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Research Paper

Investigation of hard milling process under minimum quantity lubrication condition using nano cutting fluid

Tran The Long
Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam
Corresponding author: Tran The Long

Abstract
The application of minimum quantity lubrication (MQL) condition technology using nano-cutting oil is a new research direction to improve the lubrication and cooling capacity in the cutting area, thereby improving the efficiency of the machining process. Especially for the hard milling, due to the discontinuous cutting process and high cutting temperature, the application of MQL using nano-cutting oil is such a potential technological solution. The paper content presents experimental study using Box-Behnken design to investigate the effects of cutting speed, feed rate and nanoparticle concentration on surface roughness in hard milling. The obtained results show that the use of MQL using nano cutting fluid improves the cutting efficiency when compared with the MQL using pure cutting fluid. Among the investigated parameters, the feed rate has the greatest influence on R_a*, followed by the nanoparticle concentration. The interaction effect of these two parameters also has a significant influence on the objective function. Some reasonable technological guidelines are proposed to apply nanofluid minimum quantity lubrication (NFMQL) technology for hard milling.*
Keywords: *Hard milling, hard material, difficult-to-cut material, nano cutting fluid, surface roughness.*

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I. INTRODUCTION

In recent years, there are more and more high requirements for productivity as well as quality in the field of metal cutting. Thanks to the rapid development of materials technology and CNC machine tools, machining processes are now performed with increasing productivity and quality [1]. At the same time, hard machining technology is researched and developed to meet this trend [2]. Previously, the traditional technological solution for finishing steels after heat treatment was the grinding process. The advantage of this process is its very high dimensional accuracy and surface quality [3]. However, low productivity and environmental pollution from the use of coolant in grinding are inherent disadvantages [4]. To support/replace grinding in finishing processes, hard machining technology has shown the productivity advantages while ensuring accuracy and machined surface quality [5]. In the mold manufacturing industry, hard milling has attracted great interest not only by manufacturers but also by researchers around the world. The use of geometric-defined cutting tools for directly cutting heat-treated steels has brought new technological solutions in machining [6]. Discontinuous cutting and very high cutting temperature are the major challenges that need to be addressed. The use of flood coolant is difficult due to the low ability to bring the cutting fluid deeply into the cutting zone and the thermal shock that easily occurs when using this technology. Therefore, hard milling in dry condition is the first solution to be considered. However, rapid tool wear seriously affects product quality and increases machining costs [5]. There have been a number of studies applying MQL technology to hard milling and showing initial effects in improving lubricity [7,8]. However, the low cooling capacity of MQL makes this technology not yet effective as expected. The introduction of nano cutting oil as the base cutting oil for MQL is the solution to overcome this drawback [9,10]. From the literature review, the author made an experimental study on the influence of the cutting parameters and pure/nanofluid MQL condition on surface roughness in hard milling of 60Si2Mn steel (50-52 HRC).

II. MATERIAL AND METHODS

The setup of experimental devices was shown in Figure 1. Hard milling experiments were conducted on VMC 85S milling center. The APMT 1604 carbide inserts were used. MITUTOYO SJ-210 Portable Surface Roughness Tester was used for measuring surface roughness. The 60Si2Mn steel samples were hardened to the hardness of 50-52 HRC and the chemical composition is given by Table 1. The Al_2O_3 nanoparticles were suspended in the emulsion oil to form the nano cutting fluid.

Table 1 – Chemical composition in % of 60Si2Mn steel

Element	C	Si	Mn	P	S	Cr	Ni	Fe
Weight (%)	0.56-0.64	1.50-2.00	0.60-0.90	≤0.035	≤0.035	0.35max	0.35max	Rest

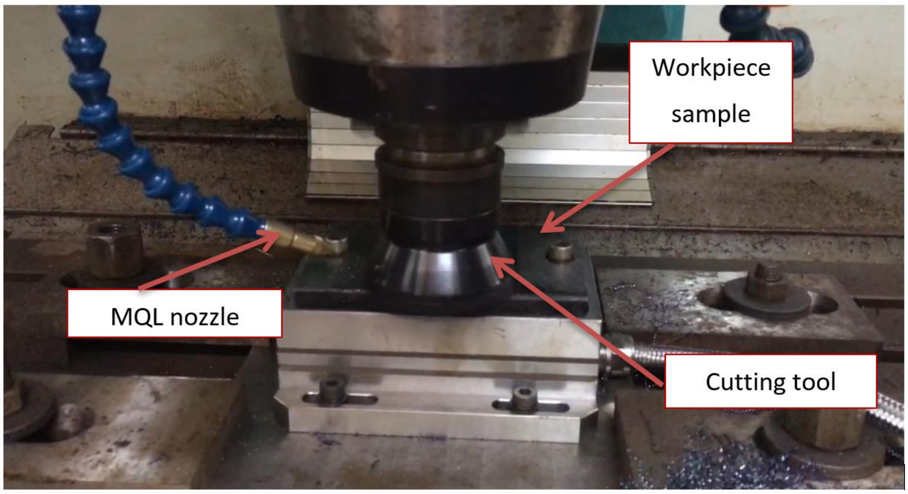

Figure 1. The experimental set up

Box-Behnken design of three factors and their levels was used and shown Table 2. Each experimental trial is carried out be following Box-Behnken design and is repeated by three times under the same cutting parameters. The measured values of surface roughness R_a were taken by the average values. The cutting depth was fixed at 0.2 mm. The experimental plan of Box-Behnken design and the measured surface roughness R_a were shown in Table 3.

Table 2. Box-Behnken design of three factors and their levels

Input machining parameters	Low level	High level
Cutting speed, V (*m/min*)	110	130
Feed rate, f (*mm/min*)	26	44
Nanoparticle concentration, NC (*%*)	0	1.0

Table 3. Box-Behnken experimental plan with test run order and measured surface roughness R_a

StdOrder	RunOrder	PtType	Blocks	V (m/min)	f (mm/min)	NC (%)	Ra (µm)
3	1	2	1	110	44	0.5	0.345
10	2	2	1	120	44	0	0.355
8	3	2	1	130	35	1.0	0.276
12	4	2	1	120	44	1.0	0.33
4	5	2	1	130	44	0.5	0.326
7	6	2	1	110	35	1.0	0.286
11	7	2	1	120	26	1.0	0.072
6	8	2	1	130	35	0	0.297
1	9	2	1	110	26	0.5	0.083
2	10	2	1	130	26	0.5	0.074
9	11	2	1	120	26	0	0.131
15	12	0	1	120	35	0.5	0.256

StdOrder	RunOrder	PtType	Blocks	V (m/min)	f (mm/min)	NC (%)	Ra (μm)
13	13	0	1	120	35	0.5	0.26
5	14	2	1	110	35	0	0.301
14	15	0	1	120	35	0.5	0.261

III. RESULTS AND DISCUSSION

The experimental trials were carried out by following Box-Behnken experimental design, and R_a values were measured by MITUTOYO SJ-210 Portable Surface Roughness Tester. The ANOVA analysis with 95% confidence level is carried out for surface roughness R_a (Table 3). The fit of the regression model is evaluated through the coefficient of determination R^2. The obtained results show that the coefficient of determination R^2 = 99.68% and the adjusted coefficient of determination R^2 = 99.11% are large, which proves that the regression model is well suitable with the experimental data. The regression equation for surface roughness R_a is given by equation (1).

R_a (μm) =0.019 - 0.0186*V + 0.06807*f - 0.152*NC + 0.000080*V*V - 0.000741*f *f + 0.0920*NC*NC - 0.000028*V*f - 0.000300*V*NC + 0.00189*f*NC (1)

Table 3. Results of ANOVA analysis of surface roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.142893	0.015877	174.66	0.000
Linear	3	0.126023	0.042008	462.13	0.000
V (m/min)	1	0.000220	0.000220	2.43	0.180
f (mm/min)	1	0.124002	0.124002	1364.16	0.000
NC (%)	1	0.001800	0.001800	19.80	0.007
Square	3	0.016548	0.005516	60.68	0.000
V (m/min)*V (m/min)	1	0.000236	0.000236	2.60	0.168
f (mm/min)*f (mm/min)	1	0.013292	0.013292	146.23	0.000
NC (%)*NC (%)	1	0.001953	0.001953	21.49	0.006
2-Way Interaction	3	0.000323	0.000108	1.18	0.404
V (m/min)*f (mm/min)	1	0.000025	0.000025	0.28	0.622
V (m/min)*NC (%)	1	0.000009	0.000009	0.10	0.766
f (mm/min)*NC (%)	1	0.000289	0.000289	3.18	0.135
Error	5	0.000455	0.000091		
Lack-of-Fit	3	0.000441	0.000147	20.98	0.046
Pure Error	2	0.000014	0.000007		
Total	14	0.143348			

The Pareto chart of the standardized effects on surface roughness R_a is shown in Figure 2. The main effects and interaction effects of the input variables on R_a are shown in figures 3, 4. From Figure 2, it can be seen that the feed rate has the strongest effect on surface roughness, followed by nanoparticle concentration. Also, the square interaction of feed rate and nanoparticle concentration cause the strong impact. From Figure 3, when increasing cutting speed and NC from 0% to 0.5%, the roughness value R_a decreases slightly, but Ra tends to increase with the increase of NC from 0.5% to 1.0%. When increasing the feed rate, the roughness value R_a increases sharply. The analysis of the interaction effect graph (Figure 4) shows that the interaction between feed rate and nanoparticle concentration (f*NC) has the large influence on Ra, while other interactions have little effect.

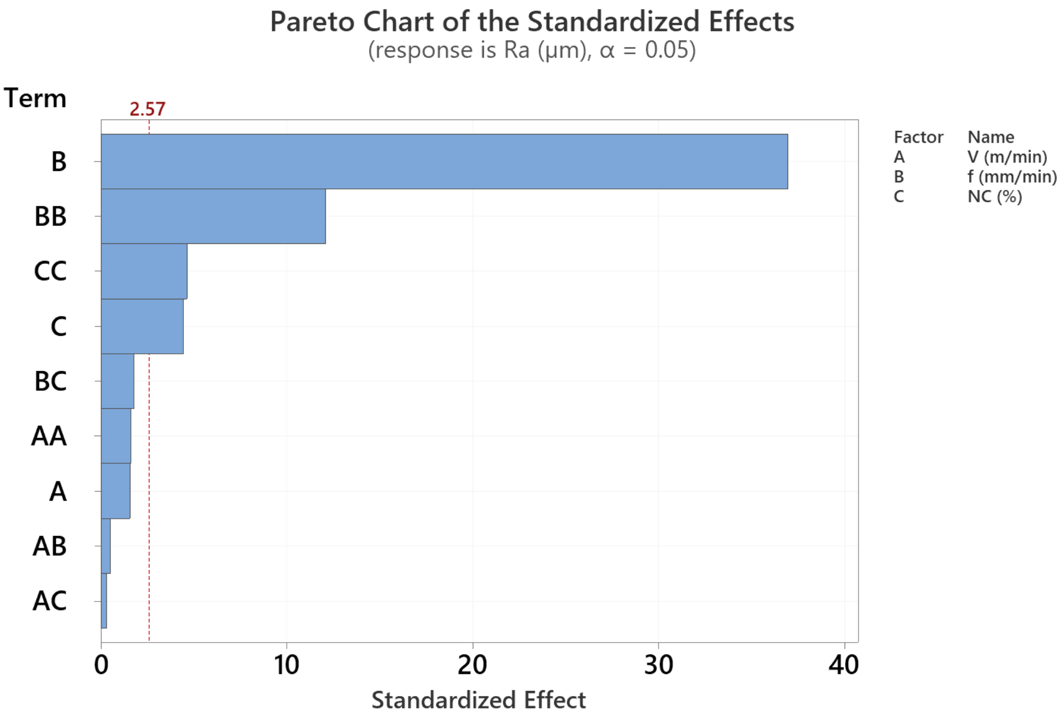

Figure 2. Pareto chart of the standardized effects on surface roughness R_a

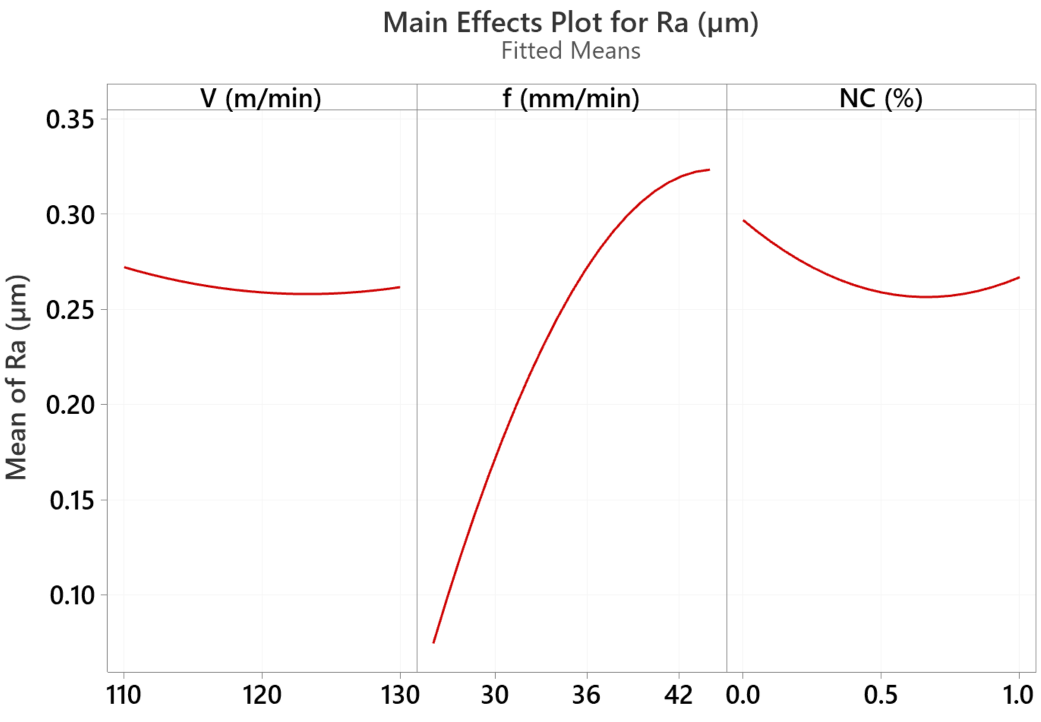

Figure 3. Main effects of input factors on surface roughness R_a

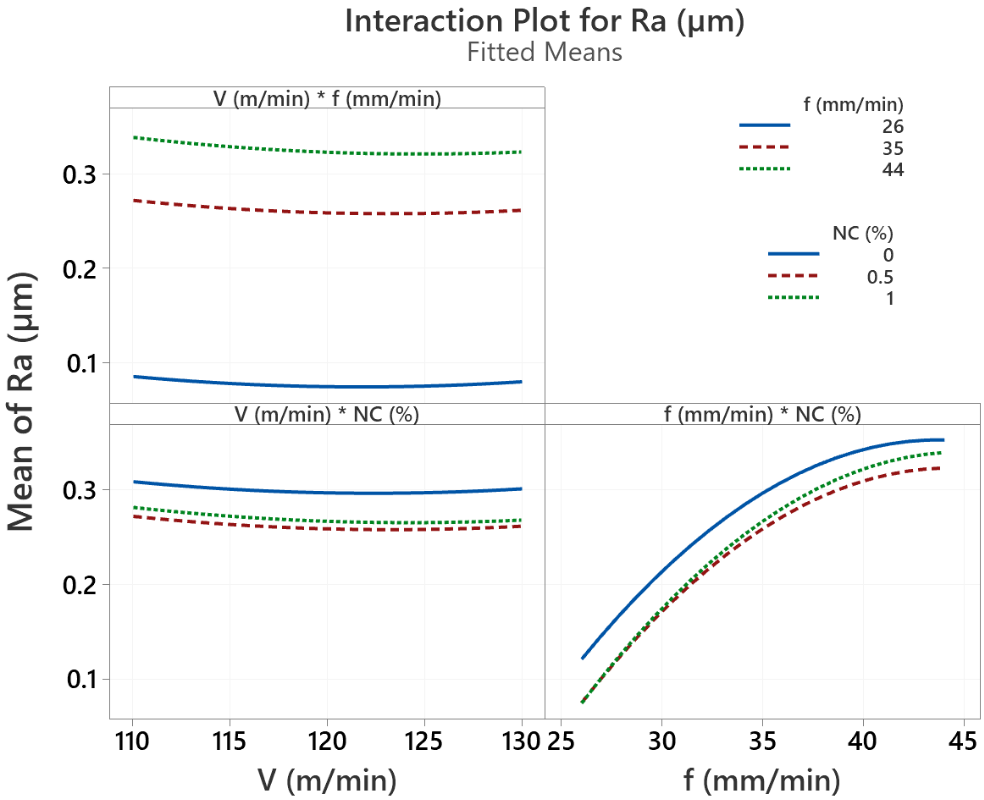

Figure 4. Interaction effects of input variables on surface roughness R_a

From the contour plots showing the interaction effects between the feed rate and cutting speed on R_a by fixing NC=0.5%, feed rate should be selected with the low levels combined with V =110-130 m/min to bring out the smaller R_a (<0.1µm) (Figure 5). In the case when feed rate is fixed at 35 mm/min, it is recommended to choose NC =0.45-0.85% and V =116-130 m/min (Figure 6) to achieve R_a <0.26 µm. In the case when cutting speed is fixed at 120m/min, NC=0.2-1.0% and f=26-27mm/min should be selected to achieve R_a <0.10µm (Figure 7). From the obtained results, it can be clearly seen that by adding Al_2O_3 nanoparticles to the base cutting oil, the lubricating performance in the cutting area was improved, thereby helping to reduce the surface roughness values.

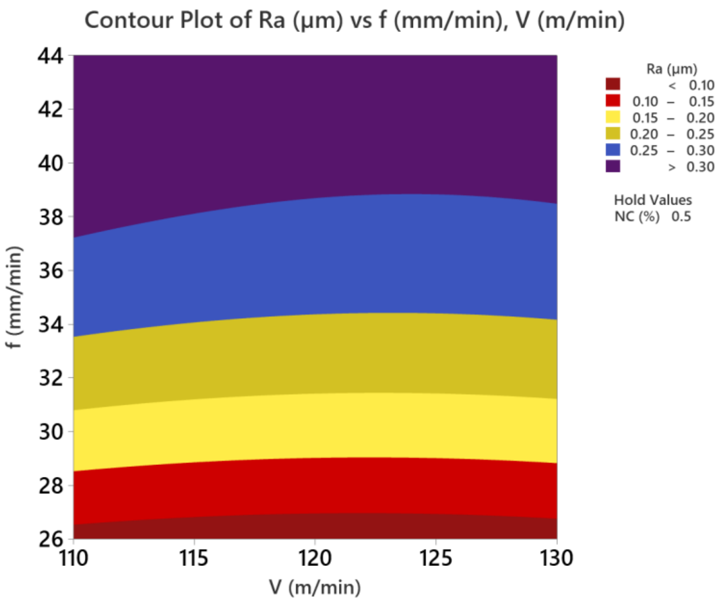

Figure 5. Contour plot of feed rate and cutting speed on R_a

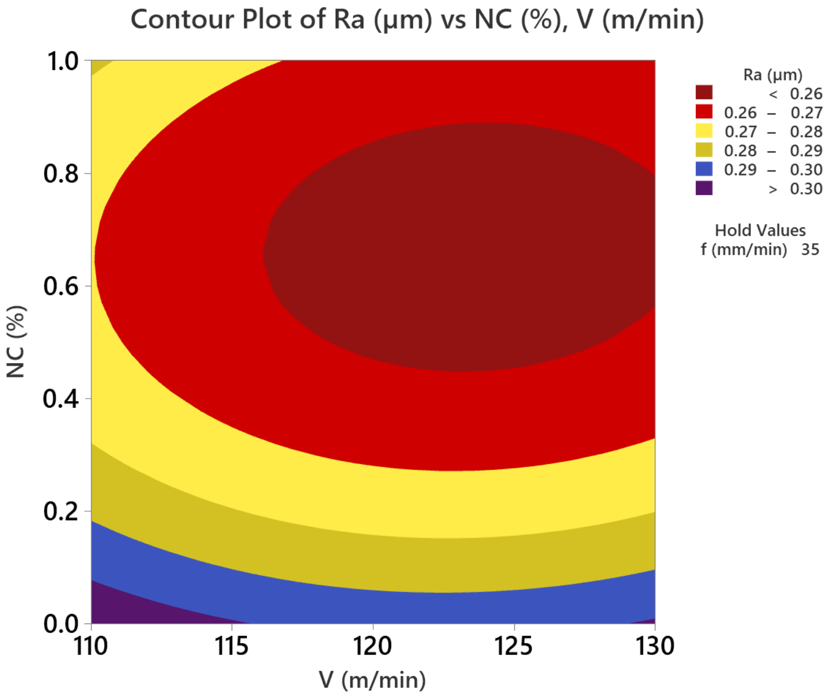

Figure 6. Contour plot of nanoparticle concentration and cutting speed on R_a

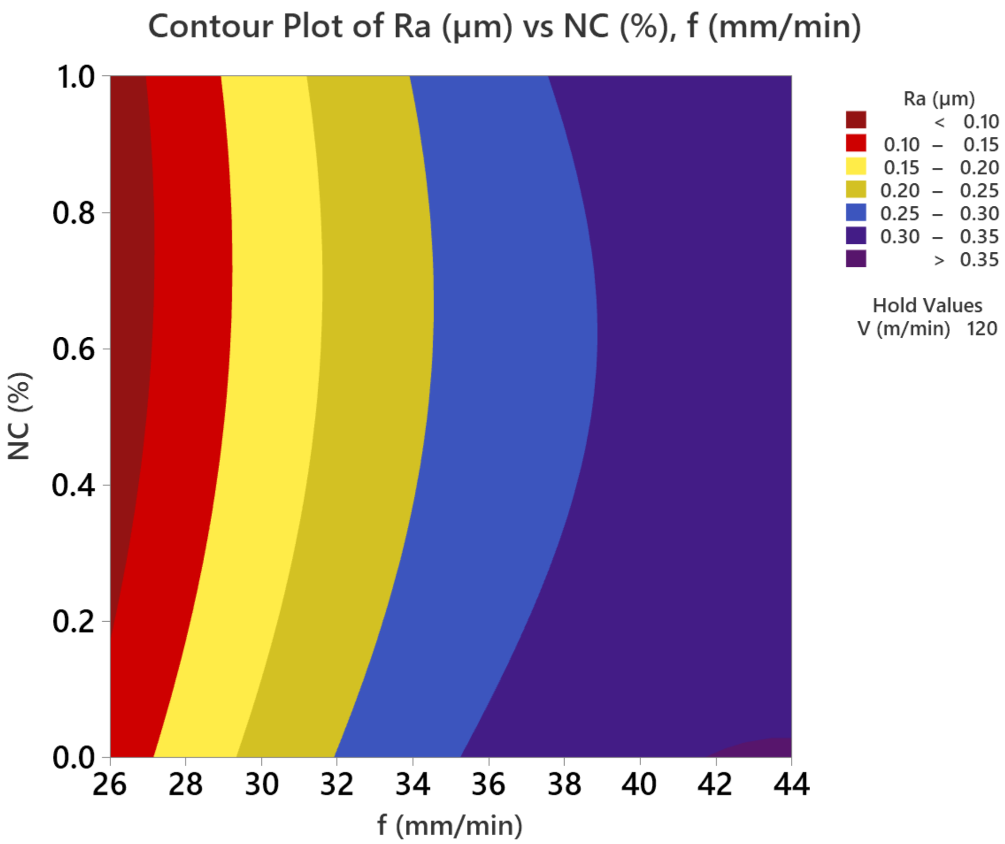

Figure 7. Contour plot of nanoparticle concentration and feed rate on R_a

IV. CONCLUSION

In this work, the effects of cutting mode and pure/nanofluid MQL condition on surface roughness R_a were experimentally investigated for hard milling of 60Si2Mn steel (50-52HRC). Box Behnken experiment design and ANOVA analysis were used to evaluate the effects of cutting speed, feed rate and nanoparticle concentration on surface roughness values. Besides, the interaction effects of these parameters are also studied and evaluated. Experimental results show that the feed rate has the greatest influence on the surface roughness, followed by nanoparticle concentration. Moreover, the interaction effects of these two parameters also have a great influence on the objective function. This work also proposes the reasonable technological parameters for each specific machining case in hard milling to achieve good surface quality. When using nano cutting oils, lubricating and cooling efficiency in the cutting zone are improved when compared to MQL using pure emulsion oil. This is a new research direction and has a lot of potential gaps for future development.

Acknowledgments

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