Int. j. adv. multidisc. res. stud. 2025; 5(3):711-714

Received: 07-04-2025
Accepted: 17-05-2025

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

Application of CuO Nanofluid MQL and Taguchi Method for Enhanced Surface Quality in Hard Milling of 9CrSi Steel

Trong-Hai Dinh
Thai Nguyen University of Technology, Viet Nam

Corresponding Author: **Trong-Hai Dinh**

Abstract
This study investigates the optimization of cutting parameters in hard milling of 9CrSi alloy steel using Minimum Quantity Lubrication (MQL) enhanced with CuO nanoparticles to achieve superior surface roughness (Ra). The Taguchi method with an L9 orthogonal array was employed to evaluate the effects of cutting speed (v: 60, 80, 100 m/min), feed rate (f: 0.01, 0.015, 0.02 mm/tooth), and depth of cut (d: 0.2, 0.3, 0.4 mm) on surface roughness. Signal-to-noise (S/N) ratio and analysis of variance (ANOVA) revealed that the optimal conditions—cutting speed of 100 m/min, feed rate of 0.01 mm/tooth, and depth of cut of 0.2 mm—yielded the lowest surface roughness (Ra = 0.225). The feed rate was identified as the most influential factor, contributing 82.43% to surface roughness variation. These findings highlight the efficacy of CuO nano-enhanced MQL in improving surface quality and promoting sustainable machining practices for high-hardness alloys like 9CrSi steel.

Keywords: Hard Milling, 9CrSi Steel, CuO Nanofluid, MQL, Taguchi Method, Surface Roughness

1. Introduction

Hard milling of high-hardness alloys, such as 9CrSi steel, is a cornerstone of precision manufacturing, particularly for producing molds, dies, and cutting tools used in industries like automotive, aerospace, and toolmaking [1, 2]. With a hardness of 50–55 HRC after heat treatment, 9CrSi steel exhibits exceptional wear resistance, high strength, and durability, making it ideal for applications requiring robust mechanical properties. However, machining this high-hardness material presents significant challenges, including elevated cutting temperatures, rapid tool wear, and compromised surface quality. These issues can result in poor dimensional accuracy, reduced surface finish, and diminished component performance, ultimately affecting the reliability, fatigue life, and corrosion resistance of precision parts [3, 4, 5]. Achieving a high-quality surface finish, measured by surface roughness, is paramount, as it directly influences the functional performance and longevity of machined components.

Traditional flood cooling, which relies on large volumes of cutting fluid, has been widely used to manage heat and friction during hard milling. However, this approach is associated with high costs, environmental pollution, and health risks for operators due to exposure to chemical coolants [6, 7]. To address these concerns, industries are increasingly adopting sustainable machining strategies. One such strategy involves the use of cutting fluids enhanced with nanoparticles to improve machining performance. These nanofluids enhance heat transfer, improve lubrication, and reduce tool wear, leading to better surface quality and higher machining efficiency [8, 9, 10, 11]. Among these, copper oxide (CuO) nanoparticles are particularly promising due to their superior thermal conductivity, lubricity, and cost-effectiveness compared to other nanoparticles like aluminum oxide or silicon dioxide [12, 13]. When integrated into cutting fluids, CuO nanoparticles enhance heat dissipation, reduce friction at the tool-workpiece interface, and improve chip evacuation, leading to lower cutting forces, better surface finish, and extended tool life. These properties make CuO nano-enhanced cutting fluids an effective solution for hard milling of high-hardness alloys like 9CrSi steel, where achieving a superior surface roughness is essential for meeting rigorous quality standards in precision manufacturing.

Optimizing cutting parameters—cutting speed, feed rate, and depth of cut—is essential for minimizing surface roughness and enhancing machining efficiency. The Taguchi method, a powerful statistical tool for experimental design, enables efficient optimization by identifying the best parameter settings with a minimal number of trials [14, 15]. Using an L9 orthogonal array, the Taguchi method systematically evaluates the effects of multiple factors and their interactions, offering a cost-effective and

reliable approach to determining optimal machining conditions. Previous studies have demonstrated the effectiveness of the Taguchi method in optimizing machining processes for high-hardness steels, particularly in achieving superior surface quality.

This study focuses on optimizing cutting parameters in hard milling of 9CrSi steel using CuO nano-enhanced cutting fluids to achieve a superior surface finish within the target range of 0.23 to 0.36 micrometers. The research employs the Taguchi method with an L9 orthogonal array to investigate the effects of cutting speed (60, 80, 100 meters per minute), feed rate (0.01, 0.015, 0.02 millimeters per tooth), and depth of cut (0.2, 0.3, 0.4 millimeters) on surface roughness. Signal-to-noise ratio and analysis of variance are used to determine the optimal cutting conditions and assess the contribution of each parameter to surface roughness variation. By leveraging the thermal and tribological advantages of CuO nanoparticles, this study aims to enhance surface quality while contributing to sustainable machining practices. The findings are expected to offer valuable insights for precision manufacturing industries, advancing the development of high-performance, environmentally friendly machining solutions for high-hardness alloys.

2. Experiment setup

The experiment was designed to optimize cutting parameters in hard milling of 9CrSi steel (50–55 HRC) using the Taguchi method with an L9 orthogonal array for efficient parameter evaluation. A CNC milling machine with a 10-millimeter TiAlN-coated carbide end mill was used. Cutting speed (60, 80, 100 meters per minute), feed rate (0.01, 0.015, 0.02 millimeters per tooth), and depth of cut (0.2, 0.3, 0.4 millimeters) were tested.

Machining was performed under MQL with a water-based cutting fluid containing 4 w% CuO nanoparticles (50 nanometers), delivered at 120 milliliters per hour and 3.5 kilograms per square centimeter air pressure. Surface roughness was measured using a Mitutoyo SJ-201 device, with multiple measurements per run for accuracy. Signal-to-noise ratio (smaller-is-better) and analysis of variance were applied to identify optimal conditions and parameter contributions. Experiments were conducted under controlled conditions, with each run replicated twice for reliability.

3. Results and Discussion

Table 1 summarizes the surface roughness values from nine experimental runs conducted using the L9 orthogonal array of the Taguchi method. Each run combines different levels of cutting speed (60, 80, or 100 meters per minute), feed rate (0.01, 0.015, or 0.02 millimeters per tooth), and depth of cut (0.2, 0.3, or 0.4 millimeters) under CuO nano-enhanced Minimum Quantity Lubrication conditions. The surface roughness values range from 0.23 to 0.35 micrometers.

Table 1: Experimental Results

Run	v (m/min)	f (mm/tooth)	d (mm)	Ra (μm)
1	60	0.01	0.2	0.230
2	60	0.015	0.3	0.280
3	60	0.02	0.4	0.350
4	80	0.01	0.3	0.235
5	80	0.015	0.4	0.290
6	80	0.02	0.2	0.310
7	100	0.01	0.4	0.245
8	100	0.015	0.2	0.240
9	100	0.02	0.3	0.320

Table 2: Response Table for Means

Level	v	f	d
1	0.2867	0.2367	0.2600
2	0.2783	0.2700	0.2783
3	0.2683	0.3267	0.2950
Delta	0.0183	0.0900	0.0350
Rank	3	1	2

Table 2 presents the response table for mean surface roughness values, summarizing the average effect of cutting speed, feed rate, and depth of cut at their respective levels under CuO nano-enhanced Minimum Quantity Lubrication conditions. The table ranks the parameters based on their influence on surface roughness, with feed rate showing the greatest impact, followed by depth of cut, and then cutting speed. This ranking indicates that feed rate is the dominant factor in determining surface quality, guiding the selection of optimal machining conditions for precision milling of 9CrSi steel.

Table 3: ANOVA Results

Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
v	2	0.000506	0.000253	13.00	0.071
f	2	0.012422	0.006211	319.43	0.003
d	2	0.001839	0.000919	47.29	0.021
Error	2	0.000039	0.000019		
Total	8	0.014806			
R-sq = 99.74%					

Table 3 presents the analysis of variance (ANOVA) results, which quantify the influence of cutting speed, feed rate, and depth of cut on surface roughness in hard milling of 9CrSi steel under CuO nano-enhanced Minimum Quantity Lubrication conditions. The ANOVA results reveal that feed rate is the dominant factor, contributing 82.43% to the variation in surface roughness, indicating its critical role in determining surface quality. Depth of cut follows as the second most influential parameter, with a contribution of 12.73%, suggesting a moderate effect on the machined surface finish. Cutting speed has the least impact, contributing only 6.98%, implying that its influence on surface roughness is relatively minor compared to the other parameters. The high R-squared value of 99.74% demonstrates that the experimental model accounts for nearly all observed variations in surface roughness, confirming the robustness and reliability of the Taguchi-based experimental design. The low error contribution (0.27%) further supports the precision of the analysis, indicating minimal influence from uncontrolled factors. These findings highlight the importance of prioritizing feed rate adjustments in optimizing machining conditions to achieve superior surface quality in precision manufacturing of high-hardness alloys like 9CrSi stee

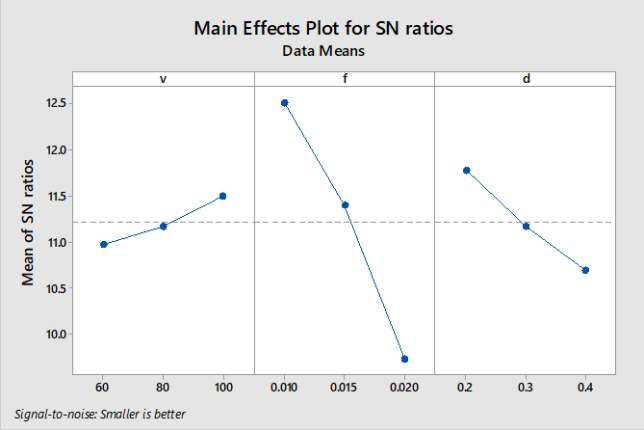

Fig 1: Main Effects Plot for SN ratios

Fig 1 displays the main effects plot for signal-to-noise ratios, illustrating the influence of cutting speed, feed rate, and depth of cut on surface roughness under CuO nano-enhanced Minimum Quantity Lubrication conditions. Using the "smaller-is-better" criterion, higher signal-to-noise ratios indicate better surface quality. The plot reveals that the optimal cutting conditions for minimizing surface roughness are a cutting speed of 100 meters per minute, a feed rate of 0.01 millimeters per tooth, and a depth of cut of 0.2 millimeters, guiding the selection of machining parameters for precision milling of 9CrSi steel.

Table 4: Verification Test Result

Experiment	v	f	d	Ra
Experiment 1	60	0.01	0.2	0.230
Verification Exp.	100	0.01	0.2	0.225

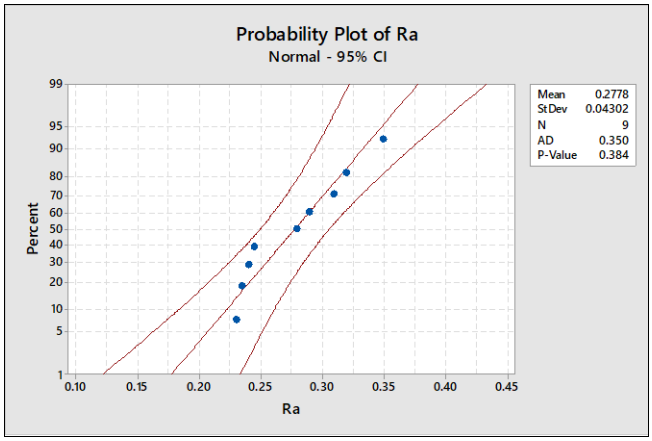

Fig 2: Probability Plot of Ra

Table 4 presents the verification test result, comparing an initial experiment (cutting speed of 60 meters per minute, feed rate of 0.01 millimeters per tooth, depth of cut of 0.2 millimeters, yielding a surface roughness of 0.230 micrometers) with a verification experiment using the optimal conditions (cutting speed of 100 meters per minute, feed rate of 0.01 millimeters per tooth, depth of cut of 0.2 millimeters, yielding a surface roughness of 0.225 micrometers). The improved surface roughness in the verification test confirms the effectiveness of the optimized cutting parameters under CuO nano-enhanced Minimum Quantity Lubrication conditions for precision milling of 9CrSi steel.

Figure 2 shows the probability plot of surface roughness values, assessing the normality of the experimental data under CuO nano-enhanced Minimum Quantity Lubrication conditions. With a P-value of 0.384, the plot indicates that the surface roughness data follows a normal distribution, as the P-value exceeds the significance threshold of 0.05. This confirms the statistical reliability of the experimental results, supporting the consistency of the Taguchi method in optimizing machining parameters for 9CrSi steel.

4. Conclusion

This study successfully optimized cutting parameters for hard milling of 9CrSi steel using CuO nano-enhanced Minimum Quantity Lubrication and the Taguchi method, achieving a superior surface roughness of 0.225 micrometers. The optimal conditions were identified as a cutting speed of 100 m/min, a feed rate of 0.01 mm/tooth, and a depth of cut of 0.2 mm. Analysis of variance revealed that feed rate was the dominant factor, contributing 82.43% to surface roughness variation, followed by depth of cut at 12.73%, and cutting speed at 6.98%. The high R-squared value of 99.74% confirmed the reliability of the experimental model. These findings provide practical guidance for achieving high-quality surface finishes in precision manufacturing of high-hardness alloys, enhancing efficiency and sustainability in industrial machining processes.

5. Acknowledgment

This research was conducted with the support of Thai Nguyen University of Technology.

6. References

1. Do T-V, Hsu Q-C. Optimization of minimum quantity lubricant conditions and cutting parameters in hard milling of AISI H13 steel, Appl. Sci. 2016; 6(3):p83.
2. Grzesik W. Machining of hard materials, Mach.-Fundam. Recent Adv. Springer Lond. UK, 2008, 97-126.
3. Davim JP. Machining of hard materials. Springer Science & Business Media, 2011.
4. Do TV. Empirical model for surface roughness in hard milling of AISI H13 steel under nanofluid-MQL condition based on analysis of cutting parameters," J. Mech. Eng. Res. Dev. 2020; 43(2):89-94.
5. Lobanov AA. Technological advantages of hard milling, Russ. Eng. Res. 2007; 27(6):396-397. Doi: 10.3103/S1068798X07060196
6. Klocke F, Eisenblätter G. Dry cutting, Cirp Ann. 1997; 46(2):519-526.
7. Tuan NA, Lam PD, Tuan TK, Huy VM, Giang TN, Hung LX. Optimization of dressing parameters for minimum surface roughness and maximum material removal rate in internal grinding of SKD11 tool steel, in E3S Web of Conferences, EDP Sciences, 2021, p01165. Accessed: May 20, 2025.
8. Bui G-T, Nguyen QM, Thi MHP, Vu MH. Multi-objective optimization for balancing surface roughness and material removal rate in milling hardened SKD11 alloy steel with SIO2 nanofluid MQL, EUREKA Phys. Eng. 2024; 2:157-169.
9. The-Vinh Do, Thanh-Dat Phan. An empirical investigation of SIO2 nano concentration under MQL

on surface roughness in hard milling of jis SKD61 steel, J. Appl. Eng. Sci. 2020; 18(3):432-437.
10. Godson L, Raja B, Lal DM, Wongwises SEA. Enhancement of heat transfer using nanofluids: An overview, Renew. Sustain. Energy Rev. 2010; 14(2):629-641.
11. Junankar AA, *et al*. A Review: Enhancement of turning process performance by effective utilization of hybrid nanofluid and MQL, Mater. Today Proc. 2021; 38:44-47.
12. Azami A, Salahshournejad Z, Shakouri E, Sharifi AR, Saraeian P. Influence of nano-minimum quantity lubrication with MoS2 and CuO nanoparticles on cutting forces and surface roughness during grinding of AISI D2 steel, J. Manuf. Process. 2023; 87:209-220.
13. ST PK, HP TP, Siddaraju C. Investigate the effect of Al2O3 & CuO nano cutting fluids under MQL technique in turning of DSS-2205, Adv. Mater. Process. Technol. 2022; 8(3):3297-3330.
14. Do T-V, Vu N-C, Nguyen Q-M. Optimization of cooling conditions and cutting parameters during hard milling of AISI H13 steel by using Taguchi method, in 2018 IEEE International Conference on Advanced Manufacturing (ICAM), IEEE, 2018, 396-398.
15. Chen W-J, Huang C-K, Yang Q-Z, Yang Y-L. Optimal Prediction and Design of Surface Roughness for CNC Turning of AL7075-T6 by Using the Taguchi Hybrid QPSO Algorithm. Trans. Can. Soc. Mech. Eng. 2016; 40:5:883-895. Doi: 10.1139/tcsme-2016-0072