Effect of Cutting Parameters on Cutting Force of Hard Milling of SKD 61 Steel under Nanofluid-MQL Condition

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***Abstract*—Proper selection of cutting parameters results in better performance of cutting force. For this purpose, a series of meticulous experiments were carried out to determine the effect of machining parameters on the cutting force during hard milling of SKD 61 steel under SiO_2 nanofluid minimum quantity lubrication (MQL). The cutting parameters selected include cutting speed, feed-rate, depth-of-cut and hardness of workpiece. The Taguchi method and the Response Surface Methodology (RSM) were integrated to design the experiment and analyze the influences of the input factors on the output factor. The L27 orthogonal array developed by G. Taguchi was used to design the experiment. Three cutting force components were measured by using a dynamometer, and then analysis of variance (ANOVA) was carried out. It is found that cutting force components becomes affected primarily by depth-of-cut and feed-rate. A quadratic mathematical model was established to predict the cutting force components during hard milling under nanofluid MQL condition. In order to obtain the maximum material removal rate (MRR) and minimum cutting force, the multi-objective optimization was conducted to find out the optimal cutting parameters.**

***Index Terms*— cutting force, nanofluid, MQL, SiO2 nanoparticle, hard milling, multi-objective optimization**

I. Introduction

Nowadays, modern machining industries tend to achieve high dimensional accuracy, good roughness, high machining productivity, low cost and low impact on the environment. In metal cutting, cutting force plays an important role because of their strong correlation with machining accuracy, tool wear, tool life, cutting temperature, and forced vibrations, etc. [1, 2]. In milling, the cutting parameters including feed-rate, depth-of-cut, cutting speed, hardness of workpiece have a great impact on cutting force [1-4]. Low cutting force is one of the criteria that shows the high machinability of an engineering material [3]. There has been a remarkable amount of research about the effects of cutting parameters on cutting forces in metal cutting. In a work reported by Ding et al. [1], an experimental investigation was conducted to determine the effect of cutting parameters on cutting forces in hard milling of AISI H13 steel. The conclusion is that feed-rate and depth-of-cut are two major factors affecting the cutting forces. Taguchi method was used in the study of Ghani et al. for the optimization of cutting parameters during hard end-milling of AISI H13 [5]. They noted that the cutting condition including high cutting speed, low feed-rate and low depth-of-cut result in low cutting force. Aouici et al. investigate the effects of cutting speed, feed rate, and depth of cut on cutting force in hard milling of 60 HRC AISI D3 steel [6]. The conclusion was that feed rate followed by depth of cut is the most influencing factor on the cutting force. In a publication of T-V Do and L-N-A Vu, the authors conducted optimization of cutting parameters to minimize cutting force during the hard milling process. They revealed that a higher cutting-velocity, lower feed-rate, lower depth-of-cut, and lower hardness of workpiece would result in lower cutting force [7].

The trend of industrial production is to reduce the impact on the environment. Traditional metal cutting has applied the wet cutting method to improve the tribological process occurring between the contact interface of the cutting tool and the workpiece. The major negative effects of wet cutting are harmful to the environment and operators [8, 9]. Any reduction, or even elimination, of the use of cutting fluids during machining will be considered as a major driving force for switching to a non-cutting-fluid method. As a successful alternative to the wet cutting, the minimum quantity lubrication (MQL) is an effective, environmentally friendly solution that has been successfully applied to the metal cutting process. MQL refers to machining using only a minute amount of cutting fluid mixed with compressed air and sprayed into the cutting zone [10, 11]. The economic and technological effectiveness of MQL in comparison to dry and wet cutting has been demonstrated. Many researchers have recognized that using MQL helps to improve roughness, reduce tool wear, increase tool life and reduce the cutting force, cutting temperature [7, 9, 12-15].

Recently, a new technology called "nanofluids" has been developed that involves adding nanoscale particles such as CNT, SiO_2, C60, TiO_2, Al_2O_3, MoS_2, diamond, etc. in the range of 10 to 100 nanometers into cutting fluids during MQL machining [16]. The nanoparticles are added to the base fluid to enhance the thermal

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conductivity with the addition of a very minute volumetric concentration [17, 18]. Additionally, the tribological characteristics of base fluid are enhanced by adding the nanoparticle. These are important characteristics of the metal cutting application. The mechanism of the nanoparticle tribological effect includes ball/rolling bearing effect, third body effect, chemical mechanical protective film effect, mending effect, and polishing effect [16, 19]. The enhancement of thermal conductivity and lubrication of base fluids by adding nanoparticles improves machining performance such as improved surface roughness, reduced cutting temperatures, reduced cutting forces, reduced tool wear, increased tool life [20, 21].

It is well-known that silicon dioxide (SiO_2) nanoparticle is a hard and brittle material, and available on the market. SiO_2 has excellent mechanical properties especially in terms of hardness. With its high hardness, SiO_2 added in cutting oil acts as a ball/rolling bearing at the interface of the tool–chip. Therefore, it reduces the coefficient of friction significantly leading to reduced cutting force [21, 22]. The reduction of cutting force is the cause of the improvement of machining performance [23].

In existing articles, the effect of cutting parameters on cutting forces as well as surveying the machining efficiency of SiO_2 nanofluid application has been studied. However, investigation of the effect of the cutting parameters on the cutting force under the condition of SiO_2 nanofluid has been not mentioned. Hence, this is our motivation to investigate the influence of cutting parameters on cutting force of hard milling of SKD 61 steel under SiO_2 nanofluid-MQL condition. In this study, the Taguchi method and the Response Surface Methodology (RSM) were integrated to analyze the influences of the cutting parameters including cutting speed, feed-rate, depth-of-cut and hardness of workpiece on cutting force. A quadratic mathematical model to predict the cutting force components was established. The multi-objective optimization was conducted to find out the optimal cutting parameters for maximizing material removal rate (MRR) and minimizing cutting force.

II. Experimental Setup

In this study, the SKD 61 steel blocks with dimensions of 200mm × 100mm × 50mm were used. The blocks were hardened to reach three levels of 40, 45, and 50 HRC. All experiments were conducted on a Victor V-center machine. The ϕ10 TiAlN coated endmill was used. Each surface was milled by a new cutting tool. The milling process selected is the slot milling. The cutting force components were measured by using a piezo-electric, three-component dynamometer (type XYZ FORCE SENSOR, model 624-120-5KN) and a System 6000 - Model 6100 scanner. Each experiment was repeated 3 times to minimize possible errors.

The nanofluid-MQL condition was applied in all experiments with 90ml/h for the flow-rate, 3kg/cm^2 for the air-pressure and CT232 cutting oil for the lubricant. On the vertical plane, the MQL nozzle was placed with the z-axis at an angle of 60 degrees. SiO_2 particles with a size of 100nm were added into cutting fluid at 2% concentration. The solution containing the nanoparticles is stirred by using a magnetic stirring device within 12 hours to obtain a homogeneous dispersion and stable suspension.

For the experiment with four factors at three levels, the L27 orthogonal array of Taguchi's DOE was applied to conduct the cutting experiments. As shown in Table I, four input factors with three levels are the cutting-speed, the feed-rate, the depth-of-cut, and the hardness-of-workpiece.

TABLE I. The Input Factors with Levels

Factors	Levels		
	1	2	3
Cutting-speed *v* (m/min)	40	60	80
Feed-rate *f* (mm/tooth)	0.01	0.02	0.03
Depth-of-cut *d* (mm)	0.2	0.4	0.6
Hardness-of-workpiece *h* (HRC)	40	45	50

III. Results and Discussion

In this work, the cutting force components including the normal force *Fx*, the feed force *Fy*, and the axial force *Fz* were measured by using a dynamometer. The values of the cutting force in three directions were calculated as the average of the values of 10 peaks in the stable region as shown in Fig. 1.

Additionally, *MRR* was calculated by the formula (1) [24].

$$MRR = (d \times a_e \times v \times f \times z \times 1000)/(3.14 \times D) \quad (1)$$

Where *MRR* is the material removal rate (mm^3/min), *d* is the depth-of-cut (mm), a_e is the width-of-cut (mm), *v* is the cutting-speed (m/min), *f* is the feed-rate (mm/tooth), *z* is the flute of the cutter (herein, the flute is 4), and *D* is the diameter of the cutting tool (mm).

Table II shows the measured result of the cutting force components and the calculated values of *MRR*.

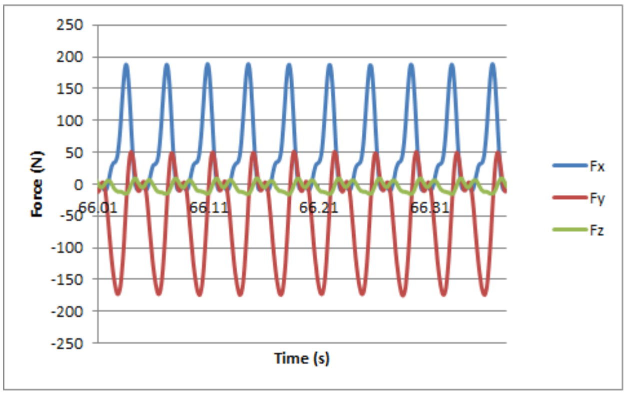

Figure 1. Ten periods of cutting force components in the hard milling

TABLE II. THE RESULT OF THE EXPERIMENT

Run	Input factors				Output factors			
	v (m/min)	*f* (mm/tooth)	*d* (mm)	*h* (HRC)	*Fx* (N)	*Fy* (N)	*Fz* (N)	*MRR* (mm^3/min)
1	40	0.01	0.2	40	45.6	37.879	5.203	101.911
2	40	0.01	0.4	45	111.8	82.75	14.988	203.822
3	40	0.01	0.6	50	157.8	187.883	22.717	305.733
4	40	0.02	0.2	45	77.1	68.434	10.1	203.822
5	40	0.02	0.4	50	163.06	161.263	23.486	407.643
6	40	0.02	0.6	40	180.32	188.541	26.691	611.47
7	40	0.03	0.2	50	122.851	102.639	15.795	305.733
8	40	0.03	0.4	40	150.37	132.01	18.82	611.465
9	40	0.03	0.6	45	233.45	230.275	32.49	917.198
10	60	0.01	0.2	45	40.319	29.211	4.81	152.866
11	60	0.01	0.4	50	116.188	95.182	15.523	305.733
12	60	0.01	0.6	40	108.261	112.044	15.457	458.599
13	60	0.02	0.2	50	82.83	55.3	9.4	305.733
14	60	0.02	0.4	40	107.176	101.336	14.596	611.465
15	60	0.02	0.6	45	140.191	172.734	23.389	917.198
16	60	0.03	0.2	40	60.661	58.623	8.275	458.599
17	60	0.03	0.4	45	133.589	127.723	18.926	917.198
18	60	0.03	0.6	50	246.585	200.07	31.9	1375.796
19	80	0.01	0.2	50	43.649	56.168	6.491	203.822
20	80	0.01	0.4	40	55.805	58.717	7.978	407.643
21	80	0.01	0.6	45	94.758	113.25	14.898	611.465
22	80	0.02	0.2	40	38.148	34.816	5.664	407.643
23	80	0.02	0.4	45	91.016	117.059	14.441	815.287
24	80	0.02	0.6	50	183.948	199.55	26.163	1222.93
25	80	0.03	0.2	45	47.843	68.857	8.524	611.465
26	80	0.03	0.4	50	160.69	159.051	22.104	1222.93
27	80	0.03	0.6	40	113.87	95.357	13.806	1834.395

TABLE III. ANOVA TABLE

ANOVA for *Fx*						
Source	DF	Adj_SS	Adj_MS	F-Value	P-Value	Cont.%
Model	14	83784.2	5984.6	69.29	0.000[a]	98.78
Linear	4	77808.2	19452.1	225.21	0.000[a]	91.73
v	1	9458.8	9458.8	109.51	0.000[a]	11.15
f	1	13652.5	13652.5	158.06	0.000[a]	16.1
d	1	45018.3	45018.3	521.20	0.000[a]	53.07
h	1	9678.6	9678.6	112.05	0.000[a]	11.41
Error	12	1036.5	86.4			1.22
Total	26	84820.7				
R-sq = 98.78%						
ANOVA for *Fy*						
Source	DF	Adj_SS	Adj_MS	F-Value	P-Value	Cont.%
Model	14	84165.0	6011.8	46.58	0.000[a]	98.19
Linear	4	76588.4	19147.1	148.35	0.000[a]	89.35
v	1	4635.3	4635.3	35.91	0.000[a]	5.41
f	1	8956.6	8956.6	69.39	0.000[a]	10.45
d	1	54205.9	54205.9	419.97	0.000[a]	63.24
h	1	8790.6	8790.6	68.11	0.000[a]	10.26
Error	12	1548.8	129.1			1.81
Total	26	85713.8				
R-sq = 98.19%						

ANOVA for *Fz*						
Source	DF	Adj_SS	Adj_MS	F-Value	P-Value	Cont.%
Model	14	1647.33	117.667	101.88	0.000[a]	99.17
Linear	4	1525.15	381.286	330.15	0.000[a]	91.81
v	1	140.11	140.110	121.32	0.000[a]	8.43
f	1	217.54	217.540	188.36	0.000[a]	13.1
d	1	986.43	986.427	854.12	0.000[a]	59.38
h	1	181.07	181.068	156.78	0.000[a]	10.9
Error	12	13.86	1.155			0.83
Total	26	1661.19				
R-sq = 99.17%						

[a] Significant

By using the Minitab 17 software, The ANOVA was conducted and its results are shown in Table III. Based on the ANOVA, the direct and interactive effects of the cutting parameters (v, f, d, and h) on the cutting force components have been analyzed. As shown in Table III, the depth-of-cut is a factor that has a remarkable influence on cutting force compared to other factors. Its effect on the normal force Fx, the feed force Fy, and the axial force Fz are 53.07, 63.24, and 59.38% respectively. The second most influential factor in cutting force is the feed-rate. It has 16.1, 10.45, and 13.1% of the total effect of factors on the normal force Fx, the feed force Fy, and the axial force Fz respectively. The effect of all input factors such as the cutting-speed, the feed-rate, the depth-of-cut, and the hardness on the cutting force have statistical significance with P-value less than 0.05.

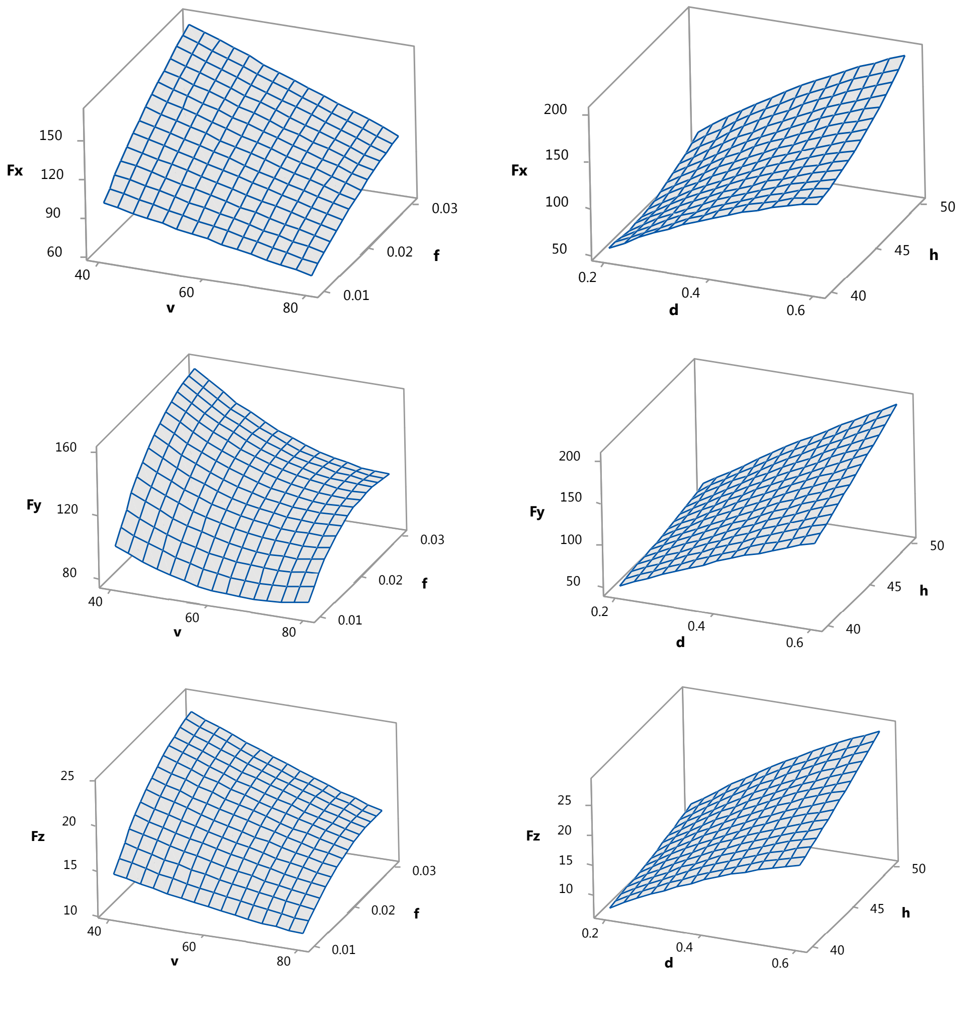

Figure 2. The response surface plot for cutting force

Fig. 2 indicates the response surface plot for cutting forces. The interaction influence of cutting-speed and feed-rate on the cutting forces in three directions is depicted in the images on the left. It reveals that an increase in the cutting-speed and a decrease in feed-rate result in a decrease in all cutting force components. It can be explained that the increasing temperature in the shear zone caused by the increase in the cutting speed lead to the thermal softening of the work-piece [25]. In other reports [26, 27], this is interpreted that the increase in the cutting-speed causes a decrease of the apparent real contact surfaces between the interfaces of tool-chip. Thus, reduced friction forces result in reduced cutting forces.

The images on the right show the interaction influence of the depth-of-cut and the hardness on cutting forces. It can be noticed that the increase of the depth-of-cut and the hardness leads to the rapid increase of cutting forces in all three directions. In particular, the influence of the depth-of-cut on cutting forces is outstanding. This influence is manifested by the large slope of the graph on the side of the depth-of-cut. The increase of factors such as the feed-rate, the depth-of-cut, and the hardness-of-workpiece producing the increase of cutting forces is explained that by the increase of these factors lead to the chip load higher for the material removal process [2, 26].

The quadratic mathematical models based on the experimental data, in this study, were established by using RSM for predicting the cutting force components in the hard milling of SKD 61 as follows:

$$Fx = 1131 - 2.84\,v - 4037\,f + 67\,d - 46.6\,h + 0.00007\,v*v - 46381\,f*f - 223.9\,d*d + 0.439\,h*h - 37.1\,v*f - 1.942\,v*d + 0.0713\,v*h + 4579\,f*d + 200.9\,f*h + 8.60\,d*h \quad (2)$$

$$Fy = 412 - 7.00\,v + 4039\,f + 82\,d - 13.1\,h + 0.0264\,v*v - 139099\,f*f - 81\,d*d + 0.035\,h*h - 39.3\,v*f - 3.572\,v*d + 0.1165\,v*h - 1221\,f*d + 146.7\,f*h + 11.03\,d*h \quad (3)$$

$$Fz = 57.9 - 0.502\,v - 125\,f + 22.9\,d - 2.21\,h + 0.00081\,v*v - 16196\,f*f - 27.7\,d*d + 0.0110\,h*h - 5.42\,v*f - 0.4403\,v*d + 0.01224\,v*h + 223\,f*d + 30.15\,f*h + 1.295\,d*h \quad (4)$$

With the determination coefficient R-sq over 98% for all three models, the models of cutting force components perfectly fit with the measured data. The P-values of all cutting force models are less than 0.05. It means that the models are statistically significant. With the analysis mentioned above, three models are the suitable mathematical tools for predicting normal force *Fx*, the feed force *Fy,* and the axial force *Fz.*

TABLE IV. THE RESULTS OF THE MULTI-OBJECTIVE OPTIMIZATION FOR ALL RESPONSES

Response	Goal	Optimum conditions				Predicted	Measured	Error (%)
		v	*f*	*d*	*h*			
Fx	Min.	80	0.03	0.297	40	55.604	52.455	6.003
Fy	Min.					56.659	60.311	6.055
Fz	Min.					7.357	7.65	3.830
MRR	Max.					954.256	907.934	5.102
Composite Desirability = 0.771								

Based on applying a desirability function, the results of the multi-objective optimization were carried out to obtain the minimum cutting forces and the maximum MRR. The results of the multi-objective optimization for all responses are shown in Table IV. The optimized values of input factors are 80 m/min for the cutting-speed, 0.03 mm/tooth for the feed-rate, 0.297mm for depth-of-cut, and 40 HRC for hardness-of-workpiece. According to the predicted results, the normal force *Fx* was 55.604N, the feed force *Fy* was 56.659N, the axial force *Fz* was 7.357N, and *MRR* was 954.256 mm3/min when the optimal condition is applied with composite desirability of 0.771. A test was performed to verify the accuracy of multi-objective optimization. As shown in Table IV, the difference between the predicted value and the value of the validation test is small (less than 10%). It means that the quadratic mathematical models given are perfectly suited for predicting cutting forces during the hard milling process of SKD 61 steel under SiO_2 nanofluid minimum quantity lubrication.

IV. CONCLUSION

In the current study, the Taguchi method and the Response Surface Methodology (RSM) were integrated to investigate the effect of cutting parameters on the cutting force components in hard milling of SKD 61 steel under SiO_2 nanofluid MQL. It could be drawn as follows:

- The depth-of-cut is the most powerful influence on cutting force components. The second most influential factor is the feed-rate.
- With the reliability level over 98%, the quadratic mathematical models given in the study are good models for predicting the cutting forces in three directions.
- The multi-objective optimization process for minimum cutting force and maximum material removal rate results in 80 m/min for the cutting-speed, 0.03 mm/tooth for the feed-rate, 0.297mm for depth-of-cut, and 40 HRC for hardness-of-workpiece. According to the multi-goal optimal conditions, the normal force *Fx* was 55.604N, the feed force *Fy* was 56.659 N, the axial force *Fz* was 7.357 N and *MRR* was 954.256 mm3/min.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

The paper and research were conducted by author The-Vinh Do. The author conducted the research, analyzed the data and wrote the paper.

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