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Investigation and Optimization of Surface Roughness in Hard Milling of 9CrSi Steel Using Al_2O_3 Nanofluid-Assisted MQL

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Abstract
This study investigates and optimizes surface roughness in the hard milling of 9CrSi steel (50–55 HRC) under minimum quantity lubrication (MQL) using Al_2O_3 nanofluid with coconut oil as the base fluid. The experiments were designed based on the Taguchi L9 orthogonal array to analyze the effects of cutting speed (60–100 m/min), depth of cut (0.2–0.6 mm), and feed per tooth (0.020–0.030 mm/tooth) on surface roughness (Ra). The results show that Ra ranged from 0.25 to 0.40 µm under the investigated conditions. Analysis of signal-to-noise ratios and ANOVA revealed that the depth of cut had the most significant influence on surface roughness, followed by feed per tooth, while cutting speed had a smaller effect. The optimal cutting parameters for minimizing surface roughness were determined as a cutting speed of 100 m/min, a depth of cut of 0.2 mm, and a feed per tooth of 0.020 mm/tooth. A regression model with a high coefficient of determination (R^2 = 96.88%) was developed to predict surface roughness. The results confirm that Al_2O_3 nanofluid-assisted MQL can effectively improve surface finish in the hard milling of 9CrSi steel.

Keywords: Hard Milling, Surface Roughness, 9CrSi Steel, MQL, Al_2O_3 Nanofluid, Taguchi method

Introduction

Surface roughness is one of the most important indicators for evaluating the quality of machined components [1, 2]. It directly influences the functional performance of engineering parts, including wear resistance, fatigue life, friction behavior, and dimensional accuracy [3]. In many mechanical systems such as molds, dies, and precision components, a lower surface roughness is essential to ensure proper contact conditions and extend service life [4, 5]. Therefore, controlling and optimizing surface roughness during machining processes has become a key objective in modern manufacturing.

Hard milling has emerged as an effective alternative to traditional grinding for finishing hardened steels [6, 7, 8]. With the development of advanced cutting tools and high-speed CNC machining centers, hard milling offers several advantages, including reduced production time, improved machining flexibility, and the ability to complete machining in a single setup [9, 10]. However, machining hardened materials typically generates high cutting temperatures and forces, which may lead to rapid tool wear and poor surface quality. Consequently, selecting appropriate cutting parameters and effective lubrication strategies is crucial for achieving high surface integrity in hard milling processes.

Among hardened tool steels, 9CrSi steel is widely used in industrial applications such as cold-work dies, cutting tools, punches, and wear-resistant mechanical components due to its high hardness, good wear resistance, and excellent dimensional stability after heat treatment. These components often require high surface quality to ensure reliable performance under severe working conditions. Nevertheless, the high hardness of 9CrSi steel makes it difficult to machine, particularly during finishing operations, where surface roughness must be strictly controlled [11, 12].

In recent years, minimum quantity lubrication (MQL) has been recognized as a sustainable and environmentally friendly machining technique [2, 13, 14]. Compared with conventional flood cooling, MQL uses a small amount of lubricant to provide effective lubrication at the cutting zone while significantly reducing fluid consumption and environmental impact [15, 16]. Furthermore, the use of nanofluids in MQL has attracted considerable attention due to their enhanced tribological and thermal properties. Nanoparticles such as Al_2O_3 can improve heat transfer, reduce friction at the tool–workpiece interface, and enhance lubrication performance [17, 18, 19]. As a result, nanofluid-assisted MQL has shown promising potential for improving machining performance and surface quality when machining difficult-to-cut materials [20, 21].

In this context, the present study aims to investigate and optimize the surface roughness in the hard milling of 9CrSi steel under Al_2O_3 nanofluid-assisted MQL conditions. The Taguchi method is employed to design the experiments and analyze the influence of cutting parameters, including cutting speed, depth of cut, and feed per tooth, on surface roughness.

Results and Discussion

The experimental results of surface roughness obtained from the Taguchi L9 design are presented in Table 1. The experiments were conducted with three cutting parameters, including cutting speed (v), depth of cut (d), and feed per tooth (f). The measured surface roughness values ranged from 0.25 µm to 0.40 µm under the investigated machining conditions.

It can be observed that surface roughness tends to increase with increasing feed per tooth and depth of cut. For example, when the feed per tooth increased to 0.03 mm/tooth and the depth of cut reached 0.6 mm, the surface roughness increased to approximately 0.40 µm. Conversely, smaller feed and depth of cut generally resulted in improved surface quality. The lowest surface roughness value of 0.25 µm was obtained at v = 100 m/min, d = 0.4 mm, and f = 0.02 mm/tooth. These results indicate that appropriate combinations of cutting parameters are essential for achieving better surface finish during hard milling of 9CrSi steel.

Table 1: Experimental Results

Exp	v (m/min)	d (mm)	f (mm/tooth)	Ra (µm)
1	60	0.2	0.02	0.27
2	60	0.4	0.025	0.31
3	60	0.6	0.03	0.4
4	80	0.2	0.025	0.26
5	80	0.4	0.03	0.34
6	80	0.6	0.02	0.33
7	100	0.2	0.03	0.29
8	100	0.4	0.02	0.25
9	100	0.6	0.025	0.36

The signal-to-noise (S/N) ratio analysis based on the "smaller-is-better" criterion was performed to determine the optimal machining conditions for minimizing surface roughness. The response table for S/N ratios is presented in Table 2.

Table 2: Response Table for Signal to Noise Ratios

Level	v	d	f
1	9.835	11.275	11.015
2	10.234	10.528	10.249
3	10.556	8.821	9.360
Delta	0.721	2.454	1.654
Rank	3	1	2

According to the delta values in Table 2, the depth of cut (d) has the most significant influence on surface roughness, followed by feed per tooth (f), while cutting speed (v) has the least influence. This ranking indicates that controlling the depth of cut is critical for maintaining good surface quality in hard milling operations.

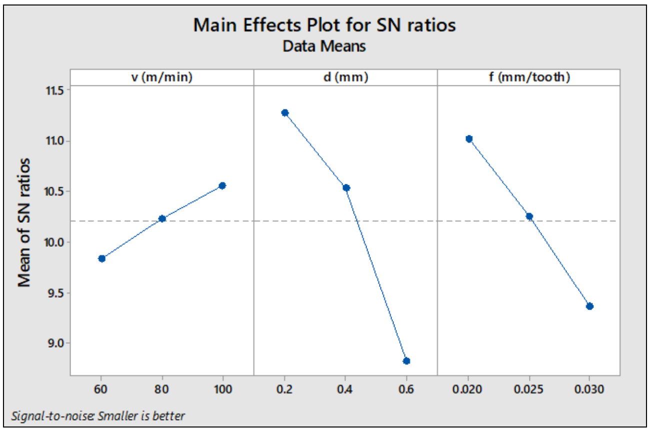

Fig 1: Main Effects Plot for S/N Ratios

The influence of machining parameters on the S/N ratio is further illustrated in Figure 1, which shows the main effects plot for S/N ratios. The figure indicates that the S/N ratio increases as the cutting speed increases and decreases as the depth of cut and feed per tooth increase. Based on the S/N analysis, the optimal cutting parameter combination for minimizing surface roughness is determined as:

- Cutting speed (v): 100 m/min
- Depth of cut (d): 0.2 mm
- Feed per tooth (f): 0.02 mm/tooth

Analysis of variance (ANOVA) was conducted to evaluate the statistical significance of the machining parameters on surface roughness. The ANOVA results are summarized in Table 3. The results show that the depth of cut has the most significant effect on surface roughness with a P-value of 0.046, indicating statistical significance at a confidence level of 95%. The feed per tooth also influences surface roughness but with a slightly higher P-value. In contrast, the cutting speed has a relatively smaller effect on surface roughness within the investigated range.

These results are consistent with machining theory, where increasing the depth of cut and feed rate generally increases cutting forces and tool–workpiece interaction, leading to higher surface roughness.

Table 3: ANOVA table

Source	DF	Adj-SS	Adj-MS	F-Value	P-Value
v	2	0.001089	0.000544	1.75	0.364
d	2	0.012822	0.006411	20.61	0.046
f	2	0.005422	0.002711	8.71	0.103
Error	2	0.000622	0.000311		
Total	8	0.019956			
R-sq = 96.88%					

A regression model was developed to predict the surface roughness based on the cutting parameters. The regression equation is expressed as:

$$Ra = 0.1256 - 0.000667*v + 0.2250*d + 6.00*f \quad (1)$$

Where:

- Ra is the surface roughness (µm),
- v is the cutting speed (m/min),
- d is the depth of cut (mm),
- f is the feed per tooth (mm/tooth).

The regression model has a coefficient of determination of R^2 = 96.88%, indicating that the model can explain most of the variability in the experimental data. This suggests a good agreement between the predicted and measured surface roughness values.

The normal probability plot of residuals shown in Figure 2 indicates that the residuals follow an approximately normal distribution, confirming the adequacy of the developed regression model.

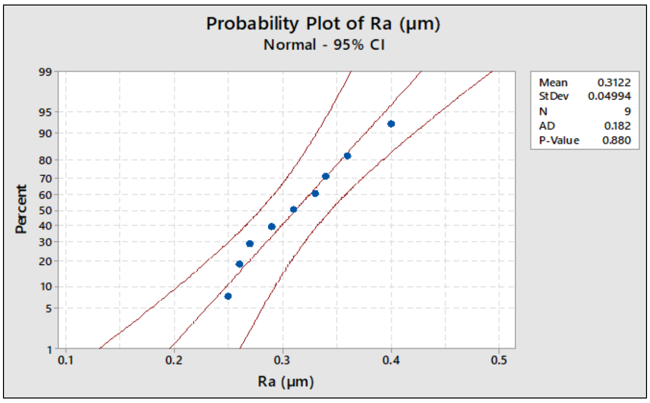

Fig 2: Normal Probability Plot for Ra

Overall, the results demonstrate that the combination of optimized cutting parameters and Al_2O_3 nanofluid-assisted MQL can effectively improve surface quality in the hard milling of 9CrSi steel.

Conclusion

This study investigated the surface roughness in hard milling of 9CrSi steel under Al_2O_3 nanofluid-assisted MQL using the Taguchi method. The experimental results showed that surface roughness ranged from 0.25 µm to 0.40 µm. Among the machining parameters, depth of cut had the most significant effect on surface roughness, followed by feed per tooth, while cutting speed had a smaller influence. The optimal cutting parameters were determined as v = 100 m/min, d = 0.2 mm, and f = 0.02 mm/tooth. The developed regression model showed good prediction capability with R^2 = 96.88%. The results indicate that Al_2O_3 nanofluid-assisted MQL can effectively improve surface quality in hard milling of hardened steels.

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