2-2.1	0.5-18	0.2-2	0.1-1.5	0.1-1	0.1-5	0.1-0.5

Figure 1. Experimental workpiece of hardened steel

3.2 Machining processes
The cutting tests were made on a medium-duty CNC lathe. A tool holder with a general specification of PSBNR 2525M12 was used in this experiment. A carbide insert (Tague make) with a general specification of WNMG080408-GM RC6125 was used as the cutting tool insert. The trials were executed following an orthogonal array design, and a Surt tonic S-128 surface roughness tester was employed to gauge surface roughness across diverse parameter combinations. These measurements adhered to ISO and DIN standards for precision. The surface roughness measurements were taken using a Piezoelectric stylus and a 2.5 mm cut-off. Figure 2 illustrates the experimental configuration and the process of surface roughness measurement. Notably, these experiments were conducted under dry turning conditions, without the use of cutting fluid.
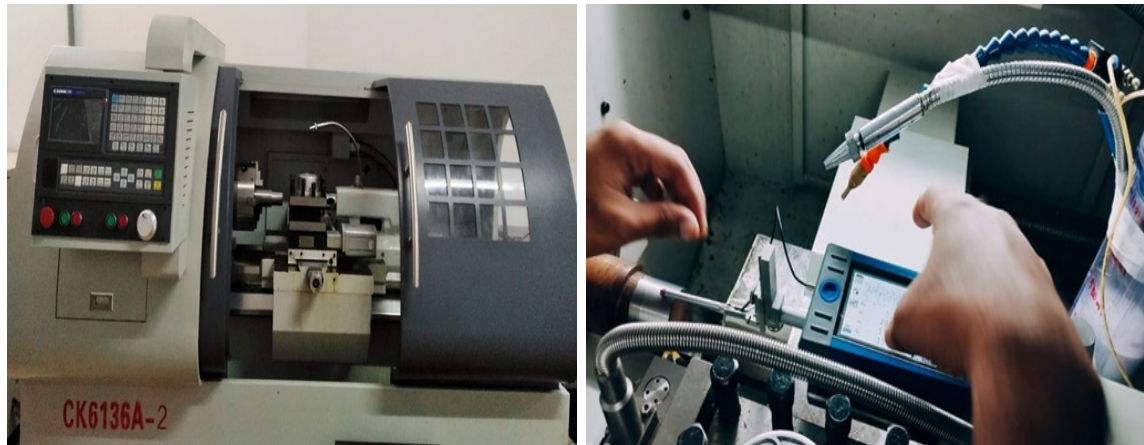
Figure 2. Experimental setup and surface roughness measurements

3.3 Design of experiment

The designed of experiments employing Taguchi's orthogonal array methodology in order to streamline the experiment count. Specifically, we employed a 3-level L9 orthogonal array for conducting these experiments. The chosen cutting parameters encompassed cutting speed, feed rate, and depth of cut. Table 2 outlines the control parameters and their respective levels.

Table 2. Turning parameters and their levels.

Symbol	Cutting Parameters	Units	Level-1	Level-2	Level-3
V	Cutting Speed (V_C)	m/min	80	100	120
F	Feed rate (f)	mm/rev	0.10	0.15	0.2
D	Depth of Cut (DOC)	mm	0.04	0.06	0.08

4. Results and discussion

The examined of outcomes of the cutting experiments through both S/N analysis and ANOVA. The findings from these analyses were used to derive and subsequently validate the best-suited cutting parameters for enhancing surface roughness.

4.1 Analysis of the S/N ratio and surface roughness measurement

In the Taguchi method, the term 'signal' denotes the favorable or mean value of the output feature, while 'noise' pertains to the unfavorable or standard deviation (S.D.) of the output feature. Consequently, the S/N ratio represents the ratio of the mean to the standard deviation and serves as a metric for quantifying how the quality characteristic deviates from the desired value

$\eta = -10 \log(M.S.D)$

Where M.S.D is the mean square deviation for the output characteristic.

To obtain optimal cutting performance, the–lower–the–better quality characteristic for surface roughness must be taken. The M.S.D. for the–lower–the–better quality characteristic can be expressed as:

$MSD = \frac{1}{m}\sum_{i-1}^{m}(Si)^2$

Here, Si represents the surface roughness value for the i-th test. Table 3 provides a summary of the experimental outcomes related to surface roughness along with the corresponding S/N ratio values. The carried-out experiments for all nine sets of cutting parameters, and the surface roughness of all components subjected to dry turning was assessed using a surface roughness tester. The evaluation of surface roughness took place following the dry turning of hardened steel. Among the results, the lowest surface roughness value achieved after the hard turning experiments was 2.6 μm.

Table 3. Experimental Results for Surface Roughness and S/N Ratio

Experiment No.	Cutting Speed, V_C (m/min)	Feed rate, f (mm/rev)	Depth of Cut, DOC (mm)	Surface roughness (µm)	S/N ratio (dB)
01	80	0.10	0.04	4.8	-13.6248
02	80	0.15	0.06	5.1	-14.1514
03	80	0.2	0.08	5.3	-14.4855
04	100	0.10	0.04	5.9	-14.4855
05	100	0.15	0.06	2.9	-9.24796
06	100	0.2	0.08	3.4	-10.6296
07	120	0.10	0.04	5	-13.9794
08	120	0.15	0.06	3.3	-10.3703
09	120	0.2	0.08	2.6	-8.29947

Surface roughness data acquired through surface roughness testing and S/N ratio values computed through Taguchi analysis were collected for all experiments and organized into a table. Table 3 presents the findings, including surface roughness and S/N ratios for all nine components. The experiments revealed that the most favorable combination of cutting parameters, which resulted in a minimum surface roughness of 2.6 µm, corresponded to a cutting speed (V) of 120 m/min, a feed rate (F) of 0.2 mm/rev, and a depth of cut (D) of 0.08 mm, yielding an S/N ratio of -8.29947.

4.2 Response table and main effect plots for S/N Ratios

The smaller is better condition is selected to obtain optimum conditions for surface roughness. Table 4 provides the average S/N ratio values for each individual parameter. In this response table, we can observe the average S/N ratio values for each parameter, along with the discrepancy between the highest and lowest average values. This difference effectively determines the parameter's influence on material surface roughness. It is evident from the table that the most substantial variation between the highest and lowest average S/N ratio values is associated with the feed parameter (3.20), followed by the depth parameter (1.08) and the cutting speed parameter (3.20). As a result, it is apparent that the feed rate is the pivotal parameter that significantly impacts surface roughness. Here, table 4 displays the S/N response table specifically for surface roughness where smaller value is better. On the other hand, table 5 shown the response table of surface roughness for means.

Table 4. Response table of surface roughness for Signal to Noise Ratios

Level	Cutting Speed	Feed Rate	Depth of Cut
1	-14.09	-14.34	-11.54
2	-11.76	-11.26	-12.62
3	-10.88	-11.14	-12.57
Delta	3.20	3.20	1.08
Rank	1	2	3

Table 5. Response table of surface roughness for means

Level	Cutting Speed	Feed Rate	Depth of Cut
1	5.067	5.233	3.833
2	4.067	3.767	4.533
3	3.633	3.767	4.400
Delta	1.433	1.467	0.700
Rank	2	1	3

A higher S/N ratio value for an individual parameter signifies the optimal parameter values required to attain minimal surface roughness. Both the Response table and the main effect plot depicted in Figure 3 highlight the optimal parameter values for achieving the lowest surface roughness in hardened steel. In this case, the ideal parameters are a cutting speed (V) of 120 m/min, a feed rate (F) of 0.2 mm/rev, and a depth of cut (D) of 0.08 mm. It's important to note that, in this context, a smaller S/N ratio indicates better performance.
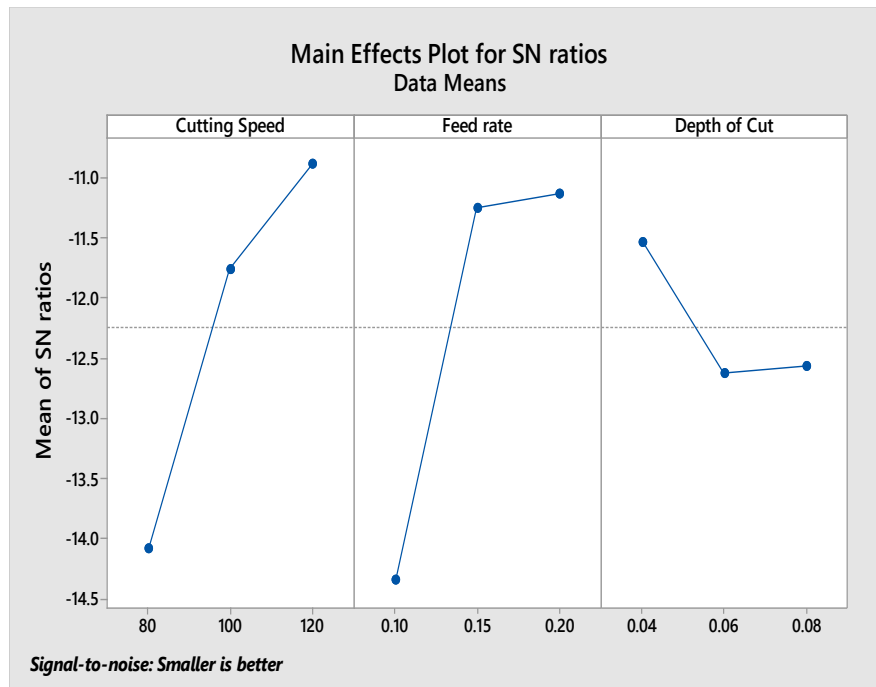
Figure 3. Main Effects plot for SN ratios Data Means

4.3 Analysis of Variance (ANOVA) for surface roughness (Ra)

Results of the analysis of variance indicate that feed rate is the most significant machining parameter, followed by cutting speed, which affects the surface roughness. Table 6 shows the analysis of variance for surface roughness data, and Table 7 also shows the coefficients for surface roughness.

Table 6. Analysis of Variance for surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	6.7900	2.2633	2.36	0.188
Cutting Speed	1	3.0817	3.0817	3.22	0.133
Feed rate	1	3.2267	3.2267	3.37	0.126
Depth of Cut	1	0.4817	0.4817	0.50	0.510
Error	5	4.7922	0.9584		
Total	8	11.5822			

Table 7. Coefficients for surface roughness

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	9.19	2.64	3.48	0.018	
Cutting Speed	-0.0358	0.0200	-1.79	0.133	1.00
Feed rate	-14.67	7.99	-1.83	0.126	1.00
Depth of Cut	14.2	20.0	0.71	0.510	1.00

The main effect plots for means and for S/N ratios of surface roughness are presented in figure 4 and figure 5 respectively. In these main effect plots, the proximity of data points to the horizontal mean line indicates a less pronounced impact, whereas those with the steepest inclination have the most substantial effect on the responses. As illustrated in both Figure 4 and Figure 5, it becomes evident that the feed rate exerts the most significant influence on surface roughness.
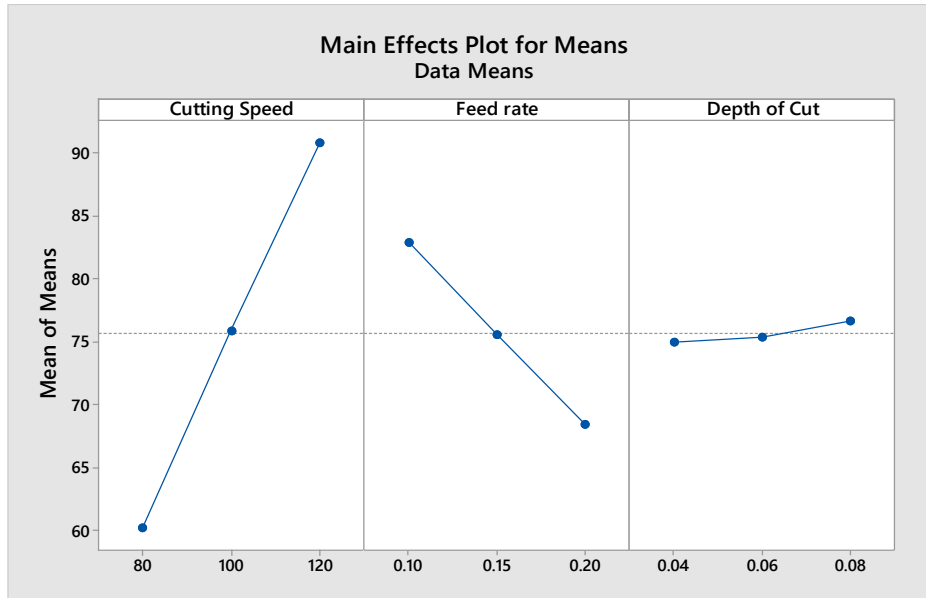

Figure 4. Main Effects plot for means Data means
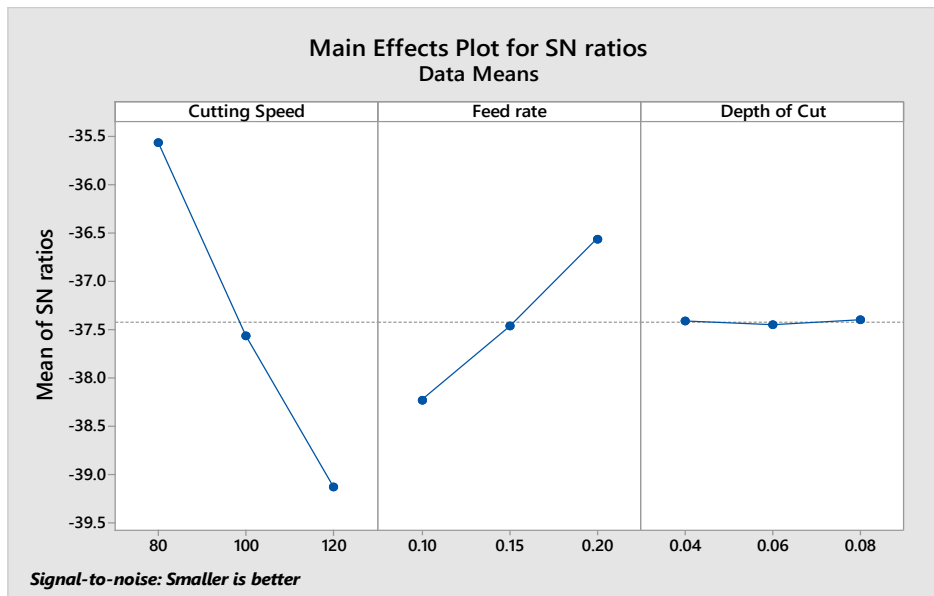
Figure 5. Main Effects plot for SN ratios Data Means

The findings reveal that as the feed rate rises, there is a consistent uptick in surface roughness values. Similarly, the main effect plot illustrates a reduction in roughness as the cutting speed is elevated.

To assess the statistical soundness of the models, several diagnostic plots were examined. An examination of the residual plots suggests that the residuals tend to align along a straight line in a normal probability plot, indicating a normal distribution of errors. This can be observed in Figure 6, which illustrates a normal probability plot for surface roughness, and in Figure 7, depicting a normal probability plot for cutting force.
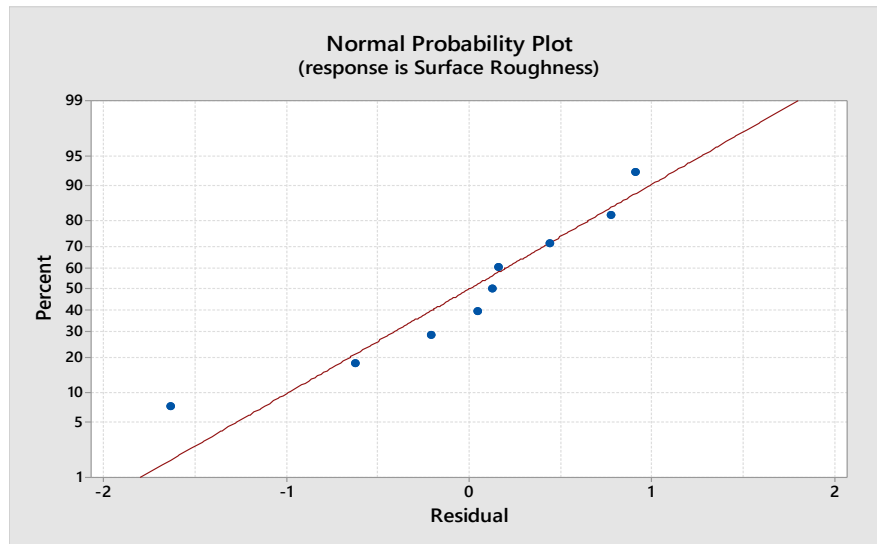
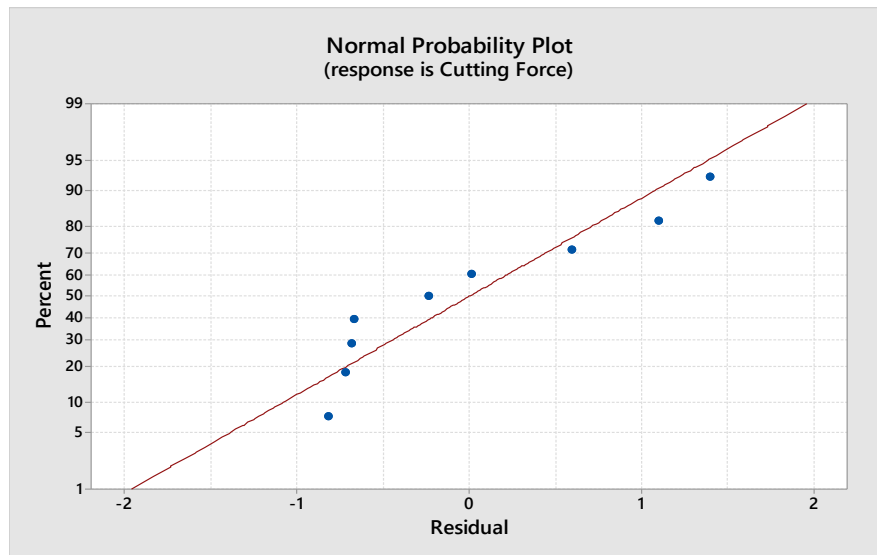Figure 6. Normal probability plot of surface roughness

Figure 7. Normal probability plot of cutting force

Figures 8 and 9 illustrate the correlation between frequency and residual values with respect to surface roughness and cutting force. This connection between frequency and residuals provides valuable insights into how surface roughness and cutting force interact. Grasping this relationship is essential for fine-tuning machining procedures and guaranteeing product quality concerning surface roughness. By scrutinizing the dynamics of frequency and residuals, researchers and engineers can make well-informed choices to enhance the effectiveness and accuracy of cutting operations.
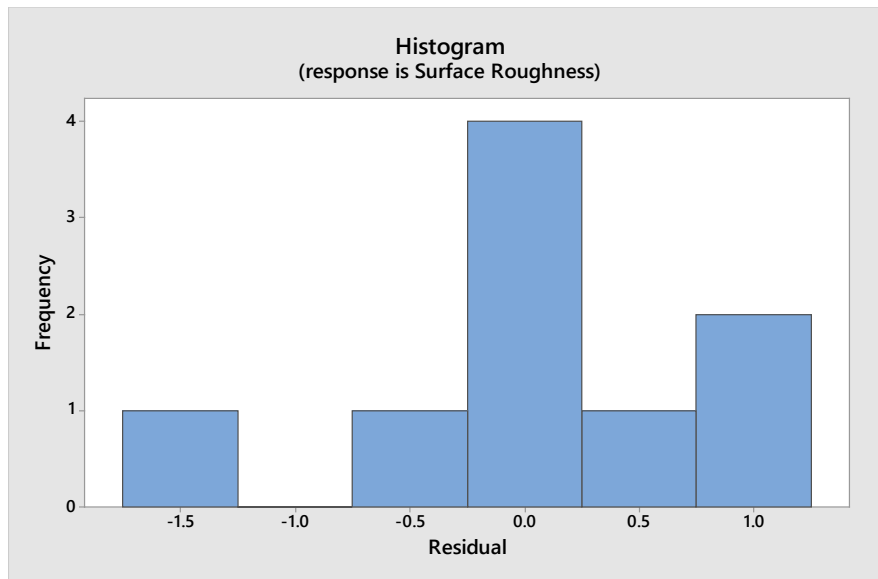
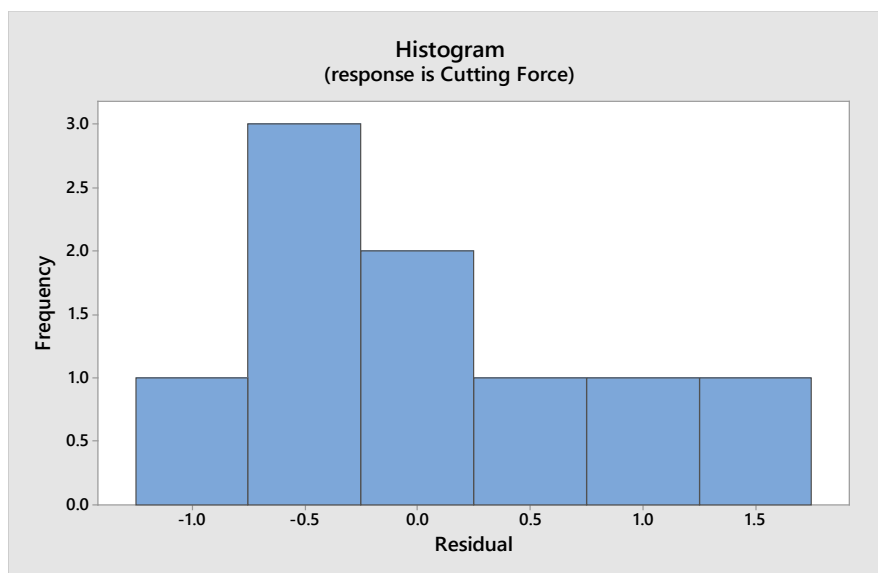Figure 8. Histogram for surface roughness (Frequency vs Residual)

Figure 9. Histogram for cutting force (Frequency vs Residual)

5. Conclusion

The dry-turning experiments were done on a CNC lathe for hardened steel using the Taguchi Method. The intention of this study, 'Taguchi Design Optimization for Improved Surface Roughness in Dry Turning of Hardened Steel,' was to address a significant issue in modern manufacturing practices: obtaining superior surface quality, particularly when machining components made of hardened steel. The experiments revealed that the most favorable combination of cutting parameters, which resulted in a minimum surface roughness of 2.6 μm, corresponded to a cutting speed (V) of 120 m/min, a feed rate (F) of 0.2 mm/rev, and a depth of cut (D) of 0.08 mm, yielding an S/N ratio of -8.29947. The research's goals included improving surface quality and increasing operational effectiveness while adhering to sustainability and financial viability standards. This study sought to provide systematic and trustworthy techniques for manufacturers and engineers to efficiently optimize machining parameters, tool selection, and process conditions by utilizing Taguchi Design Optimization. In this research, tried to find the best cutting parameters and rigorously tested and validated them using experimental design principles, but there are some limitations to machining operations. That's why analyzed a very small amount of data. If more data could be analyzed, then the result would be better.

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