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Study of Cutting Forces In Hard Milling of Hardox 500 Steel Under MQCL Condition Using Nano Additives

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Abstract

This paper presents the experimental study on cutting forces in the hard milling process of Hardox 500 steel under the MQCL condition using Al_2O_3nano additives. The cooling and lubricating performance of MQCL is improved by using nanoparticles enriched in the emulsion-based fluid. Box-Behnken experimental design and ANOVA analysis are applied to determine the influence of investigated parameters in terms of cutting forces. The obtained results indicate that feed rate and nanoparticle concentration have strong effects on cutting forces. Moreover, cutting force components reduce significantly with the increase of cutting speed to 130 m/min, which is much higher than that of the manufacturer's recommendation due to the better cooling and lubricating effects. This study also provides a new alternative solution for difficult-to-cut materials like Hardox 500 steel while remaining environmentally friendly characteristics.

Keywords — *Hard milling, MQCL, emulsion, nanoparticles,nanofluid, cutting force, hardox 500 steel.*

I. INTRODUCTION

Environmentally friendly manufacturing has attracted the growing attention of researchers and manufacturers around the world. The strict laws for encountering climate change have been introduced to promote the reduction or elimination the waste from manufacturing processes, including the used cutting fluid from the metal cutting process [1]-[3]. Accordingly, dry cutting processes had been proposed and developed to use in machining practice. High cutting temperature and the demand for high-graded cutting tools are the main limitations, especially for hard cutting [4].

Hardox 500 steel is a special type of material, which combines hardness and toughness. It also possesses the extreme wear resistance to withstand heavy impact without permanent deformation or cracking. More and more hardox 500 steel applications have been seen in practice, but this type of steel is categorized as one of the difficult-to-cut materials. It will be a big challenge for normal cutting tools under dry conditions due to low productivity and high machining cost [3],[5]-[8]. Recently, Minimum quantity lubrication (MQL) has been considered a promising alternative solution for dry and flood machining, which exhibits good lubrication due to the direct spray of oil mist to the cutting zone [9]-[10]. However, the low cooling effect is the main problem of the MQL technique, limiting the applicability to difficult-to-cut material due to enormous generated heat [11]-[13].

Minimum quantity cooling lubrication (MQCL) has been the new approach to provide the cooling and lubricating effects to the cutting zone while remaining the environmentally friendly characteristic [14]-[16]. There are only a few studies on this technique, and they are mostly focused on the idea of the MQL method with the based fluid havinga cooling effect of forming MQCL [17]-[18]. Therefore, applying a real MQCL device used for the hard machining process is needed to investigate the MQCL technique's development. The use of nano additives for MQCL based fluid is a novel research topic to improve its tribological property, from which the cutting performance enhances. In this paper, the authors are motivated to studythe hard milling process of Hardox 500 steel under the MQCL condition using nano additives in terms of cutting forces. Box-Behnken experimental design and ANOVA analysis are applied to determine the influence level of investigated parameters in terms of cutting forces.

II. MATERIAL AND METHOD

A. Experimental design

Minitab 18.0 software is used for Box-Behnken experimental design with three input parameters with two levels are listed in Table 1.

Table1. Box-Behnken experimental design

Input parameter	Symbol	Low level (-1)	High level (+)	Response parameter
Nanoparticle concentration, *np* (wt%)	x_1	0.5	1.5	Cutting forces F_x, F_y, F_z
Cutting speed, V_c (m/min)	x_2	80	130	
Feed rate, *F* (mm/tooth)	x_3	0.08	0.16	

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. The mechanical property of Hardox 500 steel

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

B. Experimental devices

Mazak vertical center smart 530C (made in Japan) was used for the experiments, shown in 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 properties are shown in Table 2, 3. The Φ50 face mill head with APMT 1604 PDTR LT30 cemented carbide inserts made by LAMINA Technologies (Sweden) was used (Figure 3). MQCL system consists of MQCL nozzle, air compressor, emulsion coolant 5 wt%., and Al_2O_3 nanoparticles with the grain size of 30nm. The MQCL parameters include air pressure of 6-8 bar, the flow rate at 0.5 ml/min. The temperature of output cool oil mist from the MQCL nozzle is 4 - 8°C with a room temperature of 24 - 27°C. The depth of the cut was fixed at 0.12 mm. For measuring cutting forces, Kistler quartz three-component dynamometer (9257BA) was used. The 3000868-Ultrasons-HD made by JP SELECTA – Spain was used to create Al_2O_3nanofluid.

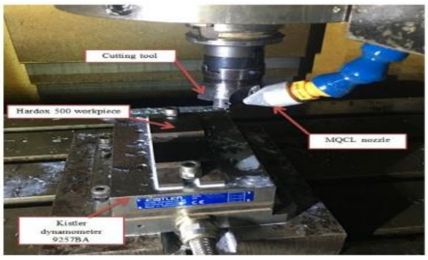


Fig 1. Experimental setup

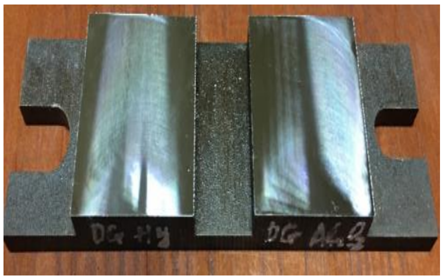


Fig 2.Hardox 500 steel sample

Fig 3. Milling head and cutting inserts

III. RESULTS AND DISCUSSION

Minitab 18 software is applied for the Box-Behnken experimental design. Each running trial is repeated three times under the same cutting parameters. The experiments are done by following the run order to obtain the cutting force values in Table 4.

Table 4. The experimental design with test run order and response parameters in term of cutting force components

StdOrder	RunOrder	PtType	x_1 (wt%)	x_2 (m/min)	x_3 (mm/tooth)	F_x (N)	F_y (N)	F_z (N)
1	10	2	0.5	80	0.12	82.5	116.1	134.5
2	2	2	1.5	80	0.12	105.3	136.3	183.9
3	1	2	0.5	130	0.12	78.4	118.5	135.0
4	18	2	1.5	130	0.12	84.7	124.9	136.1
5	16	2	0.5	105	0.08	70.1	104.8	116.2
6	22	2	1.5	105	0.08	75.6	114.6	123.9
7	4	2	0.5	105	0.16	97.8	158.7	181.2
8	24	2	1.5	105	0.16	109.5	148.9	188.8
9	30	2	1	80	0.08	75.0	121.4	141.0
10	12	2	1	130	0.08	55.8	102.4	105.0
11	29	2	1	80	0.16	84.5	124.7	143.8
12	27	2	1	130	0.16	90.9	120.3	194.5
13	15	0	1	105	0.12	81.0	133.9	148.7
14	6	0	1	105	0.12	84.5	132.1	150.2
15	11	0	1	105	0.12	73.9	130.5	148.3
16	14	2	0.5	80	0.12	74.5	111.3	130.0
17	5	2	1.5	80	0.12	101.2	124.7	180.0
18	28	2	0.5	130	0.12	74.3	106.2	128.8
19	9	2	1.5	130	0.12	84.5	128.6	146.1
20	13	2	0.5	105	0.08	65.1	102.0	125.4
21	23	2	1.5	105	0.08	85.0	117.8	128.7
22	3	2	0.5	105	0.16	85.8	128.7	188.9
23	21	2	1.5	105	0.16	104.3	146.1	182.3
24	19	2	1	80	0.08	75.3	114.6	125.0
25	8	2	1	130	0.08	61.1	102.6	112.0
26	7	2	1	80	0.16	79.8	118.9	138.7
27	25	2	1	130	0.16	98.9	131.4	172.0
28	20	0	1	105	0.12	84.8	132.7	155.8
29	26	0	1	105	0.12	87.4	135.4	154.7
30	17	0	1	105	0.12	85.3	131.3	157.2

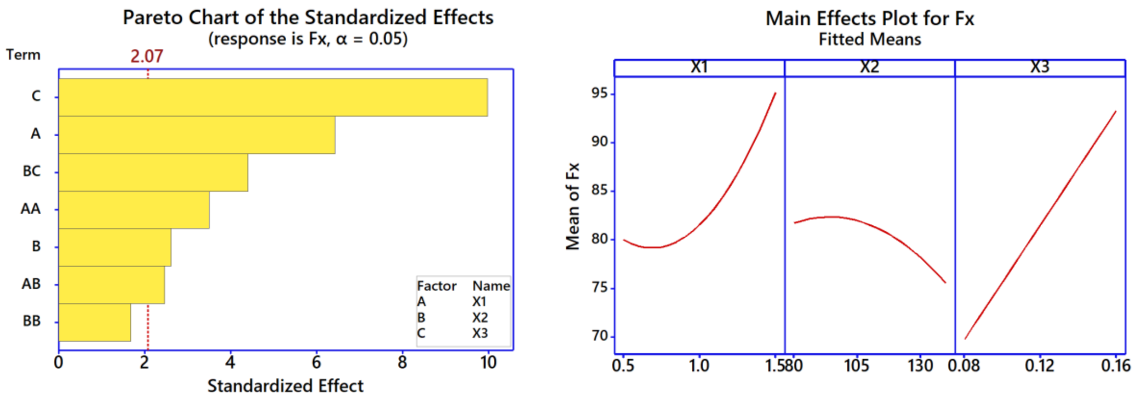
ANOVA analysis is conducted at a confidence level of 95% (i.e., 5% significance level). The regression models of cutting forces F_x, F_y, F_z with the coefficient of determination (R^2) equal to 89.59, 85.34, and 85.34 are given below

F_x =78.4 – 3.2 x_1 + 0.145 x_2 - 380 x_3 + 23.69 x_1*x_1 – 0.003 x_2*x_2 - 0.275 x_1*x_2+ 6.14 x_2*x_3 *(1)*

F_y =68.9 + 60.5 x_1 + 1.16 x_2 - 879 x_3 + 15.0 x_1*x_1- 0.010 x_2*x_2- 0.675 x_1*x_2+ 13.85 x_2*x_3 *(2)*

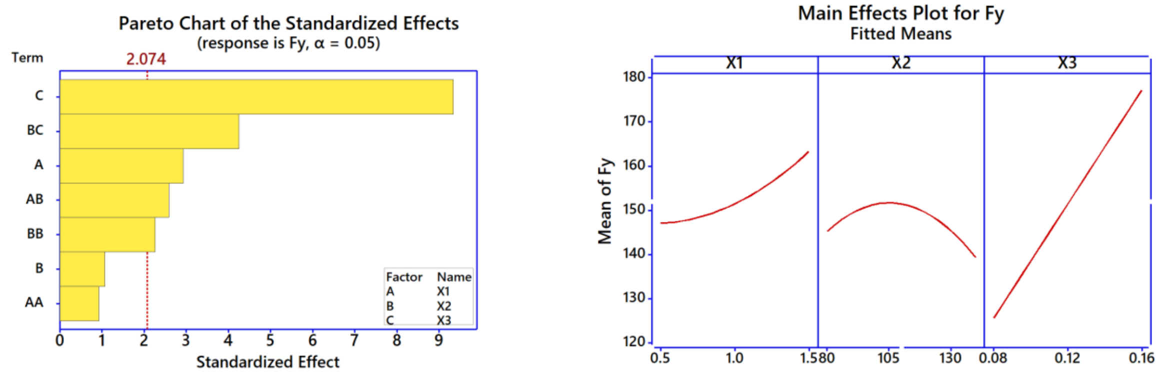
F_z =- 44.8 + 11.95 x_1 + 2.180 x_2 + 509 x_3 - 0.012 x_2*x_2- 2730 x_3*x_3 + 4.07 x_2*x_3 *(3)*

Pareto charts and the plots of the main effects of investigated parameters on cutting forces F_x, F_y, $F_z$are shown in Figures 4-6. ANOVA analysis of investigated parameters for cutting forces F_x, F_y, F_z is given in Table 5–7. The last column of these tables indicates that most 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, significantly influence the response variables F_x, F_y, F_z.



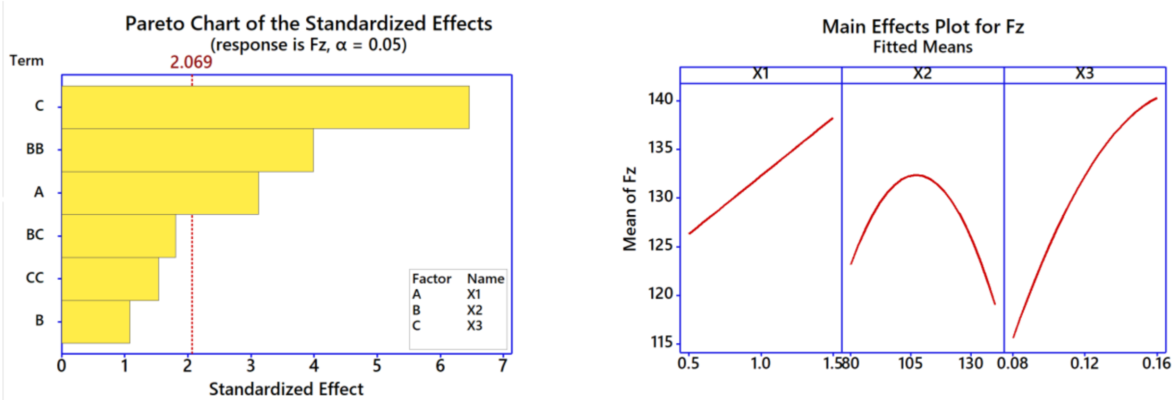
(a) *(b)*

Figure 4. Pareto chart of the effects of investigated parameters on cutting force F_x: (a) Pareto chart, (b) Plot of main effects



(a) *(b)*

Figure 5. Pareto chart of the effects of investigated parameters on cutting force F_y: (a) Pareto chart, (b) Plot of main effects



(a) *(b)*

Figure 6. Pareto chart of the effects of investigated parameters on cutting force F_z: (a) Pareto chart, (b) Plot of main effects

Table 5. Results of ANOVA analysis of cutting force F_x

Source	DF	Adj S.S.	Adj MS	F-Value	P-Value
Model	7	4226.00	603.71	27.03	0.000
Linear	3	3298.07	1099.36	49.23	0.000
x_1	1	924.16	924.16	41.38	0.000
x_2	1	153.14	153.14	6.86	0.016
x_3	1	2220.77	2220.77	99.45	0.000

Square	2	358.15	179.08	8.02	0.002
x_1*x_1	1	274.94	274.94	12.31	0.002
x_2*x_2	1	62.64	62.64	2.81	0.108
2-Way Interaction	2	569.78	284.89	12.76	0.000
x_1*x_2	1	136.13	136.13	6.10	0.022
x_2*x_3	1	433.65	433.65	19.42	0.000
Error	22	491.28	22.33		
Lack-of-Fit	5	126.37	25.27	1.18	0.361
Pure Error	17	364.91	21.47		
Total	29	4717.28			

Table 6. Results of ANOVA analysis of cutting force F_y

Source	**DF**	**Adj S.S.**	**Adj MS**	**F-Value**	**P-Value**
Model	7	15655.5	2236.5	18.29	0.000
Linear	3	11854.0	3951.3	32.32	0.000
x_1	1	1053.0	1053.0	8.61	0.008
x_2	1	140.4	140.4	1.15	0.295
x_3	1	10660.6	10660.6	87.19	0.000
Square	2	770.2	385.1	3.15	0.063
x_1*x_1	1	104.5	104.5	0.85	0.365
x_2*x_2	1	625.3	625.3	5.11	0.034
2-Way Interaction	2	3031.3	1515.6	12.40	0.000
x_1*x_2	1	820.1	820.1	6.71	0.017
x_2*x_3	1	2211.1	2211.1	18.08	0.000
Error	22	2689.8	122.3		
Lack-of-Fit	5	2004.4	400.9	9.94	0.000
Pure Error	17	685.4	40.3		
Total	29	18345.3			

Table 7. Results of ANOVA analysis of cutting force F_z

Source	**DF**	**Adj S.S.**	**Adj MS**	**F-Value**	**P-Value**
Model	6	4293.09	715.51	12.24	0.000
Linear	3	3077.58	1025.86	17.54	0.000
x_1	1	571.21	571.21	9.77	0.005

x_2	1	68.48	68.48	1.17	0.290
x_3	1	2437.89	2437.89	41.69	0.000
Square	2	1024.41	512.21	8.76	0.001
x_2*x_2	1	931.68	931.68	15.93	0.001
x_3*x_3	1	138.89	138.89	2.38	0.137
2-Way Interaction	1	191.10	191.10	3.27	0.084
x_2*x_3	1	191.10	191.10	3.27	0.084
Error	23	1344.89	58.47		
Lack-of-Fit	6	603.20	100.53	2.30	0.082
Pure Error	17	741.69	43.63		
Total	29	5637.97			

The Pareto chart of the standardized effects with α = 0.05 for the response parameters F_x, F_y, F_z is shown in Figure 4(a), 5(a), 6(a). The reference line of cutting force F_x has x coordinate of 2.07 (figure 4(a)), from which the investigated factors including nanoparticle concentration (x_1), feed rate (x_3), and interaction effects B.C. (x_2*x_3), A.A. (x_1*x_1) and A.B. (x_1*x_2) have strong influences on F_x. Among these, feed rate causes the strongest effect, followed by nanoparticle concentration. The cutting speed (x_2) and interaction effects B.B. (x_2* x_2) have very little influence.

The reference line of cutting force F_y has x coordinate of 2.074 (figure 5(a)), from which the investigated factors including feed rate (x_3), nanoparticle concentration (x_1), and interaction effects B.C. (x_2* x_3), A.B. (x_1* x_2) and B.B. (x_2* x_2) have strong influences on F_y. Among these, feed rate also causes the strongest effect, followed by nanoparticle concentration. The cutting speed (x_2) and interaction effects A.A. (x_1* x_1) have very little influence.

The reference line of cutting force F_z has x coordinate of 2.069 (figure 6(a)), from which the investigated factors including feed rate (x_3), nanoparticle concentration (x_1), and interaction effect B.B. (x_2* x_2) have strong influences on F_z. The cutting speed (x_2) and interaction effects B.C. (x_2* x_3), CC (x_3* x_3) have very little influence.

From the analysis, feed rate (x_3) has the strongest effect, followed by nanoparticle concentration (x_1), while cutting speed (x_2) has little influence.

The effects of investigated factors on cutting force components F_x, F_y, $F_z$are shown in Figure 4(b), 5(b), 6(b). In general, when increasing nanoparticle concentration (x_1) from 0.5 wt% to 1.5 wt%, the growing trend of cutting forces is reported. It is needed to make further studies to optimize this parameter. Cutting forces increase with cutting speed from 80 to 105 m/min and reach the largest values at 100-105 m/min. They much decrease when rising cutting speed from 105 to 130 m/min, suitable for the previous studies [12]. The cutting force components F_x, F_y, F_z rapidly increases with the rise of feed rate.

IV. CONCLUSIONS

The application of MQCL using Al_2O_3 emulsion-based nanofluid has a strong effect on the hard milling process of Hardox 500 steel. The ANOVA results with Box–Behnken experimental design indicates the influence level of nanoparticle concentration (x1), cutting speed (x_2), and feed rate (x_3) on cutting forces F_x, F_y, F_z. The increase of nanoparticle concentration and feed rate causes the growth of cutting forces. For increasing cutting speed from 105 to 130 m/min, cutting forces reduce significantly. It is one of the few studies on hard milling of Hardox 500 steel under MQCL using Al_2O_3 emulsion-based nanofluid, which contributes a novel alternative solution for difficult-to-cut materials.Simultaneously, this new approach remains an environmentally friendly characteristic, which is suitable for sustainable production.

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