Multi-Objective Optimization of Finishing Milling of C45 Steel using Factorial Design

Pham Ngoc Linh
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
linhpn@haui.edu.vn

Tran Ngoc Tan
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
tantn@haui.edu.vn

Vu Dinh Toan
School of Mechanical and Automotive Engineering, Hanoi University of Industry, Hanoi, Vietnam
toan_vd@haui.edu.vn

Thuy Duong Nguyen
School of Mechanical Engineering, Hanoi University of Science and Technology, Hanoi, Vietnam
duong.nguyenthuy@hust.edu.vn (corresponding author)

Received: 3 June 2024 | Revised: 10 September 2024 | Accepted: 14 September 2024

 DOI: https://doi.org/10.48084/etasr.8017

ABSTRACT

This study presents an innovative approach to optimizing the milling process of C45 steel using a factorial design of experiments. The impact of key technological parameters, including cutting speed (V_c), feed per tooth (f_z), depth of cut (a_p), and lubrication conditions (dry and flood), on surface roughness (R_a) and Material Removal Rate (MRR) was thoroughly analyzed. Through the application of Analysis of Variance (ANOVA), significant factors and their interactions were identified, with f_z and lubrication conditions showing the most substantial influence on R_a. The interaction between f_z and lubrication condition was particularly notable, highlighting the importance of these parameters in achieving optimal surface quality. Multi-objective optimization was conducted using the desirability function method to balance the objectives of minimizing R_a and maximizing MRR. The optimal V_c and f_z conditions under flood lubrication were found 200 m/min and 0.3 mm/tooth, respectively, achieving a desirability index of 0.801. Under dry lubrication, the optimal conditions were 200 m/min and 0.3 mm/tooth, respectively, with a desirability index of 0.803. These results demonstrate that both lubrication conditions can be effectively optimized to enhance machining performance. The findings provide a comprehensive framework for improving the milling process of C45 steel, contributing valuable insights into the effects of cutting parameters and lubrication conditions on surface quality and MRR.

Keywords-multi-objective optimization; factorial design; surface roughness; material removal rate; face milling

I. INTRODUCTION

Milling is a fundamental machining process extensively used in the manufacturing industry to shape and finish metal components [1, 2]. The quality of the machined surface and the efficiency of the process are critical factors that influence the performance and longevity of the final product. For materials such as C45 steel [3], which is widely used in engineering applications due to its excellent mechanical properties, optimizing the milling process parameters is essential to achieve high surface quality and maximize productivity [4]. Cutting parameters like speed (V_c), feed per tooth (f_z), and depth of cut (a_p) are crucial in determining surface roughness (R_a) and Material Removal Rate (MRR) in the milling process [5]. Additionally, lubrication conditions, whether dry or with flood cooling, significantly affect the thermal and mechanical interactions at the cutting interface, further influencing the machining outcomes. Therefore, a comprehensive understanding of how these parameters interact and affect the machine performance is necessary for optimizing the milling process [6].

Factorial Design Of Experiments (DOE) [7] is a robust statistical method that allows for the simultaneous investigation of multiple factors and their interactions. By systematically varying the levels of each factor, factorial DOE [8] provides insights into the main effects and interactions, enabling the identification of the most significant parameters influencing the responses. This study utilizes DOE to analyze the effects of cutting parameters and lubrication conditions in the milling of C45 steel, focusing on R_a and MRR.

The objectives of this research are twofold: first, to analyze the individual and interaction effects of the selected cutting parameters and conditions on R_a and MRR using ANOVA and contour plots; and second, to perform multi-objective optimization to identify the optimal machining conditions that balance the trade-offs between these two objectives. The results of this experimental research are expected to provide valuable insights and practical guidelines for improving the efficiency and quality of the milling process for C45 steel, contributing to enhanced manufacturing performance and product quality.

In the subsequent sections, we describe the experimental setup and methodology, present and discuss the results of the data analysis, and conclude with the optimal machining conditions identified through the multi-objective optimization approach.

II. RESEARCH METHODOLOGY

A. Experimental Procedure

The experiments were carried out on a 3-Axis CNC Milling Center (spindle speed range: 50 - 4000 rpm, maximum milling diameter: 300 mm, maximum milling length: 500 mm, spindle motor power: 15 kW, control system: Fanuc Oi-TF). The cutting tool used was a carbide insert, specifically ISO CNMG 120408 (Figure 1), which offers excellent wear resistance and thermal stability, ideal for machining C45 steel. The tool specifications are: Insert type: ISO CNMG 120408, material: Tungsten Carbide, coating: TiAlN (titanium aluminum nitride), number of teeth: z = 4, tool holder: ISO PCLNR 2525M12. The workpiece/cutting tool and the 3-axis milling center are presented as in Figures 1 and 2, respectively.

Fig. 1. The experimetal workpiece and cutting tool

The cutting parameters were chosen based on the experiments and the existing literature. Factorial DOE was employed to systematically predict the effects of four factors on R_a and MRR: cutting speed (V_c) of 80, 160, and 240 m/min; feed per tooth (f_z) of 0.1, 0.2, and 0.3 mm/tooth; depth of cut (a_p) of 0.1, 0.2, and 0.3 mm; and lubrication condition (CL) (dry and flood).

Fig. 2. The experimental machine

These factors and their levels were chosen to encompass a wide range of practical cutting conditions. The factorial design resulted in a total of 19 experimental runs (Table I).

TABLE I. EXPERIMENTAL RESULTS

No.	V_c	f_z	a_p	CL	R_a	MRR
	m/min	mm/tooth	mm	-	µm	cm^3/min
1	240.00	0.145	0.11	Dry	2.234	23.329
2	240.00	0.300	0.30	Dry	1.914	137.58
3	240.00	0.100	0.25	Flood	0.492	38.217
4	240.00	0.300	0.11	Flood	3.113	50.446
5	80.00	0.120	0.10	Dry	1.725	6.115
6	80.00	0.300	0.12	Flood	0.909	18.344
7	80.00	0.261	0.30	Dry	2.271	39.233
8	80.00	0.100	0.26	Flood	2.611	13.248
9	160.00	0.100	0.30	Dry	0.881	30.573
10	160.00	0.197	0.19	Flood	1.665	38.948
11	160.00	0.300	0.10	Dry	3.363	30.573
12	160.00	0.300	0.21	Flood	1.208	64.204
13	185.60	0.196	0.30	Flood	1.32	69.511
14	185.60	0.210	0.20	Dry	2.337	50.396
15	185.60	0.100	0.10	Flood	0.785	11.822
16	138.39	0.190	0.10	Flood	1.091	16.748
17	138.39	0.300	0.30	Flood	2.779	79.332
18	138.39	0.100	0.20	Dry	1.556	17.365
19	138.39	0.222	0.20	Dry	1.448	38.957

R_a was measured using a Mitutoyo Surftest JS-201 surface roughness tester, ensuring high accuracy in the assessment of the machined surface. The MRR was calculated by [9]:

$$\mathrm{MRR} = \mathrm{V_c}.\mathrm{A_c}$$

where A_c is chip section in mm^2.

III. MULTI-OBJECTIVE OPTIMIZATION

A. Analysis of Variance

The experimental data were analyzed using ANOVA analysis to determine the significance of each factor on Ra and MRR. Interaction effects were examined through contour plots, providing a visual representation of the combined influence of multiple factors. The multi-objective optimization approach, employing the desirability function method, was used to find the optimal machining conditions that balance the objectives of minimizing R_a and maximizing MRR. By systematically exploring the effects of each factor and their interactions, this study aims to provide a comprehensive understanding of the optimal machining parameters for the milling process of C45 steel, leading to enhanced machining performance and surface quality. The ANOVA was conducted to assess the significance of each factor and their interactions on Ra. The results are summarized in Table II,

TABLE II. ANALYSIS OF VARIANCE FOR SURFACE ROUGHNESS

Source	Sum of Squares	df	F-Value	P-Value
V_c	1.23	2	9.48	0.0029
f_z	3.84	2	29.55	0.00001
a_p	1.32	2	10.18	0.0022
CL	13.52	1	208.23	2.2E-09
V_c:f_z	0.11	4	0.43	0.7816
V_c:a_p	0.08	4	0.32	0.8586
V_c:CL	0.42	2	3.26	0.0714
f_z:a_p	0.49	4	1.87	0.1761
f_z:CL	1	2	7.71	0.0062
a_p:CL	0.41	2	3.19	0.0747
Residual	0.84	13	-	-

V_c:f_z is the interaction between cutting speed (Vc) and feed rate (fz), etc.

The ANOVA analysis (Table II) on the interaction effects between factors reveals several key insights. The interactions between V_c, f_z and V_c, a_p are insignificant, with high P-values indicating minimal interaction effects on R_a. Interactions such as V_c:CL and f_z:a_p, and a_p:CL show some effects but are not statistically significant, suggesting that while there is some interaction, it is not strong enough to be considered influential. However, the interaction between feed per tooth and lubrication condition (f_z:CL) is significant with a P-value of 0.0062, suggesting a notable combined effect on R_a. The results of the ANOVA analysis on the interaction effects highlight that while most interactions of V_c, f_z, a_p, and CL are not statistically significant, the interaction between f_z and CL significantly affects surface roughness. This implies that the combined influence of f_z and CL should be carefully considered when optimizing considering R_a.

B. Multiple Objective Optimization Problem Definition

The goal of this experimental research is to optimize the milling process of C45 steel by minimizing R_a and maximizing MRR to achieve high surface quality and machining efficiency. This requires identifying the optimal combination of cutting parameters including {V_c, f_z, a_p}, and lubrication conditions {dry and flood}. Mathematically, the problem can be defined as:

$$\begin{cases} minimize\ R_a \\ maximize\ MRR \end{cases} \text{Subject to:} \begin{cases} 80 \leq V_c \leq 240 \\ 0.1 \leq f_z \leq 0.3 \\ 0.1 \leq a_p \leq 0.3 \\ CL: Dry, Flood \end{cases}$$

By employing factorial DOE and analyzing the effects using ANOVA and contour plots, this study aims to understand the influences of these factors and identify the optimal settings for balancing R_a and MRR.

C. Multiple Objective Optimization Approach

To address the dual objectives of minimizing R_a and maximizing MRR, a multi-objective optimization approach was employed using the desirability function method. The mechanism transforms multiple objectives into a single composite desirability function, making it easier to identify the optimal machining parameters. First, individual desirability functions were defined for each objective. For R_a, the goal was to minimize its value, while for MRR, the goal was to maximize it. The individual desirability (d_i) for each response was scaled between 0 and 1, where 0 indicates a completely undesirable outcome, and 1 represents the most desirable outcome. The individual desirability functions were calculated as follows:

$$\begin{cases} d_{Ra} = \frac{R_{amax} - R_a}{R_{amax} - R_{amin}} \\ d_{MRR} = \frac{MRR - MRR_{min}}{MRR_{max} - MRR_{min}} \end{cases}$$

These formulas ensure that as R_a decreases, the desirability increases. By contract, as MRR increases, the desirability increases. Then, the overall desirability index (D) was calculated by combining the individual desirability using the geometric mean. The overall desirability index provides a single metric that reflects the balance between the two objectives. The formula for the overall desirability index is:

$$D = \sqrt{(d_{Ra} \times d_{MRR})}$$

where d_{Ra} and d_{MRR} are the individual desirabilities of R_a and MRR, respectively.

In this study, the multi-objective optimization calculations were performed using the Python programming language, with the support of the Statsmodels library [10] and Design Expert 13 software. By applying this optimization approach, each set of machining parameters was evaluated based on its overall desirability index. The parameters with the highest overall desirability index were considered optimal, as they provided the best balance between minimizing R_a and maximizing MRR.

D. Multiple Objective Optimization Results

1) Optimization Results for Flood Lubrication

The optimization results for the milling process of C45 steel under flood lubrication conditions reveal significant insights into achieving the best balance between R_a and MRR (Figure 3). The contour plots indicate that the highest desirability index of 0.801 is achieved at a V_c of approximately 200 m/min and a f_z of 0.3 mm/tooth. This suggests that high cutting speeds combined with moderate to high feed rates are optimal for maximizing overall machining performance under flood lubrication. The R_a contour plot shows that the minimum R_a value of around 0.5 μm is achieved at a V_c of approximately 240 m/min and a f_z of 0.1 mm/tooth. This indicates that increasing the cutting speed while maintaining a low f_z significantly improves surface finish. The ability of flood lubrication to reduce R_a can be attributed to its effectiveness in cooling the cutting zone and reducing tool wear, which in turn enhances surface quality.

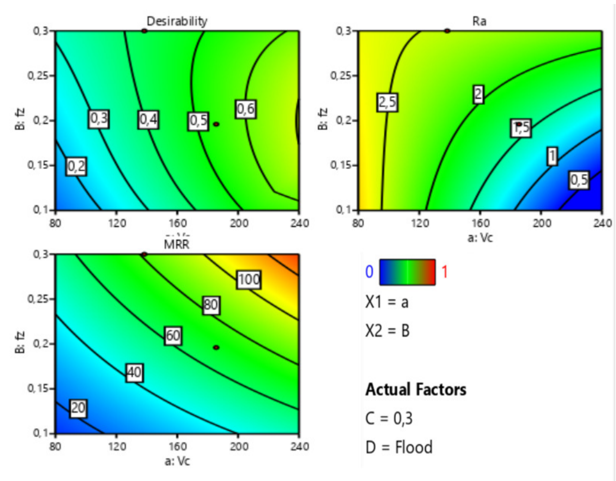

Fig. 3. Contour plot for Desirability, R_a, MRR, and flood condition.

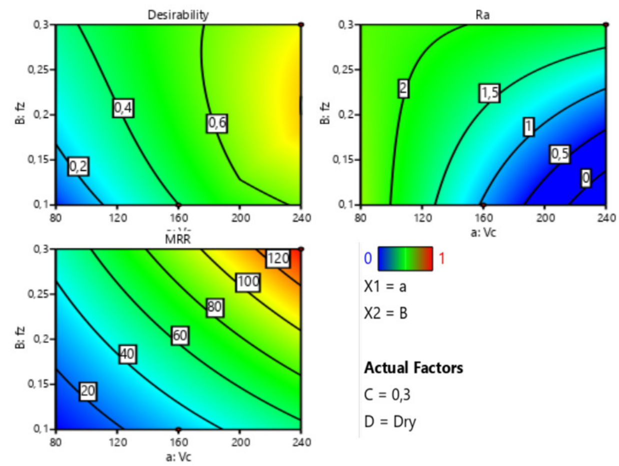

Fig. 4. Contour plot for Desirability, R_a, MRR and dry conditions.

2) Optimization Results for Dry Lubrication

Similarly, the optimization results for the milling process of C45 steel under dry conditions reveal that the highest desirability index of 0.803 is achieved at a V_c of approximately 200 m/min and a f_z of 0.3 mm/tooth (Figure 4). The minimum R_a of 0.7917 μm is obtained at V_c and f_z around 240 m/min and 0.1 mm/tooth, respectively. While R_a is slightly higher than that under flood lubrication, it still shows that increasing V_c and lowering f_z improves surface finish. The maximum MRR, consistent across both lubrication conditions, is achieved at a V_c of around 240 m/min and a f_z of 0.3 mm/tooth. This demonstrates that high V_c and f_z are optimal for maximizing overall machining performance, even in dry conditions.

The maximum MRR, consistent across both lubrication conditions, is achieved at a V_c of around 240 m/min and a f_z of 0.3 mm/tooth. This demonstrates that high V_c and f_z are optimal for maximizing MRR (Figure 5).

The comparison of dry and flood lubrication conditions shows that flood lubrication generally provides better surface roughness and higher MRR, making it more suitable for achieving optimal machining performance in terms of both surface quality and productivity (Figure 6). However, the multi-objective optimization results indicate that dry lubrication can still be effective, especially where the use of lubricants is restricted or undesirable, by carefully selecting high cutting speeds and appropriate feed rates.

When optimizing with a priority on minimizing R_a, the best results are achieved with flood lubrication at a high V_c of 240 m/min and a low f_z of 0.1 mm/tooth (Figure 6). When optimizing MRR, the maximum MRR is achieved at a V_c of 240 m/min and a f_z of 0.3 mm/tooth, regardless of the lubrication condition. When aiming to balance both R_a and MRR for an optimal overall performance, the highest desirability index is achieved at a V_c of approximately 200 m/min and a f_z of 0.3 mm/tooth under dry lubrication.

These findings provide valuable insights for optimizing the milling process of C45 steel, leading to improved machining performance and product quality.

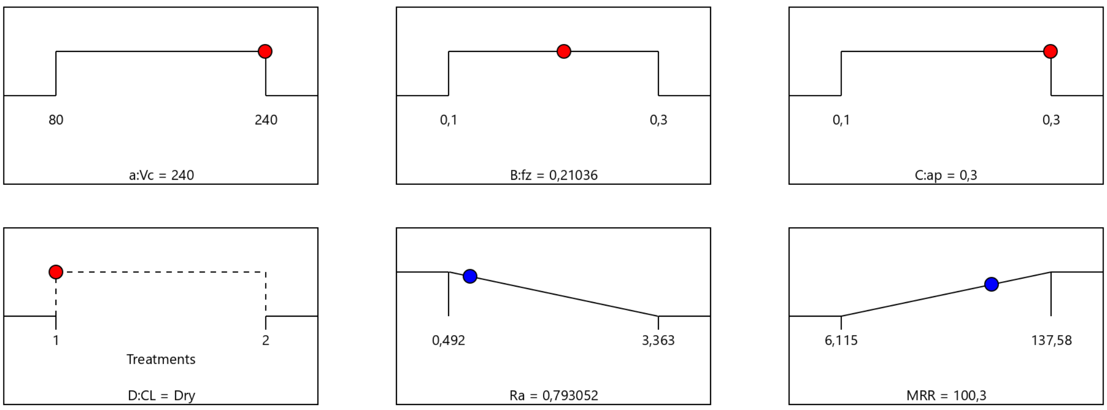

Fig. 5. Optimization results for cutting parameters and psponses.

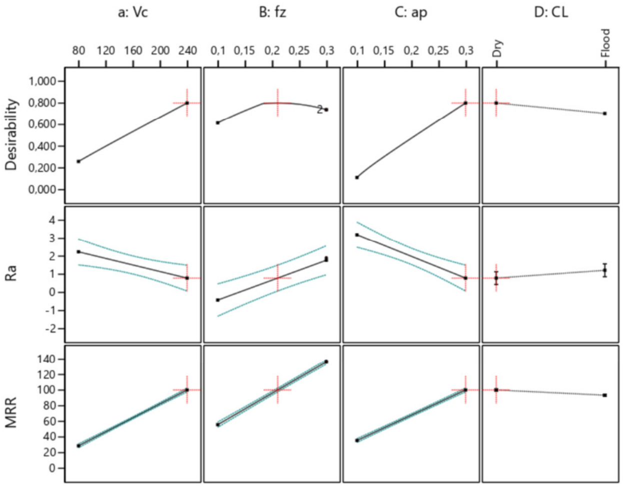

Fig. 6. Interaction plots for desirability, R_a, and MRR.

IV. CONCLUSION

The comparison of dry and flood lubrication conditions shows that flood lubrication generally provides lower R_a and higher MRR, making it more suitable for achieving optimal machining performance in terms of both surface quality and productivity. However, the multi-objective optimization results indicate that dry lubrication can still be effective, especially where the use of lubricants is restricted or undesirable, by carefully selecting high cutting speeds and appropriate feed rates.

When the optimization prioritizes minimizing R_a, the best results are achieved with flood lubrication at a high V_c of 240 m/min and a low f_z of 0.1 mm/tooth, resulting in a minimum R_a of 0.5 µm. For optimizing the MRR, the maximum MRR of 120 cm³/min is achieved at a V_c of 240 m/min and a f_z of 0.3 mm/tooth, irrespective of the lubrication condition. These findings align with those of previous studies that highlight the effectiveness of high V_c and f_z in enhancing MRR while emphasizing the role of lubrication in improving surface finish.

When aiming to balance both R_a and MRR for an optimal overall performance under dry lubrication, the highest desirability index of 0.801 is achieved at V_c and f_z of approximately 200 m/min 0.3 mm/tooth, respectively. This balance ensures a reasonable compromise between achieving a lower R_a and a higher MRR, demonstrating the feasibility of dry machining for certain applications. This is consistent with other research suggesting that dry machining, with optimized parameters, can achieve acceptable levels of surface quality and productivity, especially in environmentally sensitive or lubricant-restricted contexts.

In this study, the comparison of different lubrication methods (dry, flood) has provided valuable insights into the impact on surface roughness. The results show that dry machining tends to increase surface roughness due to higher temperatures and friction [11]. However, MQL has been demonstrated to offer better surface finish and tool life by minimizing cutting temperature and friction, especially under high-speed conditions [12]. Additionally, high-pressure coolant systems significantly reduce tool wear and improve surface quality by efficiently cooling the cutting zone [13]. These findings suggest that lubrication methods must be carefully selected based on the specific requirements of the machining process to optimize both productivity and surface quality

Additionally, this study introduces a novel approach by applying multi-objective optimization, effectively balancing R_a and MRR under varying lubrication conditions. The interaction between feed rate and lubrication conditions has been analyzed in more detail compared to previous works, providing new insights into the optimization of the milling process for C45 steel. These findings enhance the existing body of knowledge by offering more comprehensive recommendations for both productivity and surface quality in machining operations.

In summary, flood lubrication is recommended for scenarios where the highest surface quality is paramount, and productivity demands are high. In contrast, dry lubrication is a viable alternative for applications where the use of cutting fluids is limited, provided that machining parameters are carefully optimized. These findings offer valuable insights for optimizing the milling process of C45 steel, leading to improved machining performance and product quality. The results of this study contribute to the broader understanding of machining optimization and can serve as a reference for future research in the field.

REFERENCES

[1] R. V. Rao, *Advanced Modeling and Optimization of Manufacturing Processes: International Research and Development*. New York, NY, USA: Springer, 2011.

[2] T.-V. Do and N.-A.-V. Le, "Optimization of Surface Roughness and Cutting Force in MQL Hard-Milling of AISI H13 Steel," in *International Conference on Engineering Research and Applications*, Thai Nguyen, Vietnam, Dec. 2019, pp. 448–454, https://doi.org/10.1007/978-3-030-04792-4_58.

[3] N. T. Duong, P. V. Hung, N. V. Canh, and N. T. Sinh, "Study on anisotropy of surface friction of steel C45 conducted by fine-grinding method," *Journal of Science and Technology - Technical Universities*, vol. 29, no. 1, pp. 46–50, Jan. 2019.

[4] T. H. Le, V. B. Pham, and T. D. Hoang, "Surface Finish Comparison of Dry and Coolant Fluid High-Speed Milling of JIS SDK61 Mould Steel," *Engineering, Technology & Applied Science Research*, vol. 12, no. 1, pp. 8023–8028, Feb. 2022, https://doi.org/10.48084/etasr.4594.

[5] K. Weinert, I. Inasaki, J. W. Sutherland, and T. Wakabayashi, "Dry Machining and Minimum Quantity Lubrication," *CIRP Annals*, vol. 53, no. 2, pp. 511–537, Jan. 2004, https://doi.org/10.1016/S0007-8506(07)60027-4.

[6] V. C. Nguyen, T. D. Nguyen, and D. H. Tien, "Cutting Parameter Optimization in Finishing Milling of Ti-6Al-4V Titanium Alloy under MQL Condition using TOPSIS and ANOVA Analysis," *Engineering, Technology & Applied Science Research*, vol. 11, no. 1, pp. 6775–6780, Feb. 2021, https://doi.org/10.48084/etasr.4015.

[7] J. Lawson, *Design and Analysis of Experiments with R*. Boca Raton, FL, USA: CRC Press, 2014.

[8] A. W. El-Morsy, "Wear Analysis of a Ti-5Al-3V-2.5Fe Alloy Using a Factorial Design Approach and Fractal Geometry," *Engineering, Technology & Applied Science Research*, vol. 8, no. 1, pp. 2379–2384, Feb. 2018, https://doi.org/10.48084/etasr.1743.

[9] L. Norberto Lopez de Lacalle, F. J. Campa, and A. Lamikiz, "Milling," in *Modern Machining Technology*, J. Paulo Davim, Ed. Sawston, UK: Woodhead Publishing, 2011, pp. 213–303.

[10] "Statsmodels" https://www.statsmodels.org/stable/index.html.

[11] M. Grover and Z. Khan, "The Comparison on Tool Wear, Surface Finish and Geometric Accuracy when Turning EN8 Steel in Wet and Dry Conditions," in *World Congress on Engineering*, London, UK, Jul. 2014, vol. 2, pp. 1093–1097.

[12] S. N. Sakharkar and R. S. Pawade, "Effect of Machining Environment on Turning Performance of Austempered Ductile Iron," *CIRP Journal of Manufacturing Science and Technology*, vol. 22, pp. 49–65, Aug. 2018, https://doi.org/10.1016/j.cirpj.2018.04.006.

[13] N. R. Dhar and M. Kamruzzaman, "Effect of High-Pressure Coolant on Tool Wear, Tool Life and Surface Roughness in Turning Medium Carbon Steel by SNMG Insert," in *9th Cairo University International Conference on Mechanical Design and Production*, Cairo, Egypt, Jan. 2008, pp. 555–565.