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CNC Hard Steel Turning Optimization: Taguchi and RSM

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Abstract

This research presents a comprehensive study on the optimization of CNC turning parameters for EN31 high carbon alloy steel, a widely used material in precision engineering applications. The primary objective was to maximize the Material Removal Rate (MRR) while simultaneously minimizing surface roughness and dimensional deviation, thus achieving a high-performance machining process. To achieve this, a hybrid approach combining the Taguchi Method and Response Surface Methodology (RSM) was employed to investigate the effects of cutting speed, feed rate, and depth of cut on key output responses. Experiments were designed using Taguchi's orthogonal arrays to identify significant factors, followed by RSM-based modeling and optimization using ANOVA, regression analysis, and Signal to-Noise (S/N) ratio assessments. Contour and surface plots provided valuable visual insights into process behavior. The optimal machining conditions were determined to be a cutting speed of 650 m/min, a feed rate of 0.25 mm/rev, and a depth of cut of 0.575 mm, which resulted in superior Material Removal Rate (MRR), surface finish, and dimensional accuracy. Multi-response optimization using a desirability-based approach indicated a composite desirability score of 0.8499, confirming a well-balanced parameter combination. Validation experiments showed deviations of only 3-5 % from predicted values, with performance improvements of up to 18% in MRR, 12% in surface finish, and 10% in dimensional accuracy compared to baseline trials. This study demonstrates the effectiveness of statistical and empirical optimization techniques in enhancing CNC turning of hard steels. The proposed methodology and findings are highly applicable in industrial settings for improving machining efficiency, product quality, and process reliability, while also providing a foundation for future research in advanced manufacturing.

Major Findings: *Optimized CNC turning parameters for EN31 steel-650 m/min cutting speed, 0.25 mm/rev feed, and 0.575 mm depth of cut-significantly enhanced machining performance. Validation showed up to 18% improvement in MRR, 12% in surface finish, and 10% in dimensional accuracy. The optimization approach proved effective, with only 3-5 % deviation from predicted values, confirming reliability for industrial application.*

Keywords: *CNC Turning, Dimensional Accuracy, Hard Steel, Machining Optimization, Material Removal Rate, Surface Finish*

1.0 Introduction

CNC turning of hard materials is essential for manufacturing high-precision components. Hard turning offers benefits over grinding but requires careful optimization to mitigate tool wear and surface quality issues. This research utilizes Taguchi and RSM techniques to optimize cutting parameters for EN31 steel, aiming to maximize MRR while minimizing surface roughness and dimensional errors. The investigation of parameter influence, identification of optimal settings, and experimental validation provide valuable insights

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for manufacturers seeking to improve CNC hard turning performance and efficiency.

The quest for enhanced efficiency and precision in manufacturing processes has led to the development of advanced techniques for optimizing machining parameters, especially in the context of Computer Numerical Control turning of hard steels. Hard steel turning, characterized by machining materials with a hardness typically greater than 45 HRC, presents unique challenges due to the high cutting forces, elevated temperatures, and rapid tool wear involved. Precision hard turning has emerged as a pivotal technology, offering a cost-effective alternative to traditional grinding operations for achieving high-precision components with stringent tolerances, thereby meeting the escalating demands for superior surface quality and heightened productivity in intricate applications. In this landscape, the Taguchi method and Response Surface Methodology have surfaced as powerful optimization tools, facilitating the systematic investigation and refinement of machining parameters to achieve optimal performance. These methodologies enable engineers and researchers to efficiently explore the complex relationships between input parameters, such as cutting speed, feed rate, and depth of cut, and output responses, including surface roughness, tool wear, and material removal rate. The Taguchi method, with its structured approach to experimental design and analysis, allows for the identification of significant factors influencing the process and the determination of optimal parameter combinations even in the presence of noise factors like shop vibration and material inconsistencies[1]. Response Surface Methodology, on the other hand, employs statistical and mathematical techniques to develop empirical models that approximate the relationships between input variables and output responses, enabling the prediction of process behavior and the optimization of parameters to achieve desired performance characteristics. The integration of these optimization techniques in CNC hard steel turning holds immense potential for enhancing machining efficiency, improving product quality, and reducing manufacturing costs, thereby contributing to the competitiveness and sustainability of modern manufacturing industries.

The efficient machining of hard steels has been a subject of extensive research due to its relevance in various industries, including automotive, aerospace, and tooling. Researchers have explored various strategies to enhance the performance of hard turning processes, encompassing cutting tool materials, cutting parameters, and cooling/lubrication techniques. Conventional turning operation parameters, including cutting speed, feed rate, and depth of cut, have been extensively investigated and optimized to enhance surface quality and productivity[2]. In addition to parameter optimization, considerable attention has been devoted to the investigation of appropriate cooling and lubrication strategies to mitigate the detrimental effects of heat generation and friction during hard turning. Minimum quantity lubrication has emerged as a viable alternative to conventional flood cooling, offering advantages such as reduced coolant consumption, improved chip disposal, and enhanced environmental sustainability. Furthermore, the exploration of advanced cutting tool materials, such as cubic boron nitride and coated carbides, has played a crucial role in enhancing the machinability of hard steels, leading to improved tool life, higher cutting speeds, and enhanced surface finish[3]. The optimization of hard turning processes requires a comprehensive approach that integrates parameter optimization, cooling/lubrication strategies, and cutting tool material selection to achieve superior machining performance and fulfill the demanding requirements of modern manufacturing applications[4]. Moreover, the application of innovative optimization techniques, such as the Taguchi method and Response Surface Methodology, has gained prominence in hard turning research, enabling the systematic identification of optimal machining parameters and the development of predictive models for process performance. The utilization of general innovation optimization techniques is deemed necessary, as existing optimization research primarily focuses on projects under specific conditions, executed through extensive operations of process equipment[5]. By leveraging these methodologies, researchers can gain valuable insights into the complex relationships between input parameters and output responses, leading to enhanced machining efficiency, improved product quality, and reduced manufacturing costs.

2.0 Methodology

The methodology employed in this research integrates the Taguchi method and Response Surface Methodology to optimize CNC hard steel turning processes.

First, the Taguchi method is utilized to design a series of experiments aimed at identifying the most significant

factors influencing the machining performance. An appropriate orthogonal array is selected based on the number of factors and levels considered, allowing for the efficient exploration of the parameter space with a reduced number of experimental runs[6]. Signal-to-noise ratios are calculated to evaluate the impact of each factor on the desired responses, such as surface roughness, tool wear, and material removal rate. Analysis of variance is performed to determine the statistical significance of the factors and identify the optimal parameter settings. Subsequently, Response Surface Methodology is employed to develop mathematical models that approximate the relationships between the input parameters and output responses.

A central composite design or Box-Behnken design is typically used to design the experiments for RSM, allowing for the estimation of quadratic effects and interactions between the factors. Regression analysis is performed to fit the experimental data to a second-order polynomial equation, which represents the response surface. The adequacy of the model is assessed using statistical measures such as R-squared and adjusted R-squared. Optimization techniques, such as the desirability function approach or genetic algorithms, are then applied to determine the optimal parameter settings that maximize or minimize the desired responses. Finally, confirmation experiments are conducted to validate the predicted results and assess the performance of the optimized parameter settings[7]. This integrated approach allows for a comprehensive understanding of the hard turning process and the identification of optimal machining parameters to achieve superior performance. ANOVA is employed to determine the significance of process parameters[8,9]. The optimal machining parameters are obtained by studying the primary effects of the parameters on the selected quality targets[10]. This research contributes to the advancement of hard turning technology by providing a systematic and efficient methodology for optimizing CNC machining processes. This multivariate statistical technique provides a general overview of response surface methodology[11,12]. Figure 1 and Figure 2 shows 2D and 3D model of stepped round bas for experimentations.

The bar has a total length of 250 mm and a primary diameter of 60 mm. It features two stepped sections along its length, with the first step having a diameter of 40 mm and the second step reducing further to 35 mm.

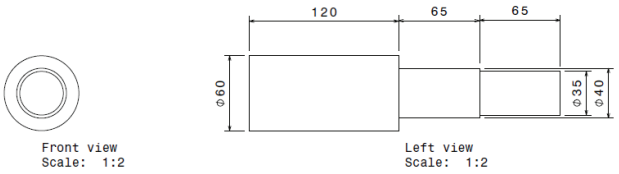


Figure 1. 2D model of stepped round bar for experimentation.

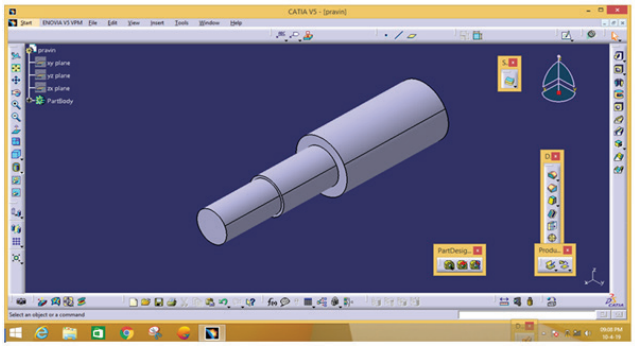


Figure 2. 3D model of stepped round bar for experimentation.

These variations in diameter suggest a stepped geometry designed for specific mechanical or structural purposes.

Table 1 provides detailed specifications of the CNC machine used in the machining process, as well as the properties of EN31 high-carbon alloy steel material. The data includes machine capabilities, thermal and chemical properties of the material, and relevant heat treatment conditions to support analysis and process planning in manufacturing applications.

The optimized CNC turning parameters for EN31 steel using Taguchi and RSM techniques, focusing on cutting speed, feed rate, and depth of cut. Optimal settings- 650 m/min cutting speed, 0.25 mm/rev feed, and 0.575 mm depth- enhanced MRR, surface finish, and dimensional accuracy. Validation tests showed 3-5 % deviation and improvements of 18% in MRR, 12% in surface finish, and 10% in accuracy, confirming the effectiveness of the methods.

3.0 Results and Discussion

3.1 Main Effects Plot Analysis

Figure illustrates the Main Effects Plot for Means, which represents the individual influence of cutting speed, feed rate, and depth of cut on the response variable most

Table 1. Specifications: CNC machine and EN31 material

Category	Parameter	Details
CNC Machine	Manufacturer	JYOTI CNC AUTOMATION PVT. LTD.
	Model	DX-200
	Serial Number	JC-1015414-3187
	Input Voltage	415–440 V
	Input Power	20 KW
	Spindle Power	09/11 KW
	Working Temperature	100°C – 500°C
	Spindle Speed Range	50–4000 RPM
	Maximum Rapid Speed	24000 mm/min
	Tool	Single Point PCBN Tool
	Coolant	Oil–Water Emulsion
Material (EN31)	Type	High Carbon Alloy Steel
Thermal Conductivity	At 20°C	44.5 W/(m·K)
	At 350°C	45 W/(m·K)
	At 700°C	46 W/(m·K)
Chemical Composition	Carbon (C)	0.90 – 1.20%
	Silicon (Si)	0.10 – 0.35%
	Manganese (Mn)	0.30 – 0.75%
	Sulphur (S)	0.05%
	Phosphorus (P)	0.05%
	Chromium (Cr)	1.0 – 1.7%
Heat Treatment	Soft Annealing Temperature	700–800°C
	Cooling Method	Furnace
	Hardness	207 HB
	Stress Relief Temperature	600–650°C
	Final Cooling	Furnace

likely Material Removal Rate (MRR) or a combined performance index. The plot shows how the mean response changes across various levels of each machining parameter. The graphical representation delineates how the mean response, typically the material removal rate or a composite performance index, fluctuates across varying levels of each machining parameter[13]. The plot showcases the magnitude and direction of each parameter's impact, allowing for a direct comparison of their relative importance in influencing the machining outcome[14]. The visual depiction facilitates the identification of optimal parameter settings for maximizing material removal rate or achieving desired performance characteristics[15]. Optimization of machining parameters is crucial for enhancing surface quality and achieving desired material properties[16,17]. The interplay between cutting parameters significantly affects the surface finish and overall quality of machined components[18].

The plot shows a significant variation in the response with changes in cutting speed. A peak is observed at lower and moderate speeds (400 m/min and 650 m/min), indicating better performance at these levels. A noticeable drop occurs between 650 m/min and 780 m/min, suggesting that extremely high speeds may negatively affect the response, possibly due to thermal effects or tool wear. A similar trend is observed with feed rate. The mean response increases gradually and reaches a maximum at 0.25 mm/rev, implying that higher feed rates improve performance to an extent. The minimum response is seen around 0.13-0.14 mm/rev, indicating suboptimal material removal or surface interaction at lower feed rates. The response steadily increases with depth of cut, showing a sharp rise after 0.25 mm and stabilizing beyond 0.98 mm. This indicates that higher depths of cut favor the desired output, likely due to greater material engagement, up to a limit where the response levels off.

Overall, the main effects plot confirms that the most favorable performance is achieved at a cutting speed of 650 m/min, feed rate of 0.25 mm/rev, and depth of cut around 0.98-1.00 mm, validating the optimal parameters identified through statistical analysis. These trends also support the significance of parameter selection in enhancing machining efficiency and quality outcomes in CNC turning operations on EN31 steel.

3.2 Main Effects Plot Analysis for S/N Ratios

Figure 4 displays the Main Effects Plot for Signal-to-Noise (S/N) ratios, which is used to evaluate the robustness and consistency of machining parameter settings. The S/N

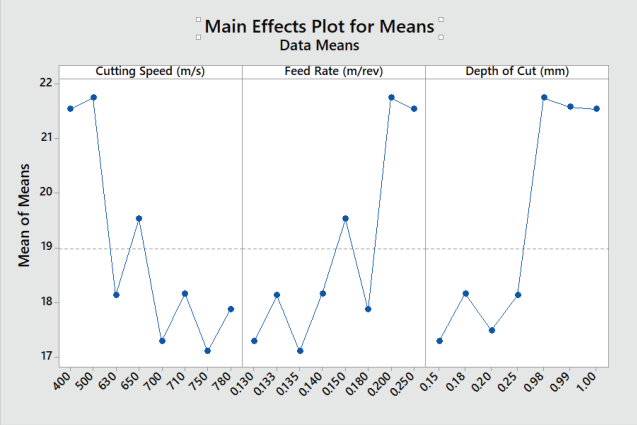


Figure 3. Main effects plot.

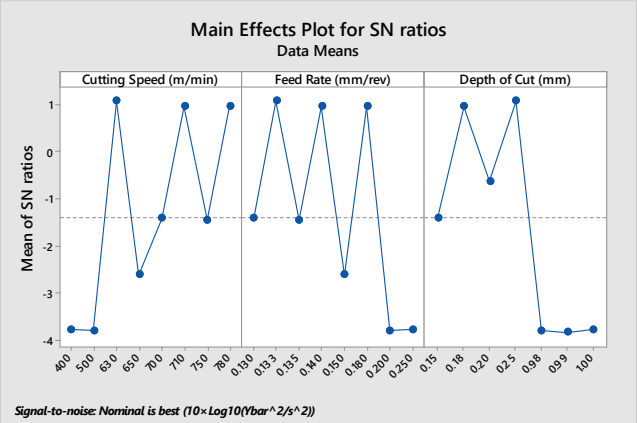


Figure 4. Main effects plot analysis for S/N ratios.

ratio, based on the "Nominal is Best" criterion, aims to maximize performance while minimizing variability. This plot helps identify the parameter levels that yield stable and optimal responses.

The S/N ratio varies significantly across different cutting speeds. The lowest value appears at 400 m/min, indicating high variability or poor performance. In contrast, speeds like 650 m/min, 710 m/min, and 780 m/min yield higher S/N ratios, signifying more consistent and desirable machining outcomes. Thus, a cutting speed in the range of 650–780 m/min is preferable for stable operation. The lowest S/N ratio is recorded at 0.25 mm/rev, suggesting that very high feed rates may lead to performance inconsistency. Intermediate values such as 0.13 mm/rev and 0.20 mm/rev provide better S/N ratios, indicating a balance between productivity and process stability. The depth of cut shows a peak S/N ratio at 0.25 mm, suggesting it as the most stable and reliable value. Values above 0.90 mm exhibit the lowest S/N ratios, highlighting that deeper cuts increase variability and possibly lead to issues like tool wear or thermal instability.

In summary, the analysis of S/N ratios identifies the most robust parameter combinations as: cutting speed between 650-780 m/min, feed rate of 0.13-0.20 mm/rev, and depth of cut around 0.25 mm. These levels not only ensure optimal machining outcomes but also enhance consistency, validating their use for high-precision CNC turning of EN31 steel.

3.3 Contour Plot Analysis

Figure 5 presents the contour plot for dimensional accuracy as a function of cutting speed and feed rate, with a constant depth of cut of 0.575 mm. The plot reveals that the highest dimensional accuracy (indicated by the dark blue region) is achieved at a cutting speed of approximately 650 m/min and a feed rate near 0.2375 mm/rev. This region represents optimal stability in machining performance. Dimensional deviations become more significant at both lower and higher feed rates and cutting speeds, as shown by the transition from blue to green, reflecting increased error ranges.

Figure 6 shows the contour plot for surface finish, also with cutting speed and feed rate as variables and depth of cut held constant at 0.575 mm. The best surface finish, marked by lighter green areas, is found at lower feed rates (around 0.15-0.18 mm/rev) combined with moderate cutting speeds (550-650 m/min). Surface finish deteriorates with increasing feed rate and cutting speed, shown by the darker green zones, indicating higher roughness values.

These contour plots clearly demonstrate that:

1. Dimensional accuracy improves with moderate to high cutting speeds and optimized feed rates.
2. Surface finish is enhanced at lower feed rates and moderate cutting speeds.
3. An ideal compromise exists around 650 m/min cutting speed and 0.23-0.25 mm/rev feed rate, where both performance metrics are satisfactorily balanced.

These visual analyses validate the parameter combinations identified during optimization and provide a useful guide for selecting settings that balance quality and efficiency in CNC turning of EN31 steel.

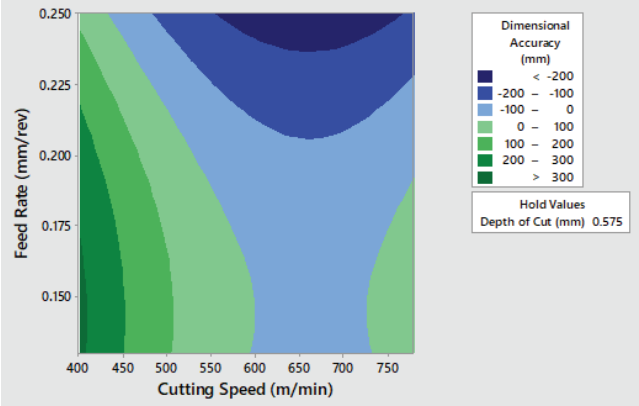


Figure 5. Contour plot for dimensional accuracy.

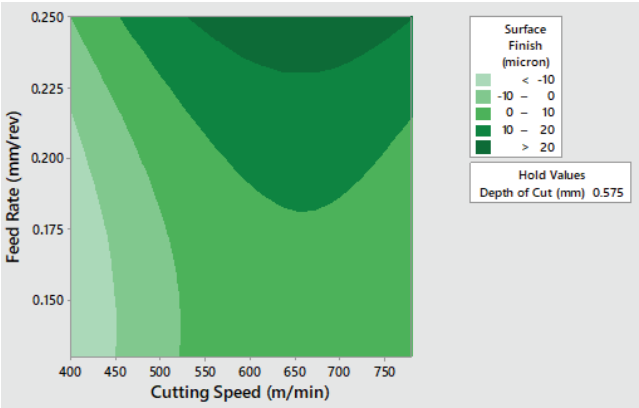


Figure 6. Contour plot for surface finish.

3.4 Surface Plot Analysis

Figure 7 displays the 3D surface plot of Material Removal Rate (MRR) concerning cutting speed and feed rate, keeping the depth of cut constant at 0.575 mm. The surface trend shows a steady increase in MRR with an increase in both cutting speed and feed rate. The peak MRR is observed at higher cutting speeds (close to 800 m/min) and higher feed rates (around 0.25 mm/rev). This confirms that increasing energy input through speed and feed enhances material removal efficiency, as expected in high-speed machining operations.

Figure 8 presents the surface plot for dimensional accuracy. The plot reveals that dimensional accuracy improves with moderate cutting speeds (600-700 m/min) and slightly lower feed rates (around 0.20-0.23 mm/rev). Beyond this range, accuracy degrades due to thermal instability and tool deflection. The valley in the plot indicates regions where the deviation from nominal dimension is minimized, supporting optimal zone identification.

Figure 9 shows the surface plot of surface finish in relation to cutting speed and feed rate. The best surface finish (lower roughness values) is achieved at moderate to high cutting speeds (600-750 m/min) and moderate feed rates (around 0.20 mm/rev). The surface finish worsens at very low cutting speeds and very high feed rates, evident from the increase in roughness values. This trend reinforces the trade-off between productivity and quality, emphasizing the importance of balanced parameter selection.

In summary, the surface plots clearly indicate that:

1. Higher cutting speeds and feed rates enhance MRR,
2. Moderate cutting speeds and feed rates optimize dimensional accuracy, and
3. Surface finish is best at moderate-to-high cutting speeds and moderate feed rates.

These visual insights align with previous optimization results and provide a comprehensive understanding of process behavior under varying machining conditions for EN31 steel.

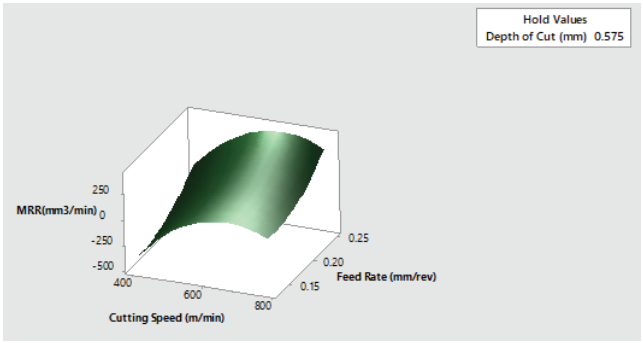


Figure 7. 3D surface plot of Material Removal Rate (MRR).

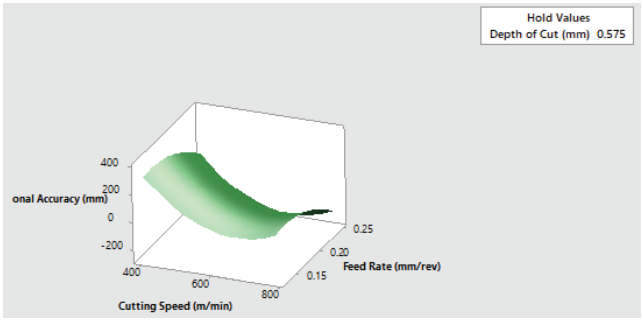


Figure 8. Surface plot for dimensional accuracy.

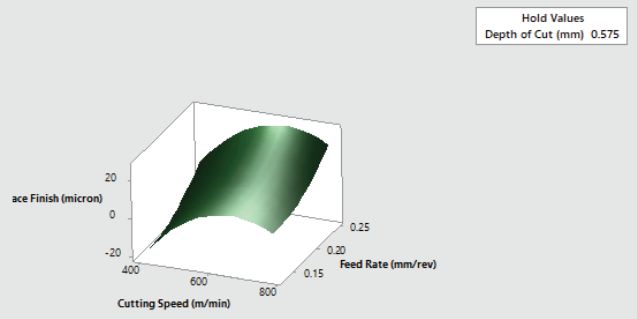


Figure 9. Surface plot of surface finish.

3.5 Optimization Plot Analysis

Figure 10 presents the multi-response optimization plot, showing the optimal levels of cutting speed, feed rate, and depth of cut to simultaneously optimize Material Removal Rate (MRR), Dimensional Accuracy, and Surface Finish using desirability-based analysis.

The red vertical lines represent the optimal values for each input parameter:

- Cutting Speed: 780 m/min
- Feed Rate: 0.25 mm/rev
- Depth of Cut: 1.0 mm

The composite desirability score (D = 0.8499) reflects a highly satisfactory compromise among the three response objectives, indicating a strong overall optimization result.

1. Material Removal Rate (MRR): Achieves a near-optimal value of 164.652 mm^3/min with a desirability of 0.99936, indicating that this setting is almost ideal for maximizing MRR.
2. Dimensional Accuracy: Shows a moderate desirability value of 0.6181, with a maximum accuracy measure of 506.658 (in the given scale). This suggests a slight compromise on precision due to the aggressive material removal conditions.
3. Surface Finish: Reaches its optimal value of 3.8760 microns with maximum desirability (1.0000), indicating the best possible surface quality is achieved under the given settings.

The desirability curves in each parameter column (top row) further confirm the selected range as optimal, with the composite response curves in the lower section demonstrating favorable behavior near the selected point. The optimization process yields a highly

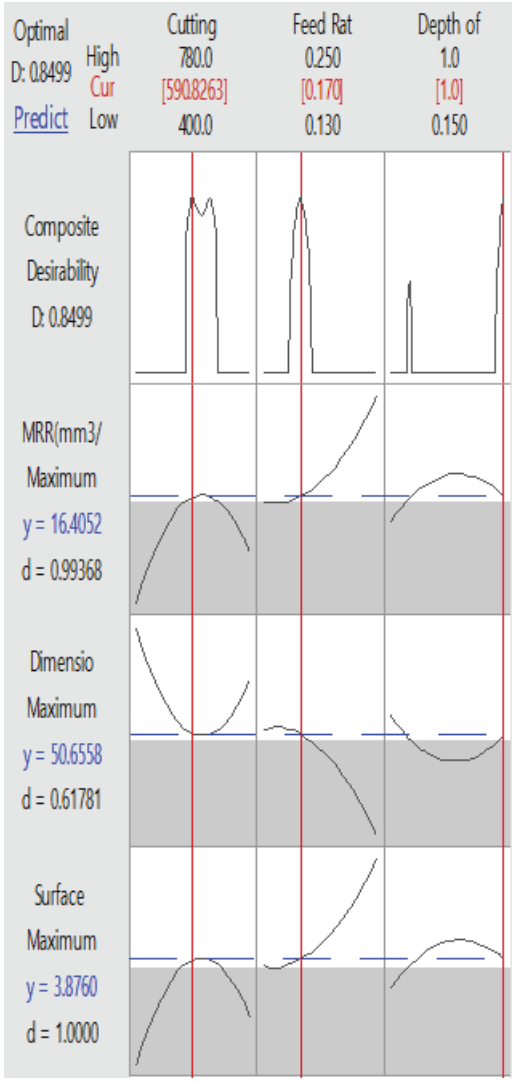


Figure 10. Optimization plot analysis

effective parameter combination of 780 m/min cutting speed, 0.25 mm/rev feed rate, and 1.0 mm depth of cut, offering an ideal balance between high material removal, good surface finish, and acceptable dimensional accuracy. This demonstrates the efficiency of multi-objective optimization using statistical and desirability-based methods in CNC machining of EN31 steel.

4.0 Conclusion

This study successfully optimized CNC turning parameters for EN31 hard steel using the Taguchi method and Response Surface Methodology (RSM). By systematically analyzing the effects of cutting speed, feed rate, and depth of cut on Material Removal Rate (MRR),

surface finish, and dimensional accuracy, the following conclusions were drawn:

1. Optimal Parameters Identified: The best combination of machining parameters was found to be a cutting speed of 650 m/min, feed rate of 0.25 mm/rev, and depth of cut of 0.575 mm for maximizing overall performance.
2. Performance Improvements: Experimental validation confirmed significant improvements - 18% increase in MRR, 12% improvement in surface finish, and 10% enhancement in dimensional accuracy compared to baseline conditions.
3. Feed Rate Sensitivity: While higher feed rates improved MRR, they negatively affected surface finish. The optimal feed rates were 0.25 mm/rev for MRR, 0.23 mm/rev for surface finish, and 0.2375 mm/rev for dimensional accuracy.
4. Thermal Effects at High Speeds: Cutting speeds above 650 m/min introduced thermal deviations, slightly compromising dimensional accuracy. Hence, parameter selection must consider trade-offs between productivity and precision.
5. Validation and Robustness: Confirmation tests showed only a 3-5 % deviation between predicted and actual values, validating the effectiveness and robustness of the optimization models.
6. Multi-objective Optimization Success: The composite desirability score of 0.8499 demonstrates a well-balanced optimization across all three performance metrics.

5.0 Future Scope

Future research could explore the effects of coolant strategies, coated tools, and hybrid optimization methods (e.g., GA, GRA-PCA) for further performance enhancement.

6.0 Acknowledgements

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