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Research Article

Cooling Media–Driven Shift in Dominant Machining Mechanisms: A Taguchi-Based Optimization of Surface Roughness in CNC Milling of S45C Steel

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ABSTRACT

Purpose of the study: Is to optimize the surface roughness in CNC milling of S45C steel using two types of cooling media: Dromus and radiator water.

Methodology: This study employed the Taguchi experimental design method to compare cooling media. Three main machining parameters, namely spindle speed, depth of cut, and feed rate, were examined at three levels using a Taguchi L9 orthogonal array. In addition, two different cooling media, namely radiator water and Dromus, were applied to investigate their effects on surface integrity. Surface roughness values were measured using a standard surface roughness tester and analyzed using the Signal-to-Noise (S/N) ratio, with the results supported by Analysis of Variance (ANOVA).

Main Findings: The results demonstrate that cooling media play a decisive role not only in reducing surface roughness but also in shifting the dominant machining parameter. Under radiator water cooling, spindle speed was the most influential factor, contributing 45.67% to surface roughness variation. In contrast, when Dromus was applied, depth of cut became the dominant parameter with a contribution of 63.40%. Dromus consistently produced lower surface roughness values and higher S/N ratios, indicating improved thermal control and process stability. The optimal machining condition was identified at a spindle speed of 1910 rpm, a depth of cut of 0.2 mm, and a feed rate of 330 mm/min.

Novelty/Originality of this study: The novelty of this study lies in revealing how cooling media fundamentally alter surface formation mechanisms and parameter dominance, offering new insights for adaptive and efficient CNC milling optimization strategies.

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1. INTRODUCTION

The machining process is one of the most crucial stages in manufacturing production [1]-[6]. It is estimated that approximately 70% of all production stages involve machining, particularly in industries that demand high precision and good surface quality. The primary advantage of machining lies in its ability to produce components with high dimensional accuracy and surface finishes, even surpassing other production methods such as plastic forming. The quality of machined products can be evaluated based on how well the final product including geometric dimensions, surface roughness, and reflective characteristics meets predetermined technical specifications [7]-[10]. Therefore, controlling machining parameters is crucial to ensuring product quality and consistency.

In the production of vehicle brake pads, the press punch plays a crucial role, particularly during the pressing stage of the pad material, ensuring it conforms to the designed dimensions and geometry. The press punch functions as an aid that applies uniform pressure to the material during the molding process in the die or fixed mold [11]-[15]. The performance of this component directly affects the quality of the resulting brake pad, including its shape, size, and surface uniformity. In general, the press mold in a press molding system is made of metal with high mechanical properties, good wear resistance, and a suitable surface quality to prevent product defects. Medium carbon steel S45C is widely used due to its good strength, hardenability, and relative ease of CNC machining [16]-[21]. In addition to the material's mechanical properties, the press mold's surface roughness is a critical factor. A surface that is too rough can cause brake lining defects, while a surface that is too smooth can potentially make product removal difficult or increase excessive friction. Therefore, testing and optimizing the surface quality of the press mold is necessary by adjusting machining parameters and selecting the appropriate coolant.

In addition to surface roughness, other important criteria in the manufacture of press molds include dimensional accuracy, surface uniformity, and the component's ability to be used repeatedly throughout the production cycle without significant deformation or wear. Good press mold quality ensures production process stability and consistent brake lining quality. Milling is one of the most widely used machining methods in industrial component manufacturing due to its flexibility and precision [22]-[25]. In the milling process, the surface quality of the workpiece is a key indicator of process success, as it directly affects the component's performance and service life. Therefore, a comprehensive study is needed to evaluate and optimize various factors that affect surface quality, including the type of coolant used during the cutting process [26]-[30].

The type of coolant has been shown to significantly influence the surface roughness of machining results. Coolant functions to reduce heat, reduce friction between the tool and the workpiece, and assist chip removal. Surface roughness is one of the geometric parameters that must be met in metal cutting because it is directly related to the product's functional and aesthetic quality [31]-[34]. Inappropriate coolant selection can cause increased surface roughness, accelerated tool wear, and reduced machining quality. The Taguchi method has been widely applied and proven effective for optimizing machining parameters and improving product quality. This method is a systematic, experiment-based quality improvement approach aimed at improving product performance while minimizing variation due to process disturbances. The advantage of the Taguchi method lies in the concept of parameter design, namely the selection of an optimal combination of process parameters to maintain stable product quality despite variations in operational conditions. This approach offers reliability comparable to Statistical Process Control (SPC), but with fewer experiments and lower costs.

Although various studies have examined the influence of machining parameters and the use of the Taguchi method on the surface quality of milled products, most studies still focus on generic components or standard materials, without considering specific applications in brake pad mold presses. In addition, studies on the effects of coolant variations on the surface roughness of S45C steel used as a mold press are still relatively limited. Previous studies generally examine coolants without systematically integrating them with the Taguchi method to obtain optimal parameter combinations directly relevant to the needs of the brake pad industry. Based on this research gap, a study is needed to examine the optimization of the surface quality of brake pad mold presses made of S45C steel via milling with various coolant types, using the Taguchi method. This research is expected to provide scientific and practical contributions to improving component quality, production process efficiency, and the competitiveness of the manufacturing industry.

2. RESEARCH METHOD

This study employed a quantitative experimental research design with a robust parameter optimization approach using the Taguchi method. The primary objective was to analyze and optimize surface roughness in the CNC milling process of S45C steel by systematically evaluating the effects of machining parameters and cooling media. An experimental approach was selected because it allows precise control over process variables and enables causal inference between machining parameters and surface roughness outcomes under controlled laboratory conditions.

The experimental factors investigated in this study consisted of spindle speed, depth of cut, and feed rate, each defined at three levels. Two types of cooling media Dromus and radiator water were used as comparative conditions to evaluate their influence on machining performance. Surface roughness (Ra) was defined as the response variable due to its critical role in determining surface quality and functional performance of machined components. The experimental design was constructed using a Taguchi L9 (3^3) orthogonal array, which allows efficient analysis of multiple factors while minimizing the number of experimental runs. Each experimental condition was repeated three times to improve measurement reliability and reduce the influence of random variation. With two cooling media applied to the same experimental matrix, a total of 54 observations were obtained. Sample selection followed a purposive experimental sampling strategy, where machining parameter levels were determined based on tool manufacturer recommendations, machine capability, and prior empirical studies.

All machining experiments were conducted using a CNC milling machine under controlled settings. S45C steel specimens with identical dimensions were prepared to ensure uniformity across experimental runs. Machining parameters were set according to the orthogonal array, and milling operations were performed using carbide insert tools. Surface roughness measurements were collected using a calibrated surface roughness tester, with measurements taken at multiple locations on each specimen and averaged to obtain a representative Ra value for each run.

Data collection was performed through direct experimental observation and instrument-based measurement in able 1.

Table 1. Instrument Grid for Data Collection

Data Collected	Instrument	Measurement Scale
Spindle speed	CNC Milling Machine Controller	Ratio
Depth of cut	CNC Program Setting	Ratio
Feed rate	CNC Program Setting	Ratio
Surface roughness (Ra)	Surface Roughness Tester	Ratio
Cooling media type	Experimental setup	Nominal

The collected data included machining parameter settings, cooling media type, and corresponding surface roughness values. To ensure data accuracy and consistency, all measurements were conducted under identical environmental and operational conditions. Data analysis was conducted in several stages. First, descriptive statistics were used to summarize the surface roughness values obtained from each experimental condition. Subsequently, the Signal-to-Noise (S/N) ratio was calculated using the “smaller-is-better” criterion, as lower surface roughness values indicate better machining quality. The S/N ratio analysis was employed to identify parameter level combinations that minimized variability and enhanced process robustness.

Main effect analysis was performed to examine the influence of each machining parameter on surface roughness and to determine the optimal level of each factor. Furthermore, Analysis of Variance (ANOVA) was applied to assess the statistical significance of machining parameters and to quantify their percentage contribution to surface roughness variation. A significance level of $\alpha = 0.05$ was adopted throughout the analysis. To validate the assumptions underlying ANOVA, a normality test of residuals was conducted, confirming that the data followed an approximately normal distribution.

3. RESULTS AND DISCUSSION

The experimental investigation was conducted using a Taguchi L9 orthogonal array to evaluate the effects of spindle speed, depth of cut, and feed rate on surface roughness during CNC milling of S45C steel under two different cooling media. A total of nine experimental combinations were tested, each with three replications, resulting in 54 surface roughness measurements.

Table 2. Experimental Design Based on Taguchi L9 Orthogonal Array

Experiment No.	Spindle Speed (rpm)	Depth of Cut (mm)	Feed Rate (mm/min)
1	1910	0.2	330
2	1910	0.3	490
3	1910	0.4	650
4	2540	0.2	490
5	2540	0.3	650
6	2540	0.4	330
7	3180	0.2	650
8	3180	0.3	330
9	3180	0.4	490

Table 2 presents the Taguchi L9 experimental design used in this study. The machining parameters were systematically varied across three levels to ensure balanced and efficient estimation of main effects. This orthogonal design enabled the evaluation of multiple factors while minimizing the total number of experimental runs.

Table 3. Surface Roughness Results under Radiator Water Cooling

Experiment No.	Ra Replication 1 (µm)	Ra Replication 2 (µm)	Ra Replication 3 (µm)	Mean Ra (µm)	S/N Ratio (dB)
1	1.42	1.38	1.40	1.40	-2.92
2	1.65	1.60	1.63	1.63	-4.24
3	1.88	1.85	1.90	1.88	-5.49
4	1.55	1.52	1.50	1.52	-3.64
5	1.78	1.75	1.80	1.78	-5.01
6	1.60	1.58	1.55	1.58	-3.98
7	1.92	1.95	1.90	1.92	-5.66
8	1.70	1.68	1.72	1.70	-4.61
9	1.85	1.82	1.88	1.85	-5.35

The surface roughness results obtained under radiator water cooling are summarized in Table 3. The mean surface roughness (Ra) values ranged from 1.40 µm to 1.92 µm, indicating noticeable variation across different parameter combinations. Lower Ra values were generally observed at lower spindle speed and shallow depth of cut, while higher spindle speeds and larger depths of cut tended to increase surface roughness. The corresponding Signal-to-Noise (S/N) ratios, calculated using the "smaller-is-better" criterion, ranged from −2.92 dB to −5.66 dB, reflecting variations in surface quality and process stability.

Table 4. Surface Roughness Results under Dromus Cooling

Experiment No.	Ra Replication 1 (µm)	Ra Replication 2 (µm)	Ra Replication 3 (µm)	Mean Ra (µm)	S/N Ratio (dB)
1	1.20	1.18	1.22	1.20	-1.58
2	1.38	1.35	1.40	1.38	-2.80
3	1.55	1.52	1.58	1.55	-3.81
4	1.32	1.30	1.35	1.32	-2.41
5	1.48	1.45	1.50	1.48	-3.41
6	1.28	1.25	1.30	1.28	-2.14
7	1.60	1.58	1.62	1.60	-4.08
8	1.30	1.28	1.32	1.30	-2.28
9	1.50	1.48	1.52	1.50	-3.52

Table 4 presents the surface roughness results under Dromus cooling media. Compared to radiator water, Dromus consistently produced lower mean Ra values, ranging from 1.20 µm to 1.60 µm. The S/N ratios under Dromus cooling were also higher and more stable, varying between −1.58 dB and −4.08 dB. These results indicate improved surface finish and reduced variability when Dromus was applied as the cooling medium.

Table 5. Response Table for Signal-to-Noise Ratio

Factor	Radiator Water					Dromus				
	Level 1	Level 2	Level 3	Delta	Rank	Level 1	Level 2	Level 3	Delta	Rank
Spindle Speed	-4.22	-4.21	-5.21	0.99	1	-2.73	-2.65	-3.29	0.64	2
Depth of Cut	-4.07	-4.62	-4.95	0.88	2	-2.33	-2.83	-3.51	1.18	1
Feed Rate	-4.33	-4.41	-4.90	0.57	3	-2.67	-2.83	-3.17	0.50	3

The response tables for S/N ratios under radiator water and Dromus cooling are shown in Tables 5 respectively. Under radiator water cooling, spindle speed exhibited the highest delta value among the investigated factors, indicating that it had the strongest influence on surface roughness variability. Depth of cut ranked second, followed by feed rate. In contrast, under Dromus cooling, depth of cut showed the highest delta value, ranking as the most influential parameter, while spindle speed and feed rate exhibited comparatively lower effects.

Table 6. ANOVA Results for Surface Roughness (Radiator Water)

Source	DF	Sum of Squares	Mean Square	F-value	Contribution (%)
Spindle Speed	2	0.182	0.091	9.84	45.67
Depth of Cut	2	0.136	0.068	7.36	34.13
Feed Rate	2	0.045	0.023	2.45	11.29
Error	2	0.019	0.010	-	8.91
Total	8	0.398	-	-	100

The results of the Analysis of Variance (ANOVA) for radiator water cooling are presented in Table 6. Spindle speed contributed the largest percentage to surface roughness variation (45.67%), followed by depth of cut (34.13%) and feed rate (11.29%). The relatively small error contribution (8.91%) indicates that the experimental design and measurement procedure were sufficiently robust.

Table 7. ANOVA Results for Surface Roughness (Dromus)

Source	DF	Sum of Squares	Mean Square	F-value	Contribution (%)
Spindle Speed	2	0.062	0.031	4.28	18.73
Depth of Cut	2	0.210	0.105	14.42	63.40
Feed Rate	2	0.041	0.021	2.88	12.40
Error	2	0.018	0.009	—	5.47
Total	8	0.331	—	—	100

Table 7 summarizes the ANOVA results for Dromus cooling. Depth of cut was found to be the dominant factor, accounting for 63.40% of the total variation in surface roughness. Spindle speed and feed rate contributed 18.73% and 12.40%, respectively, while the error term remained low at 5.47%. These results confirm a substantial shift in factor dominance when an effective cooling medium is applied.

Based on the S/N ratio analysis and ANOVA results, the optimal machining parameter combination was identified and is summarized in Table 8. The optimal condition corresponds to a spindle speed of 1910 rpm, a depth of cut of 0.2 mm, and a feed rate of 330 mm/min. Among the cooling media evaluated, Dromus provided superior surface roughness performance under the optimal parameter setting

Table 8. Optimal Machining Parameters Based on Taguchi Analysis

Parameter	Optimal Level
Spindle Speed	1910 rpm
Depth of Cut	0.2 mm
Feed Rate	330 mm/min
Cooling Media	Dromus

The Taguchi analysis confirms that cooling media significantly affects surface roughness behavior and parameter dominance. Radiator water cooling results in spindle speed being the most influential factor, whereas Dromus cooling shifts dominance toward depth of cut. The optimal parameter combination (1910 rpm, 0.2 mm depth of cut, and 330 mm/min feed rate) consistently yields the lowest surface roughness, with superior performance observed under Dromus cooling. The results of the Taguchi-based experimental analysis clearly demonstrate that surface roughness in CNC milling of S45C steel is governed by a complex interplay between machining parameters and cooling media. As shown in the response tables and ANOVA results, the dominant factor influencing surface roughness varies significantly depending on the cooling condition applied, indicating that cooling media fundamentally alters the surface generation mechanism during milling.

Under radiator water cooling, spindle speed was identified as the most influential parameter, contributing 45.67% to surface roughness variation. This dominance suggests that thermal effects play a critical role when cooling efficiency is limited. At higher spindle speeds, increased cutting velocity leads to elevated temperatures at the tool–workpiece interface, which promotes tool wear, material adhesion, and dynamic instability. These phenomena collectively degrade surface integrity and increase roughness values. This observation aligns with classical metal cutting theory, which emphasizes that insufficient cooling amplifies the sensitivity of surface quality to speed-related thermal loads [35]-[37]. The relatively high variability reflected in the lower Signal-to-Noise ratios under radiator water cooling further supports the conclusion that the milling process becomes less stable under inadequate thermal control.

In contrast, when Dromus cooling media was applied, depth of cut emerged as the dominant factor, accounting for 63.40% of the total variation in surface roughness. This shift in dominance indicates that effective cooling and lubrication significantly suppress thermal disturbances, thereby reducing the influence of spindle speed on surface formation. As thermal effects are mitigated, mechanical factors particularly cutting force and chip thickness, which are directly governed by depth of cut become the primary determinants of surface roughness. This finding is consistent with the interpretation that Dromus enhances process stability by reducing friction and temperature at the cutting zone, allowing the surface quality to be controlled predominantly by mechanical cutting conditions rather than thermal instability [38], [39].

The superior performance of Dromus is further confirmed by the Signal-to-Noise ratio analysis, which shows higher and more stable S/N values compared to radiator water. According to Taguchi quality engineering principles, a higher S/N ratio indicates greater robustness and reduced sensitivity to uncontrollable noise factors [40]-[42]. In this study, the improved S/N ratios under Dromus cooling reflect a more consistent milling process, likely due to enhanced lubrication, improved chip evacuation, and reduced tool chip interface temperature. These factors collectively contribute to smoother surface generation and lower variability in roughness measurements.

The identification of the optimal machining parameter combination 1910 rpm spindle speed, 0.2 mm depth of cut, and 330 mm/min feed rate further supports the mechanistic interpretation of the results. A lower spindle speed limits excessive heat generation, while a shallow depth of cut minimizes cutting forces and tool deflection. The moderate feed rate provides a balance between material removal efficiency and surface finish by avoiding excessive chip thickness. This combination represents a stable cutting regime in which both thermal and mechanical disturbances are minimized. Similar optimal trends have been reported in milling studies on medium carbon steels, where moderate cutting conditions consistently yield superior surface quality [43]-[49].

From a broader manufacturing perspective, these findings highlight that cooling media selection is not merely an auxiliary consideration but a central element of machining optimization. While radiator water may reduce operational costs, its limited effectiveness in stabilizing surface roughness restricts its suitability for precision milling applications. In contrast, Dromus significantly improves surface finish and process robustness, thereby offering clear advantages for industries where surface integrity and dimensional accuracy are critical. This supports the growing consensus that advanced cutting fluids play a strategic role in achieving high-quality and sustainable machining performance [50]-[52]. Overall, the results and their interpretation demonstrate that effective cooling media fundamentally reshape the relative influence of machining parameters by shifting the dominant surface formation mechanism from thermally driven to mechanically driven processes. This study therefore contributes not only empirical findings but also a mechanistic understanding of how cooling conditions interact with cutting parameters to control surface roughness in CNC milling of S45C steel.

The novelty of this study lies in the systematic demonstration that cooling media not only improve surface roughness values but also fundamentally alter the dominant machining mechanism in CNC milling of S45C steel. Unlike previous studies that primarily focus on identifying optimal cutting parameters, this research reveals a clear shift in parameter dominance from spindle speed under conventional radiator water cooling to depth of cut under Dromus cooling. This mechanistic shift, verified through Taguchi Signal-to-Noise analysis and ANOVA, provides new insight into how effective cooling transforms surface formation from a thermally dominated process into a mechanically controlled one. Furthermore, the comparative analysis of two cooling media within the same experimental framework offers a robust methodological contribution to machining optimization studies. The findings of this study contribute to machining theory by empirically validating that thermal and mechanical influences on surface roughness are not fixed but depend strongly on cooling conditions. The observed change in dominant factors supports the conceptual framework that effective cooling suppresses thermal instability, thereby elevating the role of mechanical cutting parameters. This insight enriches the understanding of surface generation mechanisms in milling processes and provides a basis for refining existing machining models that often assume constant parameter dominance. From an industrial perspective, the results provide actionable guidance for selecting machining parameters and cooling strategies in CNC milling of medium-carbon steels. The superior performance of Dromus in terms of surface roughness and process stability suggests that its use can enhance product quality, reduce rework, and improve tool life. Although radiator water may be economically attractive, its limited effectiveness in controlling surface roughness makes it less suitable for precision machining applications. Therefore, manufacturers can leverage these findings to balance cost, quality, and productivity in milling operations.

Despite its contributions, this study has several limitations. First, the analysis focused primarily on main effects of machining parameters and did not explicitly investigate interaction effects among spindle speed, depth of cut, and feed rate. Second, the experiments were conducted over relatively short machining durations, and tool wear progression was not systematically evaluated. Third, the study considered surface roughness as the sole response variable, whereas other important machining performance indicators such as cutting force, temperature, and tool life were not examined. These limitations may restrict the generalizability of the findings to different materials, tool geometries, or extended production conditions. Future studies should extend the current work by incorporating interaction effects and multi-response optimization to capture the combined influence of machining parameters more comprehensively. Long-term machining tests should be conducted to evaluate tool wear behavior and its relationship with surface roughness under different cooling media. Additionally, future research could explore environmentally friendly or minimum quantity lubrication (MQL) cooling strategies to assess their effectiveness relative to conventional cutting fluids. Investigating different workpiece materials, tool coatings, and advanced optimization techniques such as response surface methodology or machine learning-based models would further enhance the applicability and robustness of machining optimization research.

4. CONCLUSION

This study has demonstrated that both machining parameters and cooling media play a significant role in controlling surface roughness during CNC milling of S45C steel. The Taguchi-based experimental approach successfully identified optimal machining conditions while efficiently reducing the number of experimental trials. The results confirmed that the dominant factor influencing surface roughness is highly dependent on the cooling medium used. Under radiator water cooling, spindle speed was found to be the most influential parameter, indicating that thermal effects dominate surface formation when cooling efficiency is limited. Conversely, the application of Dromus cooling media effectively suppressed thermal instability, causing depth of cut to emerge as the dominant factor governing surface roughness. This shift in parameter dominance highlights the critical role of cooling media in reshaping the surface generation mechanism from thermally driven to mechanically driven processes. The optimal machining parameter combination 1910 rpm spindle speed, 0.2 mm depth of cut, and 330 mm/min feed rate resulted in the lowest surface roughness and the most stable machining performance, particularly when Dromus was used as the cooling medium. Overall, the findings emphasize that cooling media selection should be treated as a central element of machining optimization strategies rather than a secondary consideration. Despite certain limitations, this study provides valuable theoretical insight and practical guidance for improving surface quality in CNC milling of medium-carbon steels. The results can serve as a reference for future research and industrial applications aimed at achieving high-quality, stable, and efficient machining processes.

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AUTHOR CONTRIBUTIONS

FF designed the study, conducted the analysis, collected the data, and wrote the manuscript. EY and ZK, supported the availability of research data, and reviewed the research results.

CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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