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Investigation of Surface Roughness in Nanofluid MQL-Assisted Hard Milling of Hardened 9CrSi Steel on a CNC Vertical Machining Center

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Abstract

Hard milling is widely used as an alternative to grinding for machining hardened steels while maintaining high surface quality. This study investigates the influence of cutting parameters on surface roughness during CNC hard milling of hardened 9CrSi steel (56–60 HRC) under CuO nanofluid-assisted minimum quantity lubrication (MQL) conditions. Experiments were conducted on a Mazak VCS-530C vertical machining center using a nano-composite coated carbide end mill. A total of 45 experimental runs were performed by varying cutting speed (Vc), feed per tooth (fz), and depth of cut (d). The experimental data were analyzed using the Taguchi signal-to-noise ratio and analysis of variance (ANOVA). The results indicated that feed per tooth was the most influential factor affecting surface roughness, with a contribution of 44.36%, followed by cutting speed (42.22%) and depth of cut (6.74%). The minimum surface roughness of 0.21 μm was achieved at Vc = 150 m/min, fz = 0.02 mm/tooth, and d = 0.10 mm. The findings confirm the effectiveness of CuO nanofluid MQL in improving surface quality during hard milling of hardened 9CrSi steel.

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

Introduction

Hardened steels are widely used in the manufacturing of dies, molds, gears, and other critical mechanical components due to their excellent hardness, wear resistance, and dimensional stability [1, 2, 3, 4]. Traditionally, grinding has been employed as the final finishing process for hardened materials to achieve high surface quality. However, recent advances in cutting tool materials and CNC machining technologies have enabled hard milling to become a viable alternative to grinding. Hard milling offers several advantages, including reduced machining time, lower production costs, greater flexibility, and the ability to machine complex geometries in a single setup [5, 6, 7]. Consequently, improving surface quality in hard milling has become an important research topic in modern manufacturing.

Surface roughness is one of the most significant indicators of machined surface quality because it directly influences the functional performance, wear resistance, fatigue strength, and service life of machined components [8, 9, 10]. In hard milling operations, surface roughness is affected by various machining parameters, such as cutting speed, feed rate, and depth of cut [11, 12, 13, 14]. Among these factors, feed per tooth is often considered the dominant parameter due to its direct relationship with the geometrical formation of the machined surface. Therefore, understanding the influence of cutting parameters on surface roughness is essential for selecting appropriate machining conditions and improving product quality.

In recent years, environmental concerns and the increasing demand for sustainable manufacturing have encouraged the replacement of conventional flood cooling methods with more eco-friendly lubrication techniques. Minimum Quantity Lubrication (MQL) has attracted considerable attention because it significantly reduces lubricant consumption while maintaining satisfactory machining performance [15, 16, 17, 18]. Furthermore, the incorporation of nanoparticles into base oils has led to the development of nanofluid-assisted MQL systems, which provide enhanced lubrication and heat dissipation capabilities. Among various nanoparticles, copper oxide (CuO) has demonstrated promising tribological and thermal properties, contributing to reduced friction, lower cutting temperatures, and improved surface finish during machining processes [19, 20].

The application of nanofluids in machining has emerged as an effective approach for enhancing the performance of MQL systems. Nanoparticles dispersed in a base lubricant can significantly improve thermal conductivity, load-carrying capacity, and tribological behavior at the tool–workpiece interface [21, 22, 23, 24]. As a result, nanofluid-assisted MQL has been reported to reduce friction, decrease cutting temperature, suppress tool wear, and improve machined surface quality compared with conventional MQL [22, 25, 26]. Among various nanoparticles, copper oxide (CuO) is particularly attractive due to its good thermal conductivity, chemical stability, and relatively low cost. These characteristics make CuO nanofluids suitable for hard machining operations where effective lubrication and heat dissipation are critical for achieving superior surface integrity.

Although numerous studies have investigated hard milling under MQL and nanofluid-assisted conditions, limited information is available regarding the machining performance of hardened 9CrSi steel under CuO nanofluid MQL environments. Therefore, this study aims to investigate the effects of cutting speed (Vc), feed per tooth (fz), and depth of cut (d) on surface roughness during CNC hard milling of hardened 9CrSi steel using CuO nanofluid-assisted MQL. The experimental results are analyzed using the Taguchi signal-to-noise ratio and analysis of variance (ANOVA) to identify the most influential machining parameters and determine the optimal cutting conditions for achieving minimum surface roughness.

Experimental Procedure

The milling experiments were performed on a Mazak VCS-530C CNC vertical machining center using a nano-composite coated carbide end mill (D = 6 mm) manufactured by MOLDINO Tool Engineering, Ltd. (Japan). The workpiece material was hardened 9CrSi steel with a hardness of 56–60 HRC.

A nanofluid-assisted minimum quantity lubrication (MQL) system was employed during machining. The lubricant consisted of canola oil mixed with 2 wt.% CuO nanoparticles. The lubricant was supplied at a flow rate of 100 mL/h under an air pressure of 4 bar to improve lubrication and cooling performance in the cutting zone.

Three machining parameters, namely cutting speed (Vc), feed per tooth (fz), and depth of cut (d), were selected as input variables. Each factor was investigated at three levels, as listed in Table 1. A total of 45 milling experiments were conducted, and the surface roughness (Ra) was measured as the response variable. The experimental data were analyzed using the Taguchi signal-to-noise ratio and analysis of variance (ANOVA).

Table 1: Machining parameters and their levels

Factor	Level 1	Level 2	Level 3
Vc (m/min)	100	125	150
fz (mm/tooth)	0.02	0.03	0.04
d (mm)	0.08	0.1	0.12

Results and Discussion

The experimental results of surface roughness obtained under different machining conditions are presented in Table 2. The measured Ra values ranged from 0.21 to 0.46 µm, indicating that the selected cutting parameters significantly influenced the machined surface quality. The minimum surface roughness of 0.21 µm was achieved at a cutting speed of 150 m/min, a feed per tooth of 0.02 mm/tooth, and a depth of cut of 0.10 mm. In contrast, the highest Ra value of 0.46 µm was observed at Vc = 100 m/min, fz = 0.04 mm/tooth, and d = 0.12 mm.

Table 2: Experimental results of surface roughness in hard milling of 9CrSi steel

Run	Vc	fz	d	Ra
1	150	0.03	0.12	0.26
2	150	0.02	0.1	0.23
3	125	0.03	0.1	0.29
4	150	0.03	0.08	0.245
5	150	0.04	0.1	0.31
6	100	0.03	0.12	0.34
7	125	0.03	0.1	0.29
8	100	0.02	0.1	0.3
9	150	0.03	0.08	0.255
10	150	0.03	0.12	0.275
11	125	0.03	0.1	0.28
12	100	0.03	0.08	0.32
13	150	0.02	0.1	0.22
14	125	0.03	0.1	0.29
15	125	0.03	0.1	0.275
16	125	0.04	0.08	0.315
17	100	0.02	0.1	0.295
18	150	0.03	0.08	0.24
19	125	0.04	0.12	0.36
20	100	0.04	0.1	0.4
21	125	0.03	0.1	0.28
22	150	0.04	0.1	0.3
23	125	0.04	0.12	0.35
24	100	0.03	0.12	0.36
25	125	0.04	0.08	0.31
26	125	0.02	0.08	0.26
27	125	0.02	0.12	0.28
28	100	0.02	0.1	0.29
29	125	0.02	0.08	0.25
30	125	0.02	0.12	0.27
31	100	0.03	0.08	0.33
32	100	0.03	0.12	0.37
33	150	0.03	0.12	0.27
34	125	0.03	0.1	0.28
35	125	0.03	0.1	0.275
36	150	0.04	0.1	0.32
37	125	0.04	0.08	0.325
38	100	0.03	0.08	0.325
39	100	0.04	0.1	0.39
40	100	0.04	0.1	0.38
41	125	0.02	0.12	0.265
42	125	0.03	0.1	0.275
43	150	0.02	0.1	0.21
44	100	0.02	0.08	0.28
45	100	0.04	0.12	0.46

The significance of machining parameters was evaluated using ANOVA, and the results are summarized in Table 3. All investigated factors exhibited statistically significant effects on surface roughness, with P-values lower than 0.05. Feed per tooth (fz) was identified as the most influential parameter, contributing 44.36% to the total variation in Ra. Cutting speed (Vc) was the second most important factor with a contribution of 42.22%, while depth of cut (d) accounted for only 6.74%. The model showed excellent agreement with the experimental data, achieving an R^2 value of 94.94%, indicating that the selected factors explained most of the variation in surface roughness.

Table 3: ANOVA results for surface roughness (Ra)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	C (%)
Vc	2	0.047023	0.023511	158.57	0	**42.22**
fz	2	0.049401	0.0247	166.59	0	**44.36**
d	2	0.007506	0.003753	25.31	0	**6.74**
Error	38	0.005634	0.000148	–	–	**5.06**
Total	44	0.111374	–	–	–	**100**
R^2 (%) = 94.94						

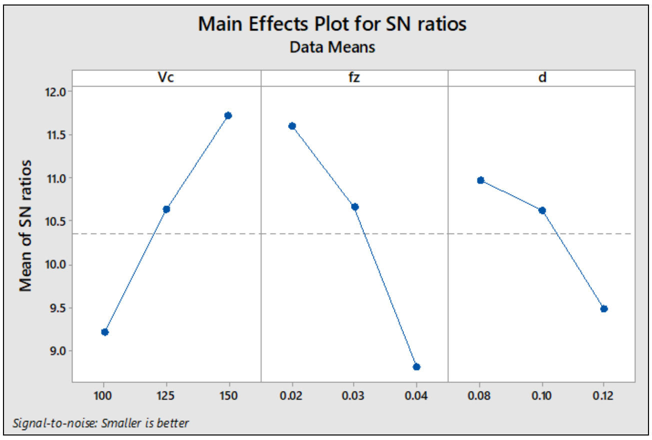

Fig 1: Main effects plot of S/N ratios for surface roughness

Figure 1 illustrates the main effects plot of S/N ratios for the smaller-the-better quality characteristic. Increasing the cutting speed from 100 to 150 m/min significantly improved the S/N ratio, indicating a reduction in surface roughness. This behavior can be attributed to smoother chip formation and reduced cutting forces at higher cutting speeds. In contrast, increasing the feed per tooth resulted in a substantial decrease in the S/N ratio due to the larger feed marks generated on the machined surface. The influence of depth of cut was comparatively less pronounced. Based on the S/N analysis, the optimal parameter combination for minimizing surface roughness was determined as Vc = 150 m/min, fz = 0.02 mm/tooth, and d = 0.10 mm.

Conclusions

This study investigated the effects of cutting parameters on surface roughness during CuO nanofluid MQL-assisted hard milling of hardened 9CrSi steel. The results showed that feed per tooth was the most influential factor, contributing 44.36% to the variation in surface roughness, followed by cutting speed (42.22%) and depth of cut (6.74%). The optimal cutting conditions were determined as Vc = 150 m/min, fz = 0.02 mm/tooth, and d = 0.10 mm, resulting in a minimum surface roughness of 0.21 µm. The findings demonstrate that CuO nanofluid-assisted MQL is an effective lubrication technique for improving surface quality in CNC hard milling of hardened 9CrSi steel.

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