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SURFACE ROUGHNESS INVESTIGATION IN MQCL HARD MILLING OF HARDOX 500 STEEL USING EMULSION-BASED NANOFLUID

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ABSTRACT
This paper presents the experimental study on surface roughness in MQCL hard milling of Hardox 500 steel by using Al_2O_3 emulsion-based nanofluid. Box-Behnken experimental design and ANOVA analysis are used to investigate the influence of investigated factors on surface roughness. The obtained results indicate that feed rate hasa strong effect on surface roughness. Moreover, in the investigated range, R_a value is smallest at cutting speed of 105 m/min and is about 0.102 µm – 0.374 µm, which is equivalent to grinding. It is also proven that cutting performance improves due to the better cooling and lubricating effects of Al_2O_3 nanofluid. In this study, the novel alternative solution for difficult-to-cut material like Hardox 500 steel is presented while retaining the environmentally friendly character.

Keywords: Hard milling; MQCL; emulsion; nanoparticles; nanofluid, surface roughness, hardox 500 steel.

INTRODUCTION
Recently, environmentally friendly manufacturing has gained much attention not only of researchers but also ofthe manufacturers around the world. The stricter environmental laws have been introduced for protecting our Earth, which promote the reduction or elimination the usage of coolants from metal cutting processes [1-3]. Hence, machining under dry condition has been considered an alternative solution for wet cutting [4-5], especially for hard machining processes using geometrical defined cutting edges. These processes exhibit many advantages like productivity, cost benefits, and low machine tool investment [4], but they always demand high-graded cutting tools like coated carbide, ceramic, (P)CBN, and so on [6-9]. The very large amount of cutting temperature generated from contact zone limits and requires the careful selection of the cutting condition [4,6], which is also given by manufacturer's recommendation. Along with the technological advances, the modern materials possess high mechanical properties, excellent wear and oxidized resistance, which also make the cutting processes difficult. Hardox 500 steel is the typical example of the difficult-to-cut materials, which combines high hardness and toughness and extreme wear resistance. The cutting process under dry condition will face a big challenge by using normal cutting tools, which causes the rapid tool wear and high generated heat. The productivity is very low, and the manufacturing cost will increase. In some last decades, minimum quantity lubrication (MQL) was developed and indicated the good lubricating effect due to spray the cutting fluid in form of oil mist to cutting zone directly [10]. There have been many studies on machining processes under MQL condition [11-13], but this method faces the difficulty when applying on hard materials due to low cooling effect [4]. The use of nano additives enriched in MQL based fluid and minimum quantity cooling lubrication (MQCL) have been the novel approaches to overcome this problem while remaining the environmentally friendly characteristic [6,14,15]. MQCL has not been gained for enough attention, so there are only a few studies, which were mostly focused on the idea of MQL method with the based fluid having cooling effect to form MQCL [16-17]. The use of the real MQCL equipment consisting of cooling and lubricating components is needed to study for the development of MQCL method [18-20]. Nanofluid instead of the pure fluid for MQCL is also a new research topic for tribological improvement. In this paper, the authors are motivated to make an experimental study on surface roughness in MQCL hard milling of Hardox 500 steel using Al_2O_3 nanofluid. Box-Behnken experimental design and ANOVA analysis are used to investigate the influence of investigated variables on surface roughness.

MATERIAL AND METHOD

2.1 Experimental design
Box-Behnken experimental design with the help of Minitab 18.0 software is utilized for three input parameters with two levels listed in Table 1.

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Table1.Box-Behnken experimental design

Input variables	**Symbol**	**Low level (-1)**	**High level (+)**	**Response variable**
Nanoparticle concentration, *np*(wt%)	x_1	0.5	1.5	Surface roughness R_a
Cutting speed, V_c(m/min)	x_2	80	130	
Feed rate, *F*(mm/tooth)	x_3	0.08	0.16	

2.2 Experimental devices

Mazak vertical center smart 530C was used for conducting the experimental study (Figure 1). Hardox 500 steel samples with the dimensions of 150 mm × 40 mm × 40 mm are used (Figure 2). The chemical composition and mechanical property are shown in Table 2,3. The Φ50 face mill head with APMT 1604 PDTR LT30 carbide inserts made by LAMINA Technologies (Sweden) was used (Figure 3). MQCL system consists of MQCL nozzle, air compressor, water-based emulsion 5 wt% and Al_2O_3 nanoparticles with the grain size of 50nm. The MQCL parameters consist of: air pressure of 6-8 bar, flow rate at 0.5 ml/min. The temperature of output cool oil mist from MQCL nozzle is 4 - 8°C with room temperature of 24 - 27°C.The depth of cut was fixed at 0.12 mm. SJ-210 Mitutoyo (made in Japan) for surface roughness was used (Figure 4). The 3000868-Ultrasons-HD made by JP SELECTA – Spain was used to form Al_2O_3 nanofluid.

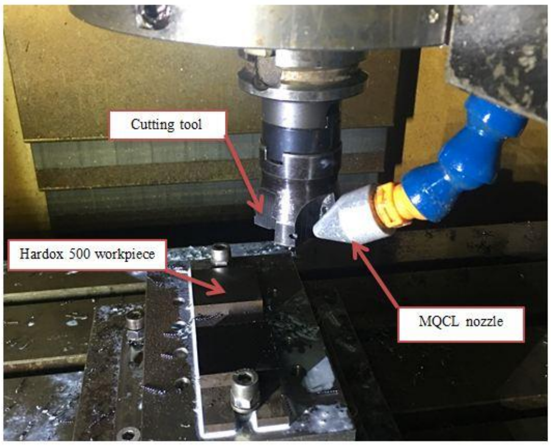

Figure 1.Experimental set up

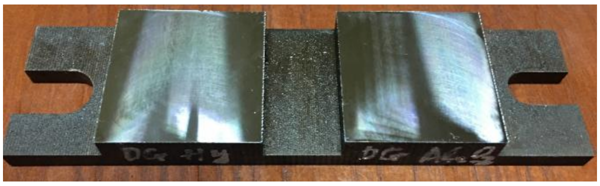

Figure 2.Hardox 500 steel workpiece

Figure 3. Milling head and inserts

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Figure 4.SJ-210 Mitutoyo for surface roughness

Table 2.Chemical composition of hardox 500 steel

Element	C	Si	Mn	P	S	Cr	Ni	Mo	B
Weight (%)	0.3	0.7	1.6	0.25	0.01	1.5	1.5	0.6	0.005

Table 3.Mechanical property of Hardox 500 steel

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness (HRC)
1250	1400	10	49 - 50

RESULTS AND DISCUSSION

Following Box-Behnken experimental design, the cutting trials are done to obtain the values of surface roughness (Table 4). Each running trial is repeated by three times under the same cutting parameters. The surface roughness is measured three times and taken by the average value.

Table 4.The experimental design with test run order and response variables in term of surface roughness

Std Order	Run Order	PtType	x_1 (wt%)	x_2 (m/min)	x_3 (mm/tooth)	R_a (µm)
1	10	2	0.5	80	0.12	0.187
2	2	2	1.5	80	0.12	0.128
3	1	2	0.5	130	0.12	0.354
4	18	2	1.5	130	0.12	0.164
5	16	2	0.5	105	0.08	0.102
6	22	2	1.5	105	0.08	0.115
7	4	2	0.5	105	0.16	0.147
8	24	2	1.5	105	0.16	0.173
9	30	2	1	80	0.08	0.139
10	12	2	1	130	0.08	0.110
11	29	2	1	80	0.16	0.387
12	27	2	1	130	0.16	0.141
13	15	0	1	105	0.12	0.112

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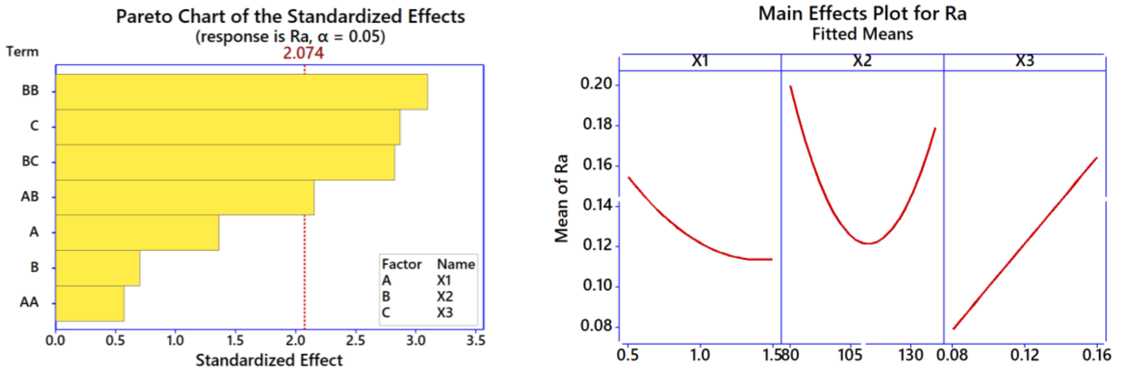
14	6	0	1	105	0.12	0.114
15	11	0	1	105	0.12	0.136
16	14	2	0.5	80	0.12	0.134
17	5	2	1.5	80	0.12	0.175
18	28	2	0.5	130	0.12	0.335
19	9	2	1.5	130	0.12	0.144
20	13	2	0.5	105	0.08	0.108
21	23	2	1.5	105	0.08	0.126
22	3	2	0.5	105	0.16	0.141
23	21	2	1.5	105	0.16	0.158
24	19	2	1	80	0.08	0.126
25	8	2	1	130	0.08	0.123
26	7	2	1	80	0.16	0.374
27	25	2	1	130	0.16	0.112
28	20	0	1	105	0.12	0.138
29	26	0	1	105	0.12	0.118
30	17	0	1	105	0.12	0.112

ANOVA analysis is conducted at a confidence level of 95% (i.e., 5% significance level). The regression model of surface roughness R_a is given below

$R_a = 0.045 + 0.193\, x_1 - 0.008 x_2 + 6.52\, x_3 + 0.050\, x_1 * x_1 - 0.003\, x_1 * x_2 - 0.05\, x_2 * x_3$ *(1)*

Pareto charts and the plots of main effects of investigated parameters on surface roughness R_a is shown in Figures 5. ANOVA analysis result of investigated parameters for surface roughness is given by Table 5. The last column of these tables indicates that most of p-values are smaller than the significance level (0.05). It means that the control factors, such as nanoparticle concentration, cutting speed, and feed rate, have a significant influence on the response variable.



(a) *(b)*

Figure 5. Pareto chart of the effects of investigated parameters on surface roughness R_a: (a) Pareto chart, (b) Plot of main effects

Table 5. Results of ANOVA analysis of surface roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	0.116861	0.016694	4.70	0.002
Linear	3	0.037586	0.012529	3.53	0.032
X_1	1	0.006602	0.006602	1.86	0.186
X_2	1	0.001743	0.001743	0.49	0.491
X_3	1	0.029241	0.029241	8.24	0.009

Square	2	0.034482	0.017241	4.86	0.018
X_1*X_1	1	0.001152	0.001152	0.32	0.575
X_2*X_2	1	0.034049	0.034049	9.59	0.005
2-Way Interaction	2	0.044793	0.022397	6.31	0.007
X_1*X_2	1	0.016471	0.016471	4.64	0.042
X_2*X_3	1	0.028322	0.028322	7.98	0.010
Error	22	0.078098	0.003550		
Lack-of-Fit	5	0.073680	0.014736	56.70	0.000
Pure Error	17	0.004418	0.000260		
Total	29	0.194959			

The Pareto chart of the standardized effects with α = 0.05 for the response variable is shown in Figure 5(a). The reference line of surface roughness R_a has x coordinate of 2.074 (figure 5(a)), from which the investigated factors including feed rate (x_3), and interaction effects BB (x_2*x_2),BC (x_2*x_3), AB (x_1*x_2) have strong influences on R_a. Among these, feed rate causes a strongest effect. The nanoparticle concentration (x_1), cutting speed (x_2) and interaction effects AA (x_1*x_1) have very little influence.

The plot of main effects of investigated factors on surface roughness R_a is shown in Figure 5(b). For increasing nanoparticle concentration (x_1) from 0.5 wt% to 1.5 wt%, the values of surface roughness R_a decrease, which is suitable with the previous studies [15]. The R_a values increase with the rise of feed rate. In the investigated range of cutting speed from 80 to 130 m/min, the smallest values of surface roughness R_a occur at V_c = 105 m/min.

CONCLUSION

The application of MQCL using Al_2O_3 emulsion-based nanofluid was successfully applied to hard milling of Hardox 500 steel. The influence of control variables including nanoparticle concentration (x_1), cutting speed (x_2), and feed rate (x_3) on surface roughness R_a is studied. Feed rate and interaction effects BB (x_2*x_2), BC (x_2*x_3) cause strongest influence on surface roughness. The good R_a values obtained from hard milling are about 0.102 µm – 0.374 µm, which is equivalent to those of grinding, so some of grinding processes can be replaced. Moreover, the environmentally friendly character of MQCL, which is suitable for sustainable production, still remains, and this study contributes an alternative solution for difficult-to-cut materials by using normal cutting tools while ensuring the technical and economical requirements. In future work, more investigation is needed to study the vegetable oil as the based fluid for MQCL technique instead of emulsion-based fluid in order to reduce the negative effect on environment.

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