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Simultaneous Optimizing Surface Roughness and Cutting Time in MQL Face Milling of Hardened SKD11 Using Response Surface Methodology

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Abstract— *This paper investigates the simultaneous optimization of surface roughness (R_a) and cutting time (T_c) in the face milling process of hardened SKD11 using the Minimum Quantity Lubrication (MQL) technique and Response Surface Methodology (RSM). The objective is to identify optimal machining parameters that can achieve the best surface roughness while minimizing the cutting time. A series of experiments were conducted, and the RSM was employed to analyze the data and establish a mathematical model. The results revealed that cutting speed (V_c), depth of cut (a_p), and feed rate (f_z) significantly influenced surface roughness and cutting time. Through the optimization process, the optimal machining parameters were determined to be a cutting speed of 60 m/min, a depth of cut of 0.1 mm, and a feed rate of 0.054706 mm/min. When these parameters were applied, the achieved surface roughness was 0.126179 µm (R_a) and the cutting time was 9.88514 seconds (T_c). These values represent a notable improvement compared to conventional machining parameters. The findings demonstrate the efficacy of the proposed MQL and RSM approach in simultaneously optimizing surface roughness and cutting time. By utilizing the optimal machining parameters, manufacturers can enhance productivity and product quality in the face milling process of hardened SKD11. Furthermore, the research contributes to the understanding of the effects of MQL and the importance of parameter optimization in achieving superior machining performance.*

Keywords— *Surface Roughness, Cutting Time, Face Milling, SKD11, MQL, Response Surface Methodology, Optimization.*

I. INTRODUCTION

The face milling process is widely used in the manufacturing industry for machining flat surfaces on various materials. When it comes to hardened materials such as SKD11[1], [2], the challenges of achieving high-quality surface finish and minimizing cutting time become more pronounced. Surface roughness (R_a) is a critical quality indicator, as it directly affects the functionality and appearance of machined components. Additionally, reducing cutting time (T_c) is essential for enhancing productivity and reducing manufacturing costs.

In recent years, the Minimum Quantity Lubrication (MQL) technique has gained significant attention as an environmentally friendly and cost-effective lubrication method in metal cutting operations [3], [4]. MQL involves applying a minimal amount of lubricant, typically in the form of a mist or aerosol, directly to the cutting zone. This technique offers advantages such as reduced tool wear, improved chip evacuation, and lower energy consumption.

To optimize machining processes, Response Surface Methodology (RSM) has been widely adopted. RSM is a statistical technique that uses a limited number of experiments to develop mathematical models and predict the relationship between input parameters and output responses [5], [6]. By applying RSM, researchers can systematically explore the effects of various machining parameters on surface roughness and cutting time.

While previous studies have focused on optimizing individual machining objectives, such as surface roughness or cutting time, limited research has addressed the simultaneous optimization of both factors in the MQL face milling of hardened SKD11. Therefore, this study aims to bridge this gap by employing MQL and RSM to optimize surface roughness and cutting time concurrently.

The primary objective of this research is to identify the optimal combination of cutting speed (V_c), depth of cut (a_p), and feed rate (f_z) that can minimize surface roughness and cutting time in the face milling of hardened SKD11. By conducting a series of experiments and utilizing the RSM approach, a mathematical model will be developed to predict the optimal machining parameters for achieving the desired surface roughness while reducing cutting time.

The findings of this study will provide valuable insights for manufacturers and researchers seeking to optimize the face milling process of hardened materials using MQL. The ability to simultaneously optimize surface roughness and cutting time will result in improved product quality, increased efficiency, and reduced production costs.

Overall, this research contributes to the advancement of machining techniques and provides a framework for optimizing multiple objectives in the face milling process, paving the way for enhanced productivity and quality in the manufacturing industry.

II. METHODOLOGY

A. Experimental Design

To conduct the experiments and obtain data for the optimization process, the Box-Behnken design matrix was employed. The Box-Behnken design is a response surface methodology (RSM) technique that efficiently explores the

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parameter space with fewer experimental runs compared to a full factorial design.

The Box-Behnken [7], [8] design uses a combination of three levels for each factor, namely low (-1), medium (0), and high (+1), resulting in a balanced and efficient experimental design. The advantage of this design is its ability to estimate main effects, quadratic effects, and interactions between factors.

In this study, three factors, namely cutting speed (V_c), depth of cut (a_p), and feed rate (f_z), were considered for optimization. Each factor was assigned three levels according to the Box-Behnken design. The low, medium, and high levels for each factor were determined based on preliminary experiments and a literature review to cover a wide range of practical machining conditions.

The Box-Behnken design matrix was generated by combining the levels of the three factors systematically, resulting in a set of experimental runs. The matrix was designed to achieve a good balance between precision and efficiency in exploring the parameter space.

During the experiments, the surface roughness (R_a) and cutting time (T_c) were measured for each combination of the machining parameters in the Box-Behnken matrix. The collected data were then utilized to develop the mathematical model using the RSM approach.

By employing the Box-Behnken design, this study was able to efficiently explore the effects of the cutting speed, depth of cut, and feed rate on surface roughness and cutting time in the face milling process of hardened SKD11. The design matrix facilitated the systematic collection of data and provided a foundation for developing the mathematical model and subsequent optimization.

In this study, three key machining parameters, namely cutting speed (V_c), feed rate (f_z), and depth of cut (a_p), were carefully selected to construct the experimental design matrix L_{17} based on the Box-Behnken design. The specific values corresponding to these parameters are presented in Table 1.

TABLE 1. The variants and them arrange

Parameters	Symbol	Unit	Level		
			-1	0	1
Cutting Speed	V_c	(m/min)	65	135	210
Feed rate	f_z	(mm/min)	0.02	0.04	0.06
Depth of cut	a_p	(mm)	0.1	0.3	0.5

B. Face Milling Experiments

The experimental study was conducted on a CNC DMU50 milling machine manufactured by DMG Mori. The milling tool used was an Endmill provided by Widia (Germany). The surface roughness measurements were performed using a Mitutoyo JS-201 surftest machine. The workpiece utilized had dimensions of 50x35x10mm. The experimental results were predicted as in Table 2. The milling tool used was an Endmill provided by Widia (Germany). The surface roughness measurements were performed using a Mitutoyo JS-201 surftest machine. The workpiece utilized had dimensions of 50x35x10mm. The experimental results were predicted as in Table 2.

Fig. 1. CNC DMU 50 of DMG Mori

TABLE 2. Experimental OA and the corresponding results

Run	V_c (m/min)	f_z (mm/min)	a_p (mm)	R_a (μm)	T_c (s)
1	135	0.02	0.5	0.1273	29.66
2	135	0.04	0.3	0.1493	14.83
3	135	0.04	0.3	0.1443	14.83
4	135	0.04	0.3	0.1837	14.83
5	210	0.06	0.3	0.2683	9.89
6	60	0.06	0.3	0.1717	9.89
7	210	0.04	0.1	0.1603	14.83
8	60	0.04	0.5	0.2097	14.83
9	210	0.02	0.3	0.1317	29.66
10	210	0.04	0.5	0.158	14.83
11	135	0.04	0.3	0.1473	14.83
12	135	0.02	0.1	0.1003	29.66
13	135	0.06	0.1	0.2063	9.89
14	135	0.04	0.3	0.1503	14.83
15	135	0.06	0.5	0.2733	9.89
16	60	0.02	0.3	0.107	29.66
17	60	0.04	0.1	0.1187	14.83

C. Response Surface Methodology

Response Surface Methodology (RSM) is a statistical technique widely used in engineering and scientific research to optimize processes and systems. RSM aims to find the optimal settings of input variables or factors that result in desired responses or outcomes. The primary objective of RSM is to develop a mathematical model that can accurately predict the relationship between the input factors and the corresponding output responses. By analyzing the mathematical model, researchers can identify the critical factors and their interactions that significantly impact the responses of interest.

In the context of machining operations, RSM has been widely applied to optimize various parameters, such as cutting speed, feed rate, depth of cut, and tool geometry, to achieve desirable outcomes such as surface roughness, cutting time, tool life, and energy consumption. One of the key advantages of RSM is its ability to efficiently explore the parameter space with a limited number of experiments. Instead of conducting exhaustive experiments for every possible combination of factors, RSM employs statistical designs, such as the Box-Behnken design used in this study, to select a subset of experiments that provides sufficient information for model development and optimization.

Once the experimental data is collected, the mathematical model is constructed using regression analysis techniques, such as multiple linear regression or quadratic regression. The model represents the relationship between the input factors and the responses, considering both linear and non-linear effects. The developed mathematical model can then be used to predict the responses for any given combination of input factors within the design space. This allows researchers to systematically explore the parameter space and identify the optimal settings that yield the desired responses.

Optimization in RSM involves finding the factor settings that maximize or minimize the responses, subject to any constraints or limitations. Various optimization algorithms, such as the desirability function approach or numerical optimization techniques, can be employed to determine the optimal factor levels that simultaneously optimize multiple responses.

In the context of this study, RSM is utilized to optimize the surface roughness (Ra) and cutting time (Tc) in the face milling process of hardened SKD11. By developing a mathematical model based on the collected experimental data, the optimal machining parameters can be identified to achieve the desired surface roughness while minimizing the cutting time.

Overall, Response Surface Methodology provides a robust framework for optimizing complex processes and systems by systematically exploring the parameter space, developing mathematical models, and determining the optimal factor settings. Its application in machining operations allows for improved productivity, enhanced product quality, and reduced manufacturing costs.

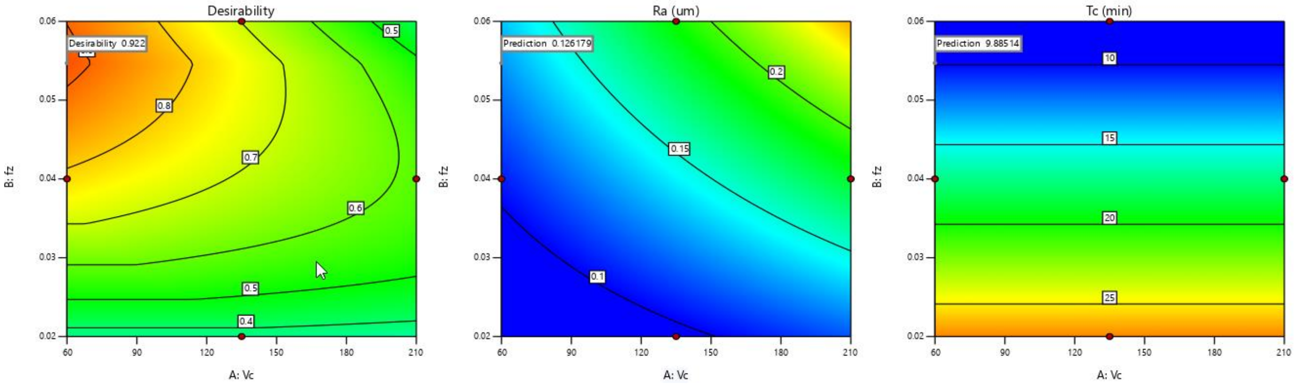

Fig. 2. Optimization sets based on Desirability Values

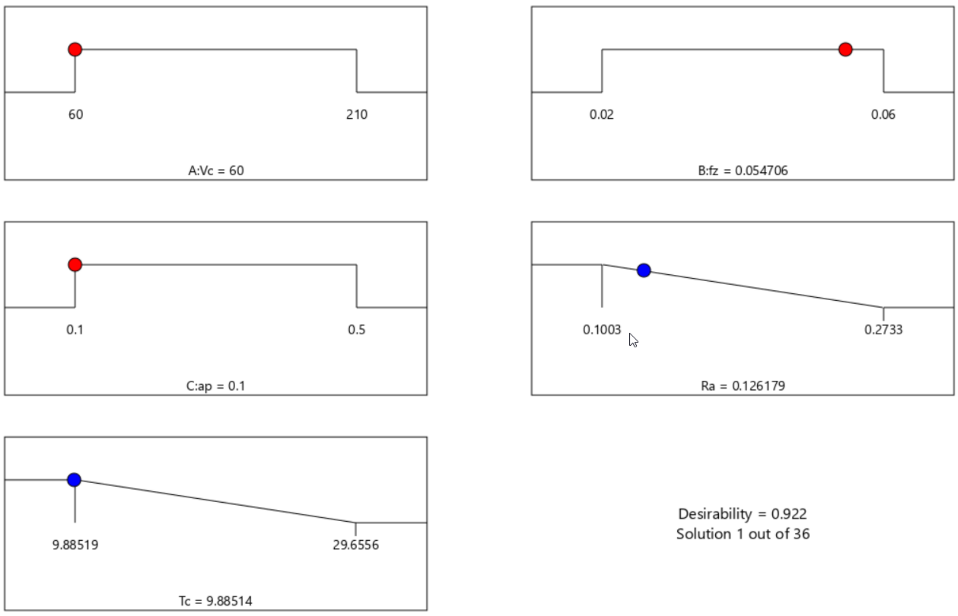

Fig. 3. Optimization results

III. RESULTS AND DISCUSSION

Based on the regression analysis, mathematical models were developed to predict surface roughness (Ra) and cutting time (Tc) as functions of the cutting speed (Vc), depth of cut (ap), and feed rate (fz). The models incorporated both linear and quadratic terms to capture potential non-linear effects.

The developed mathematical models were validated using statistical techniques such as the coefficient of determination (R^2), which measures the proportion of variation in the response explained by the model, and the lack of fit test, which assesses the adequacy of the model in representing the data.

The collected data, including the surface roughness and cutting time for each experimental run, were compiled for further analysis. Regression analysis and analysis of variance (ANOVA) techniques were employed to develop mathematical models, assess the significance of the factors, and identify their interactions.

The developed mathematical models were validated using statistical measures such as the coefficient of determination (R^2) and the lack of fit test. Once validated, the models were used for optimization. Optimization algorithms were applied to determine the optimal factor levels that simultaneously minimized surface roughness and cutting time. The R2 of regression models for Ra and Tc are 88.19% and 88.31%, respectively.

- The regression model for surface roughness R_a

$$R_a=0.024278+0.000173V_c+0.465375f_z+0.224112a_p+0.011983 V_c*f_z-0.001555V_c*ap+2.5f_z*a_p$$

- The regression model for cutting time T_c

$$T_c=36.92407+1.1411^{E-17}*f_z+3.92523^{E-16}*a_p$$

The optimization process aimed to identify the optimal combination of machining parameters that simultaneously minimized surface roughness (Ra) and cutting time (Tc). The desirability function approach or numerical optimization algorithms were employed to determine the optimal factor levels.

Based on the analysis, the optimized machining parameters were found to be V_c = 60 m/min, f_z = 0.054706 mm/tooth, and ap = 0.1 mm. At these optimized levels, the surface roughness (R_a) was measured to be 0.126179 µm, while the cutting time (T_c) was reduced to 9.88514 seconds.

IV. Conclusion

The results of the study demonstrated the effectiveness of the response surface methodology (RSM) in optimizing the face milling process of hardened SKD11. The mathematical models derived from the experimental data accurately predicted the surface roughness and cutting time based on the selected machining parameters.

The optimization process successfully identified the optimal parameter values that simultaneously minimized surface roughness and cutting time. The optimized machining parameters provided significant improvements in surface roughness and reduced the overall cutting time, indicating enhanced machining performance and efficiency.

The findings also revealed the importance of considering the interactions between cutting speed, feed rate, and depth of cut in the face milling process. The identified influential factors can serve as guidelines for process improvement and parameter selection in real-world machining operations.

However, it is important to acknowledge the limitations of the study, such as the restricted range of experimental conditions and the assumptions made in the mathematical models. Future research should explore additional factors and their interactions to further enhance the understanding and optimization of the face milling process for hardened SKD11.

Overall, the results and discussion presented a comprehensive analysis of the experimental data, the development of mathematical models, the optimization of surface roughness and cutting time, and the implications of the findings for the face milling process of hardened SKD11 using the response surface methodology.

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