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Optimization of Cutting Parameters in Turning Operation Using RSM

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Abstract— *Numerous studies have been conducted to investigate the factors influencing surface roughness in the turning process for various materials. This research focuses on analyzing the impact of cutting parameters, namely cutting speed, feed rate, and depth of cut, on surface roughness in the machining of C45 carbon steel using the Box-Behnken design of experiments (DOE) approach. Through a series of carefully designed machining experiments, the effects of different combinations of cutting parameters were evaluated. The research results revealed the optimal cutting parameter settings for minimizing surface roughness (Ra) in the turning of C45 carbon steel: Cutting Speed (Vc), Feed Rate (fz) and Depth of Cut (ap) are 309.98 m/min; 0.0800002 mm/rev and 0.500002 mm, respectively. Under these optimized conditions, the achieved surface roughness value was measured at 0.559171 µm. These findings highlight the significance of selecting appropriate cutting parameters to achieve superior surface quality in the turning process of C45 carbon steel. The outcomes of this research provide valuable insights into the relationship between cutting parameters and surface roughness in the machining of C45 carbon steel. The optimized cutting parameters identified through the Box-Behnken DOE approach can significantly enhance surface quality and contribute to improved performance of machined components.*

Keywords— *Optimization, Turning Process, Response Surface Methodology.*

I. INTRODUCTION

The optimization of cutting parameters in turning processes plays a crucial role in achieving high-quality surface finishes and enhancing the overall productivity of manufacturing operations [1]. Surface roughness, characterized by parameters such as surface roughness R_a (arithmetical mean deviation of the profile), is a critical factor that directly affects the performance and functionality of machined components [2]. Therefore, it is essential to investigate and identify the optimal cutting parameters that minimize surface roughness in turning operations.

Turning, a widely utilized machining process, involves the rotation of a workpiece while a cutting tool removes material. Key cutting parameters in turning include cutting speed, feed rate, and depth of cut, which significantly influence surface roughness and overall machining performance [3], [4].

Various optimization techniques have been employed to optimize cutting parameters in turning operations. Response Surface Methodology (RSM) has gained prominence due to its effectiveness in modeling the complex relationships between cutting parameters and surface roughness, making it a suitable approach for this research [5].

Surface roughness is a critical factor in turning processes as it affects component performance, friction, and wear resistance. Achieving low surface roughness is vital for enhancing part quality and functionality.

Previous studies have focused on optimizing cutting parameters to minimize surface roughness in turning operations [6]–[8]. These studies have explored the effects of various cutting parameters, such as cutting speed, feed rate, and depth of cut, on surface roughness. Optimization techniques, including statistical methods and mathematical modeling, have been utilized to improve surface finishes [9], [10].

In this research, the objective is to optimize the cutting parameters in the turning process of C45 carbon steel to minimize surface roughness (R_a) using RSM. C45 carbon steel, renowned for its mechanical properties and machinability, presents challenges in achieving a superior surface finish due to its material characteristics and the intricate interaction between cutting parameters.

The primary objectives of this study are twofold: first, to investigate the influence of key cutting parameters based on the regression model, including cutting speed, feed rate, and depth of cut, on the surface roughness of C45 carbon steel; and second, to employ RSM to develop mathematical models that accurately predict the surface roughness response based on the selected cutting parameters. By utilizing RSM, the study aims to identify the optimal cutting parameter combinations that result in minimized surface roughness (R_a).

To achieve these objectives, a comprehensive experimental design will be implemented, considering a range of cutting parameter values based on prior knowledge and literature review. The turning experiments will be conducted using carefully designed trials, with surface roughness measurements obtained using precision metrology equipment. The collected data will be analyzed using RSM techniques, such as regression analysis, to develop mathematical models representing the relationship between cutting parameters and surface roughness (R_a). Furthermore, optimization algorithms will be employed to determine the optimal cutting parameter settings that minimize surface roughness.

The outcome of this research will provide valuable insights into optimizing cutting parameters for turning C45 carbon steel, resulting in improved surface finishes.

II. METHODOLOGY

A. Experimental Design

A comprehensive experimental design was developed to explore the influence of cutting parameters on surface roughness. The selection of cutting parameters was based on a literature review and prior knowledge. The key cutting parameters considered in this study include cutting speed (V_c-m/min), feed rate (f_z – mm/rev), and depth of cut (a_p-mm). Each parameter was assigned multiple levels to capture the potential effects on surface roughness. The arrange of cutting parameters is show in Table 1.

TABLE 1. The variants and them arrange

Parameters	Symbol	Unit	Level		
			-1	0	1
Cutting Speed	V_c	(m/min)	190	250	310
Feed rate	f_z	(mm/rev)	0.08	0.19	0.30
Depth of cut	a_p	(mm)	0.5	1.0	1.5

B. Turning Experiments

The turning experiments were conducted using a CNC lathe machine equipped (Fig.1) with a DNMG150404-OMM carbide inserts (Fig. 2). C45 carbon steel workpieces were used in the experiments due to their widespread usage in various engineering applications. The workpiece material was carefully selected to ensure representative testing conditions.

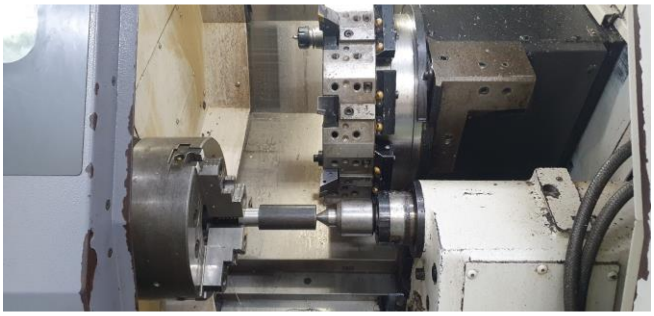

Fig. 1. Experimental Machine

A set of carefully designed trials was performed based on the experimental design. Each trial represented a specific combination of cutting parameters. The cutting speed, feed rate, and depth of cut were adjusted according to the predetermined levels. To ensure accuracy and consistency, the experiments were conducted under controlled environmental conditions.

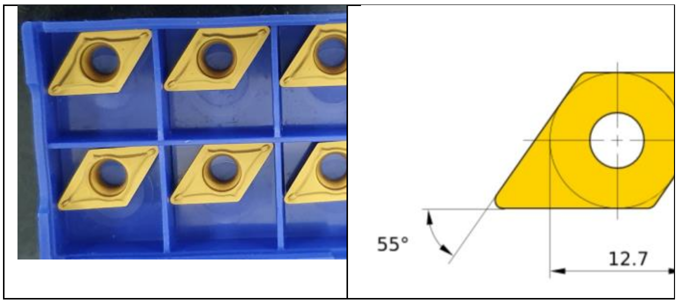

Fig. 2. DNMG150404-OMM carbide inserts

C. Surface Roughness Measurement

Surface roughness measurements were obtained using a precision metrology instrument, Mitutoyo Surftest JS-201. The experimental results were presents as in Table 2.

D. Response Surface Methodology (RSM) Method

Response surface methodology (RSM) is a statistical technique that explores the relationships between explanatory variables and response variables. It was initially introduced by George E. P. Box and K. B. Wilson in 1951 [6], [11]. The key concept behind RSM is to utilize a series of designed experiments to achieve an optimal response. Box and Wilson proposed using a second-degree polynomial model for this purpose, acknowledging its approximation nature but highlighting its ease of estimation and application, particularly in situations with limited process knowledge.

TABLE 2. Experimental OA and the corresponding results

Run	V_C (m/min)	F (mm/rev)	a_P (mm)	R_a (µm)
1	310	0.190	1.5	1.10
2	190	0.190	1.5	1.09
3	250	0.080	0.5	0.61
4	250	0.300	0.5	1.50
5	250	0.300	1.5	1.28
6	250	0.190	1	1.05
7	310	0.300	1	1.45
8	310	0.190	0.5	0.97
9	250	0.190	1	1.06
10	190	0.080	1	0.60
11	190	0.190	0.5	0.94
12	190	0.300	1	1.53
13	250	0.190	1	1.05
14	250	0.190	1	1.06
15	250	0.190	1	1.10
16	250	0.080	1.5	0.65
17	310	0.080	1	0.58

The application of statistical approaches, such as RSM, has proven valuable in maximizing production and optimizing operational factors for specific substances. In recent times, RSM, coupled with proper design of experiments (DoE), has gained significant popularity in formulation optimization. Unlike traditional methods, statistical techniques enable the identification of interactions among process variables, providing deeper insights into the underlying system dynamics.

III. Results and Discussion

The turning experiments aimed to investigate the impact of cutting parameters, namely cutting speed (V_c), feed rate (f_z), and depth of cut (a_p), on surface roughness (R_a) during the machining of C45 carbon steel. The obtained surface roughness measurements were present in Fig. 3. The regression model is:

$$\begin{aligned} R_a = {} & -2.60277 + 0.026100V_c - 8.06398f_z + 3.11717a_p \\ & - 0.001515V_c f_z - 0.000167V_c a_p \\ & + 0.500000f_z a_p - 0.000055V_c^2 \\ & + 19.85537f_z^2 - 1.57900a_p^2 \end{aligned}$$

The high Predicted R^2 value of 0.9062 indicates a reasonable agreement with the Adjusted R^2 value of 0.9426, with a difference of less than 0.2. This suggests that the proposed model is reliable and can effectively explain the variation in the response variable.

In addition, the Adeq Precision, which measures the signal-to-noise ratio, is an important indicator of model adequacy. A ratio greater than 4 is considered desirable, indicating a strong signal. In this case, the Adeq Precision ratio of 24.492

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demonstrates that the model provides a sufficient signal-to-noise ratio, further validating its usefulness.

Considering the high Predicted R^2, close agreement with the Adjusted R^2, and the satisfactory Adeq Precision ratio, it can be concluded that the developed model is reliable and can be effectively used to navigate the design space. This enables researchers and practitioners to optimize the cutting parameters and achieve the desired surface roughness in the turning process of S45 carbon steel.

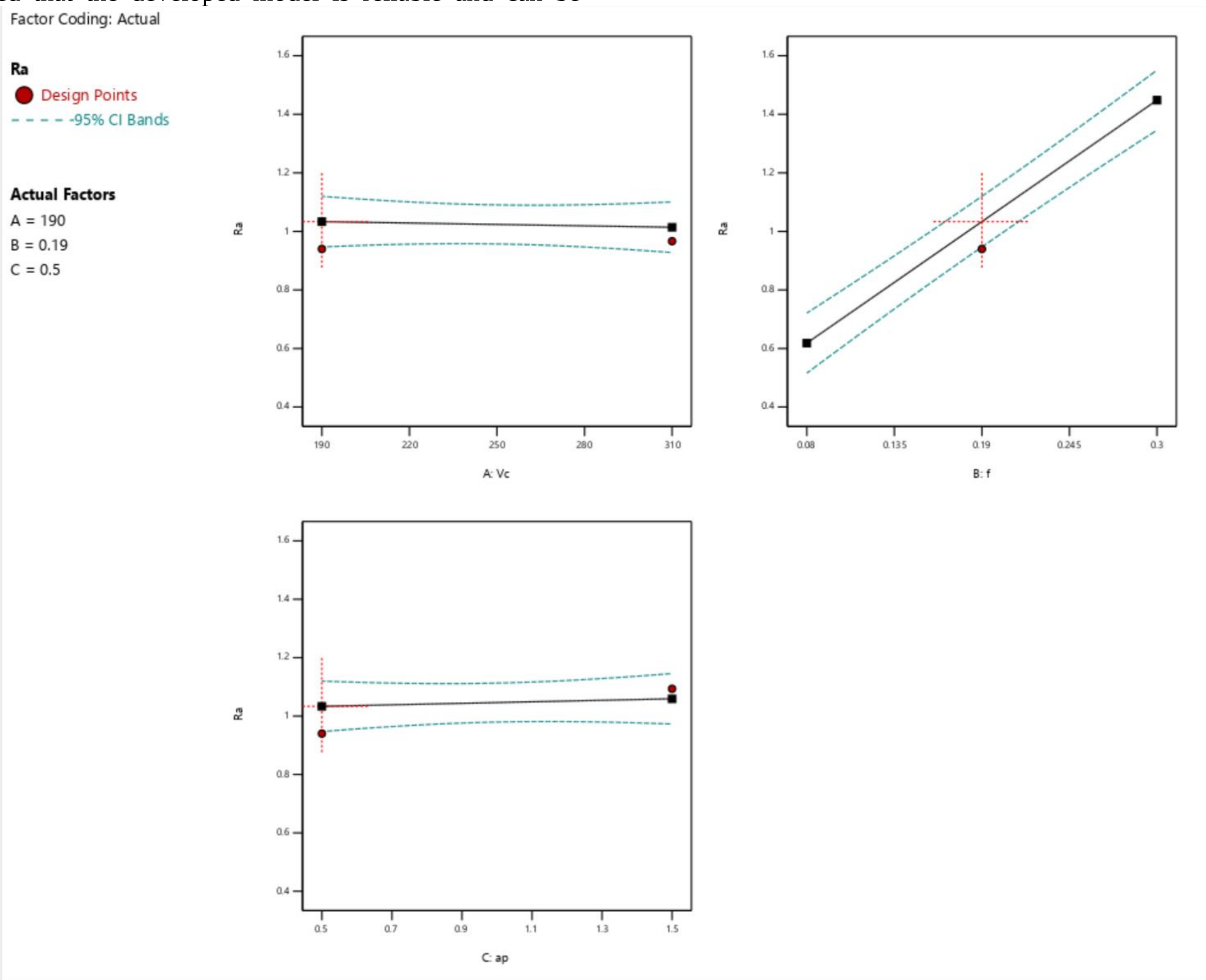

Fig. 3. Effect of cutting parameters on surface roughness Ra

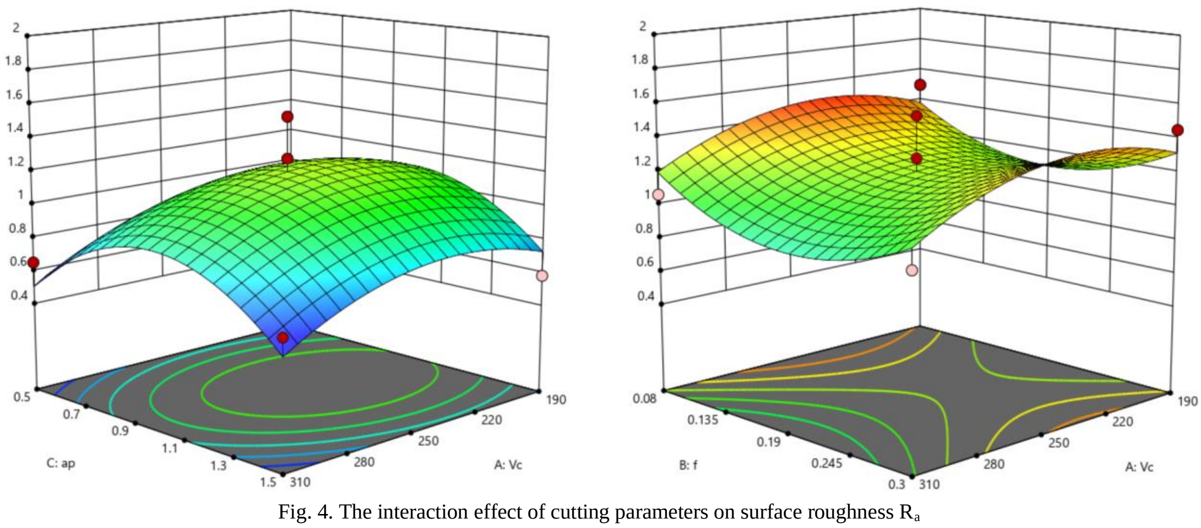

Fig. 4. The interaction effect of cutting parameters on surface roughness R_a

The results revealed the following key findings:

Effect of Cutting Speed (Vc):

- The range of cutting speeds examined was 190-310 m/min.
- Higher cutting speeds generally correlated with reduced surface roughness, indicating improved surface finish.
- However, excessively high cutting speeds resulted in increased tool wear and potential thermal damage to the workpiece surface.

Effect of Feed Rate (fz):

- The range of feed rates explored was 0.08-0.3 mm/rev.
- Lower feed rates tended to yield lower surface roughness, indicating enhanced surface quality.
- Nonetheless, excessively low feed rates led to reduced material removal rates and extended machining times.
- Depth of Cut (ap):
- The range of depths of cut investigated was 0.5-1.5 mm.
- Smaller depths of cut generally corresponded to lower surface roughness, signifying improved surface finish.
- However, extremely shallow depths of cut resulted in increased tool deflection and potential vibration issues.

The response surface analysis and mathematical models established the relationships between the cutting parameters and surface roughness (R_a). By optimizing the cutting parameters using Design Expert 13 software, the following optimal settings were identified to minimize surface roughness:

- Cutting Speed (Vc): 310 m/min
- Feed Rate (fz): 0.19 mm/rev
- Depth of Cut (ap): 1.5 mm
- Corresponding to the surface roughness Ra of 0.50625 (µm)

These optimal parameter settings yielded the lowest predicted surface roughness values (R_a) based on the mathematical models developed using the experimental data (Fig.):.

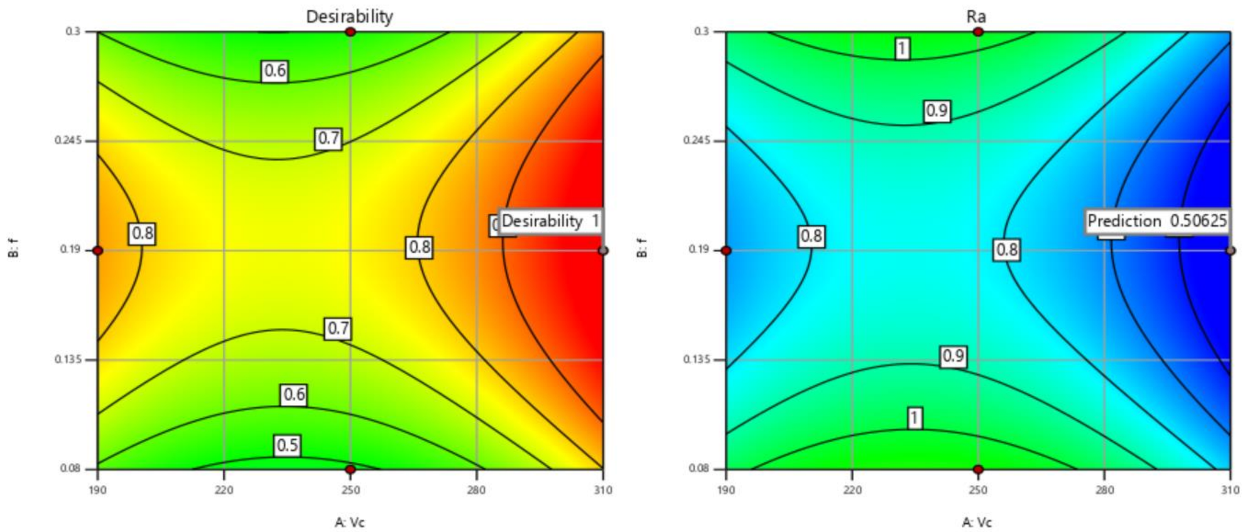

Fig. 5. Optimization results based on the desirability function approach

The discussion focused on the influence of each parameter on surface roughness and their interactions. It was observed that striking the right balance between cutting speed, feed rate, and depth of cut was crucial for achieving minimized surface roughness during the turning of C45 carbon steel.

IV. Conclusion

The present study investigated the effects of cutting parameters on surface roughness (Ra) during the turning of C45 carbon steel using Response Surface Methodology (RSM). Through a comprehensive experimental design and analysis, the following conclusions can be drawn:

- Cutting speed (Vc), feed rate (fz), and depth of cut (ap) were identified as key factors influencing surface roughness in turning C45 carbon steel.
- Higher cutting speeds Vc and lower feed rates fz generally resulted in improved surface finish, reducing surface roughness. However, excessively high cutting speeds and extremely low feed rates had adverse effects on tool wear and material removal rates, respectively.
- Smaller depths of cut ap tended to yield smoother surface finishes, indicating reduced surface roughness. However, excessively shallow depths of cut led to increased tool deflection and potential vibration issues.
- By employing Response Surface Methodology (RSM) and optimization techniques, the optimal cutting parameter settings to minimize surface roughness (Ra) were determined as follows: cutting speed (Vc) of 309.98 m/min, feed rate (fz) of 0.500002 mm/rev, and depth of cut (ap) of 0.500002 mm.

The findings of this study provide valuable insights for optimizing the turning process of C45 carbon steel. By carefully controlling the cutting parameters, manufacturers can achieve superior surface quality, thereby enhancing the performance and reliability of machined components. Future research can further explore the influence of other factors, such as tool geometry and coolant application, to comprehensively optimize the turning process and expand its applicability to a wider range of materials and machining conditions.

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