

Evaluation of MQCL Technique Using MoS₂ Nanofluids During Hard Milling Process of SKD 11 Tool Steel

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Abstract: The current study demonstrates the effect of minimum quantity cooling lubrication (MQCL) using MoS₂ emulsion-based nanofluid on hard milling of SKD tool steel (52-60 HRC) with coated cemented carbide inserts. The input machining parameters including nanoparticle concentration, cutting speed and hardness on cutting forces are investigated in term of cutting force components by using ANOVA analysis applied for the Box-Behnken experimental design. The results indicate that the hardness and nanoparticle concentration have a strongest influence on cutting forces. The interaction effects of investigated parameters are studied in detail and provide the important direction for using MoS₂ nanofluid efficiently with the proper concentration of 1.0-1.1 wt%. Moreover, the cutting performance of carbide tools is significant improved during hard milling process due to the better cooling and lubricating effects of MQCL technique.

Keywords: Hard Milling, MQCL, Emulsion, MoS₂ Nanoparticles, Nanofluid, Concentration, Cutting Force

1. Introduction

SKD11 tool steel is among the high-carbon and high-chromium alloy steel and has good wear resistance and size ability after heat treatment. Accordingly, it is used for making long-life high-precision cold-work dies, but it is grouped in difficult-to-cut materials [1]. In conventional approach, the finishing process of hardened steels is grinding with flood coolant, but the growing demand for high productivity, machining of complex parts, good surface quality and especially the elimination of cutting fluids due to the concerns with the environmental and health problems needs to find the alternative solution. Recently, hard cutting processes are developed to machine the difficult-to-cut materials and are proven to replace many of traditional finish grinding operations. These processes directly use the geometrically defined cutting edges to cut the steels in hardened state with the hardness of 45–70 HRC [2]. In the earliest type, hard machining is carried out in dry condition,

which is also considered the environmental friendly process. There are numerous studies of cutting performance of dry hard machining. C. Y. Wang et al [3] studied the wear and breakage of coated carbide tool during high-speed hard milling processes in dry condition. The results showed the type of dominant wear patterns and modes of breakage. The authors also pointed out the influence of rake angle on the cutting forces and friction coefficient. K. Zhang et al [4] investigated the effect of nano-scale textures on cutting performance of WC/Co-based Ti5Al45N coated tools in dry hard turning. The study aimed to reduce the contact length at tool-chip interface at rake face, from which the friction coefficient, cutting forces, cutting temperature, and tool wear reduced. The similar observation had been made for studying hard turning performance using coated carbide tools [5]. However, the necessity of using high-grade inserts such as coated cemented carbide, ceramics, (P) CBN, PCD tools due to the high hardness materials as well as the enormous amount of generated heat [4-9]. Moreover, the use of flood coolant in hard machining faces the difficulty due to the

thermal shock, and the high generated temperature from cutting zone causes the thermal distortion of machined parts, handling, and testing process. Hence, minimum quantity lubrication (MQL) technique has been developed to be an alternative solution for flood and dry machining. This technique provides the high lubricating effectiveness, which contributes to the decrease of friction coefficient, cutting forces, cutting temperature and tool wear as well as the improvement of surface quality and tool life [10-14]. The low cooling effect is the main drawback of MQL method, which demands new methods for developing the cooling and lubricating performance of MQL. Recently, MQL technique using nanofluids and minimum quantity cooling lubrication (MQCL) have been studied and gained much attention of researchers around the world. Many studies focus on the use of nano additives, such as Al₂O₃, MoS₂, SiO₂, TiO₂, CNT, CuO, hBN and so on, suspended in MQL fluid and prove the promising results because of the enhancement of the tribological property and viscosity of the based fluid. Accordingly, the cutting forces, cutting temperature and friction coefficient are reduced, and the improvement of surface quality and cutting performance are reported [14-26]. Besides, minimum quantity cooling lubrication (MQCL) is considered to be an attractive solution to improve the cooling effect of MQL method. R. W. Maruda *et al.* [27-29] studied MQCL parameters and chip formation during hard turning process. The results indicated that the surface quality and surface topography improved when compared to dry machining due to the better cooling and lubricating performance. S. Pervaiz *et al.* [30] investigated the influence of MQCL during turning process of Ti6Al4V alloy, a difficult-to-cut material. The obtained results indicated that cutting forces and tool wear decreased and surface quality improved when compared to dry and flood cutting. The main reason is the better cooling and lubricating effect of MQCL technique. Nevertheless, the cooling effect of MQCL

technique is based on the property of the based fluids. There is a little information about the use of real cooling method combined with MQL technique to form MQCL used in hard machining. Hence, the authors are motivated to study the effectiveness of MQCL technique during hard milling process of SKD 11 tool steels (52-60 HRC). Furthermore, the study also investigates the effect of MoS₂ nanoparticles suspended in emulsion-based fluids in MQCL hard milling.

2. Material and Methods

2.1. Experimental Set Up

The experimental set up is shown in Figure 1. The experiments were done in Mazak vertical center smart 530C. The APMT 1604 PDTR LT30 PVD submicron carbide inserts of LAMINA Technologies (made in Switzerland) was utilized (Figure 2). The MQCL system includes Frigid-X Sub-Zero Vortex Tool Cooling Mist System (made by Nex Flow™, compressed air, pressure stabilization device, water-based emulsion 5.0% and MoS₂ nanoparticles. The cutting forces are directly measured by Kistler quartz three-component dynamometer (9257BA) connected to A/D DQA N16210 (made by National instruments, USA), which is linked to the computer having DASYlab 10.0 software [33]. MoS₂ nanoparticles made by Luoyang Tongrun Info Technology Co., Ltd with the size of 30nm (average) were used. (Figure 3). KEYENCE VHX-6000 Digital Microscope is used to study the surface topography (Figure 4). In this research, the SKD 11 tool steels with hardness of 52÷60 HRC were used. The chemical composition is shown in Table 1. To ensure uniform suspension of MoS₂ nanoparticles in emulsion-based fluids, the prepared nanofluids are kept in Ultrasons-HD ultrasonicator (JP SELECTA in SPAIN) (seen in Figure 5), generating 600W ultrasonic pulses at 40 kHz for 6 hours to ensure the uniform distribution of the nanoparticles.

Table 1. Chemical composition of SKD 11 steel (According to JIS G4404: 1983).

Chemical composition (%)										
C	Si	Mn	Ni	Cr	Mo	W	V	Cu	P	S
1.4 - 1.6	0.4	0.6	0.5	11.0 - 13.0	0.8 - 1.2	0.2 - 0.5	≤ 0.25	≤ 0.25	≤ 0.03	≤ 0.03

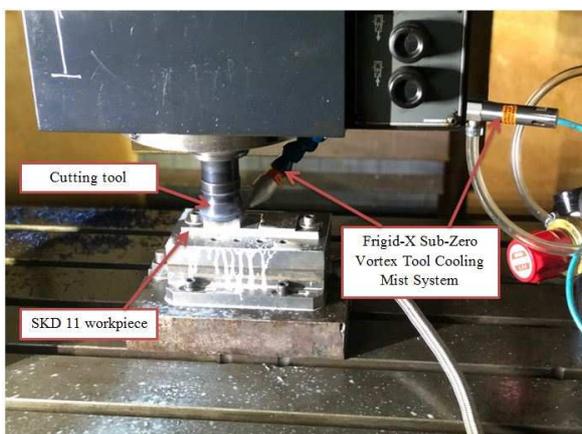


Figure 1. The experimental set up [33].



Figure 2. APMT 1604 PDTR LT30 PVD submicron carbide inserts.

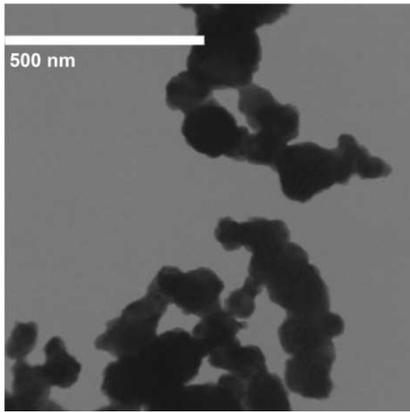


Figure 3. TEM image of MoS₂ nanoparticles [23].



Figure 4. KEYENCE VHX-6000 Digital Microscope is used to study the surface topography [23].



Figure 5. Ultrasons-HD ultrasonicator [23].

2.2. Experiment Design

Minitab 18.0 software is applied for the Box-Behnken experimental design with three control parameters and their values on three levels are listed in Table 2. Table 3 summarizes the design of experiment with test run order and output in term of cutting forces. The fixed parameters are the feed rate of 0.012 mm/tooth, depth of cut of 0.12 mm, air pressure of 6 Bar, flow rate of 0.5 ml/min; the room temperature 24 ÷ 27°C; the temperature of output cool air 4 ÷ 8°C. The experimental trials are repeated by three times under the same cutting parameters.

Table 2. Control factors and their levels.

Control factor	Unit	Symbol	Level		
			Low	Medium	High
Nanoparticle concentration (np)	wt%	x ₁	0.5	1.0	1.5
Cutting speed	m/min	x ₂	90	100	110
Hardness	HRC	x ₃	52	56	60

Table 3. The design of experiment with test run order and output in term of cutting forces.

Std Order	Run Order	PtType	Blocks	Input machining parameters			Response variables		
				X ₁	X ₂	X ₃	F _x	F _y	F _z
1	20	2	1	0.5	90	56	60.50	116.70	179.90
2	30	2	1	1.5	90	56	62.70	101.30	135.70
3	7	2	1	0.5	110	56	43.70	99.80	131.83
4	41	2	1	1.5	110	56	53.10	90.08	136.40
5	4	2	1	0.5	100	52	45.40	125.24	157.80
6	39	2	1	1.5	100	52	47.90	103.10	129.80
7	32	2	1	0.5	100	60	52.60	73.20	120.48
8	14	2	1	1.5	100	60	45.77	69.90	137.90
9	16	2	1	1	90	52	41.40	90.70	98.37
10	29	2	1	1	110	52	37.45	82.60	97.70
11	22	2	1	1	90	60	72.20	86.30	168.90
12	18	2	1	1	110	60	45.04	76.90	149.53
13	23	0	1	1	100	56	57.40	90.10	140.85
14	43	0	1	1	100	56	50.00	77.90	134.94
15	19	0	1	1	100	56	53.70	83.95	137.90
16	11	2	1	0.5	90	56	61.50	170.10	178.70
17	21	2	1	1.5	90	56	50.40	103.10	136.00
18	13	2	1	0.5	110	56	55.40	120.96	173.52
19	37	2	1	1.5	110	56	52.20	100.20	142.79
20	38	2	1	0.5	100	52	42.80	79.70	151.65
21	33	2	1	1.5	100	52	52.40	105.10	145.79
22	12	2	1	0.5	100	60	54.30	80.45	154.08
23	9	2	1	1.5	100	60	62.59	87.80	171.50
24	28	2	1	1	90	52	43.10	83.96	92.85
25	45	2	1	1	110	52	47.60	99.50	112.40
26	10	2	1	1	90	60	40.40	68.53	141.90

Std Order	Run Order	PtType	Blocks	Input machining parameters			Response variables		
				X ₁	X ₂	X ₃	F _x	F _y	F _z
27	2	2	1	1	110	60	37.30	80.83	134.87
28	15	0	1	1	100	56	65.70	94.90	145.03
29	36	0	1	1	100	56	50.40	84.60	130.40
30	27	0	1	1	100	56	58.05	89.75	137.50
31	6	2	1	0.5	90	56	46.20	151.90	160.10
32	17	2	1	1.5	90	56	58.60	102.50	138.70
33	5	2	1	0.5	110	56	58.60	124.90	163.76
34	3	2	1	1.5	110	56	56.40	114.70	140.28
35	35	2	1	0.5	100	52	43.50	65.80	112.00
36	25	2	1	1.5	100	52	52.60	77.00	141.55
37	42	2	1	0.5	100	60	61.90	90.95	145.90
38	1	2	1	1.5	100	60	48.90	70.10	132.25
39	31	2	1	1	90	52	40.77	87.90	126.20
40	26	2	1	1	110	52	40.50	57.20	84.78
41	8	2	1	1	90	60	52.60	76.70	142.50
42	40	2	1	1	110	60	66.00	80.06	136.51
43	44	0	1	1	100	56	64.60	94.80	142.85
44	24	0	1	1	100	56	44.76	84.39	140.22
45	34	0	1	1	100	56	54.68	89.60	141.37

3. Results and Discussion

The ANOVA analysis is carried out at a confidence level of 95% (i.e. 5% significance level). The regression models of cutting forces F_x, F_y, F_z are given below in Eqs. 1-3.

$$F_x = -1422 - 18.9x_1 + 4.52x_2 + 44.1x_3 + 9.48x_1^2 - 0.0232x_2^2 - 0.383x_3^2 \tag{1}$$

$$F_y = -2248 - 160.4x_1 - 25.03x_2 + 133.1x_3 + 71.7x_1^2 + 0.1232x_2^2 - 1.198x_3^2 \tag{2}$$

$$F_z = -2403 - 158.0x_1 + 10.0x_2 + 73.2x_3 + 70.6x_1^2 - 0.0519x_2^2 - 0.621x_3^2 \tag{3}$$

The Pareto chart of the standardized effects with $\alpha = 0.05$ for the response parameter R_a is shown in Figures 6-8. The hardness has a strongest influence on cutting forces F_x, F_z (shown in Figures 6-8, but nanoparticle concentration has a strongest effect on cutting force F_y in Figure 7. The nanoparticle concentration contributes a significant effect on the cutting forces F_y, F_z (Figures 7-8). The effects of these input machining parameters are also reflected by the

corresponding coefficients in Eqs. 1-3. In contrast, the cutting speed has a very little effect on cutting forces. The interaction effects CC (x₃x₃), AA (x₁x₁) reveal the significant influence on the investigated function, which is contrary to BB (x₂x₂). The other interaction effects of x₁x₂, x₁x₃, x₂x₃ have a very little influence and is not investigated in the model. From the analysis of the effects of three input machining parameters.

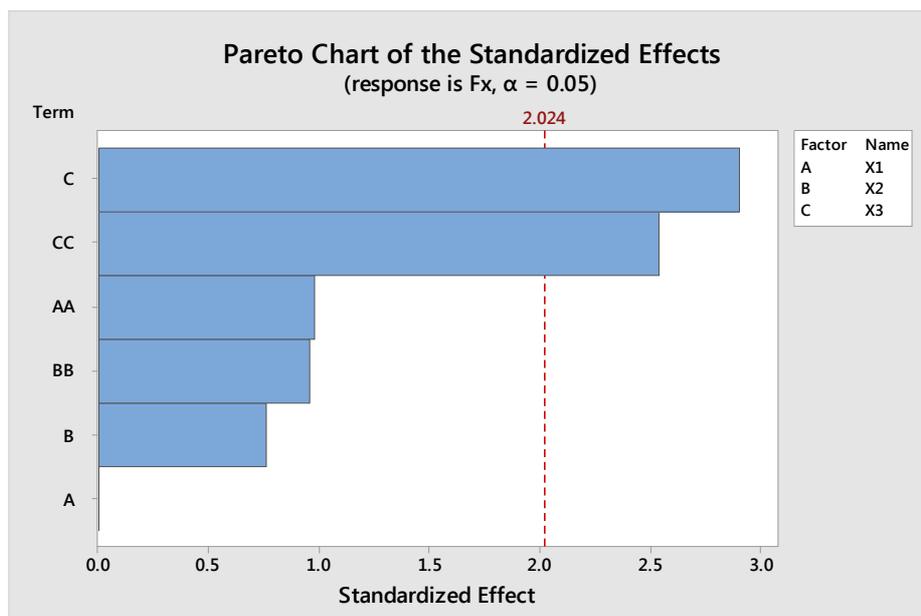


Figure 6. Pareto chart of the effects of investigated parameters on cutting force F_x.

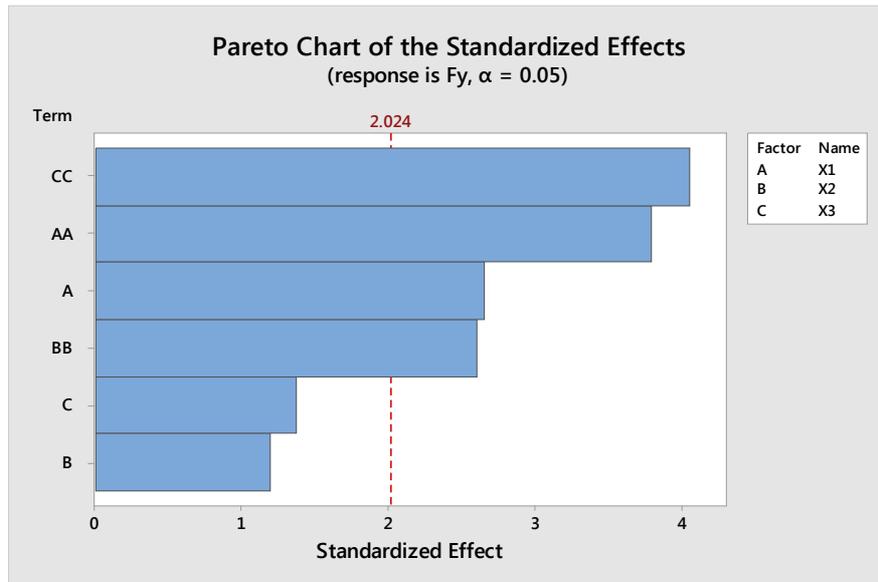


Figure 7. Pareto chart of the effects of investigated parameters on cutting force F_y .

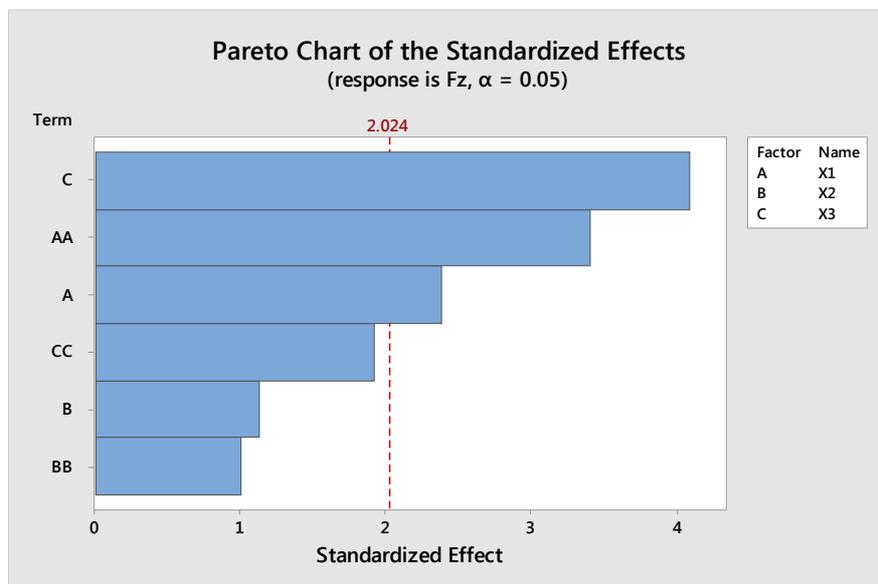


Figure 8. Pareto chart of the effects of investigated parameters on cutting force F_z .

The interaction effects of nanoparticle concentration, cutting speed, and hardness on cutting force F_x are shown in the surface plots and contour plots (Figures 9-11). The nanoparticle concentration has a strong influence on cutting force component F_x . When considering the interaction effects of cutting velocity and hardness, the proper value of concentration is about 1.0 wt%, which leads to the reduction of cutting force F_x (Figures 9-10). The main reason is that MoS_2 nanoparticles have the layer structure of a hexagonal crystal system combining Mo and S through a covalent bond, and the bond between them is short, but the spacing between sulfur atoms is large. Accordingly, the bond between two adjacent sulfur atom layers is weak to form “an easy-to slide plane” from weak binding of sulfur atoms between molecular

layers by cutting forces, from which the friction coefficient in cutting zone reduces [15, 34]. The formation of oil mist is decreased by the reduction of MoS_2 concentration, but the oil mist disappears when increasing the concentration over the proper value [23, 31]. The concentration should be used by 0.75 – 1.25 wt% when changing cutting speed shown in Figure 9. From Figure 10, the MoS_2 nanoparticle concentration has a little effect with the change of hardness, so it can be used in the range of 0.5-1.5wt%. From Figure 9 and Figure 11, the cutting force F_x is largest at the cutting speed of 100 m/min, and it reduces when increasing the cutting speed to 110 m/min and increases with the rise of hardness. Depending on the specific requirements, the input parameters could be selected to fulfill.

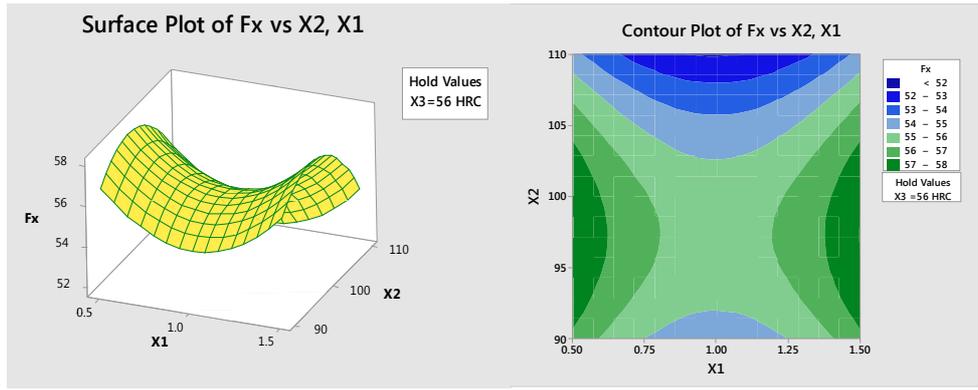


Figure 9. The effects of cutting speed and nanoparticle concentration on cutting force F_x .

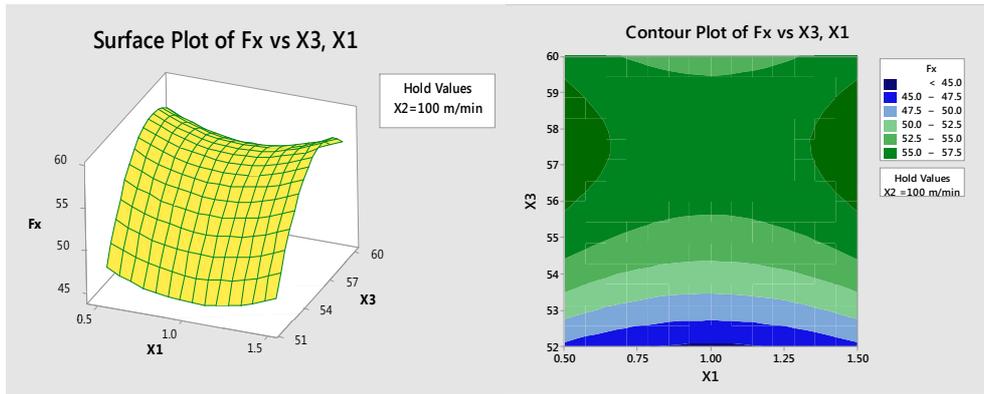


Figure 10. The effects of hardness and nanoparticle concentration on cutting force F_x .

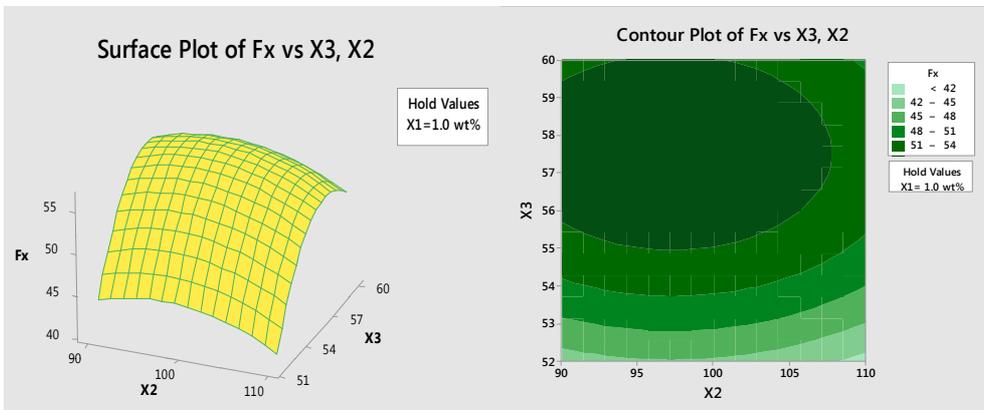


Figure 11. The effects of hardness and cutting speed on cutting force F_x .

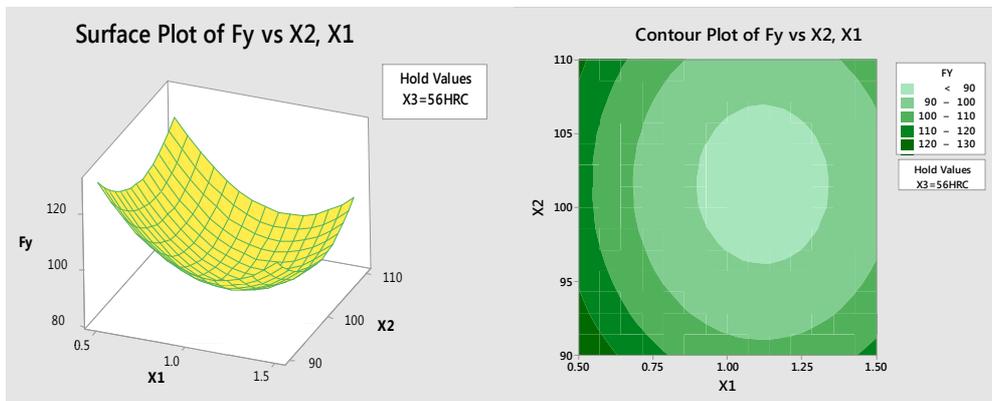


Figure 12. The effects of cutting speed and nanoparticle concentration on cutting force F_y .

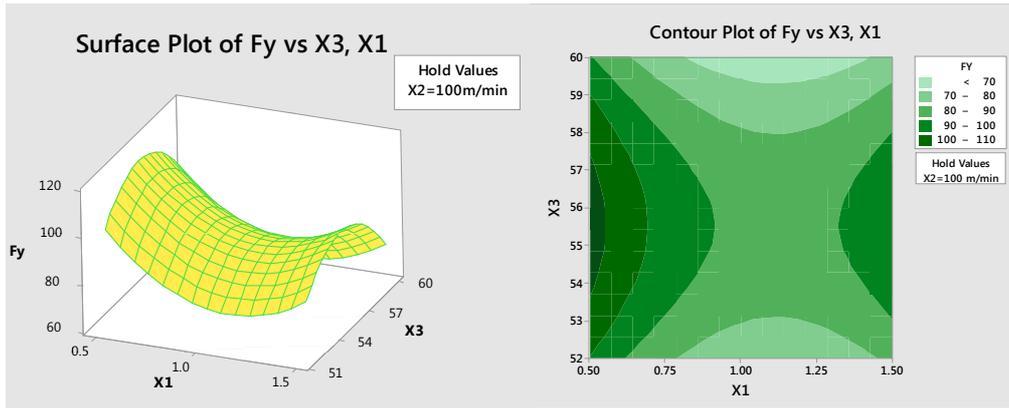


Figure 13. The effects of hardness and nanoparticle concentration on cutting force F_y .

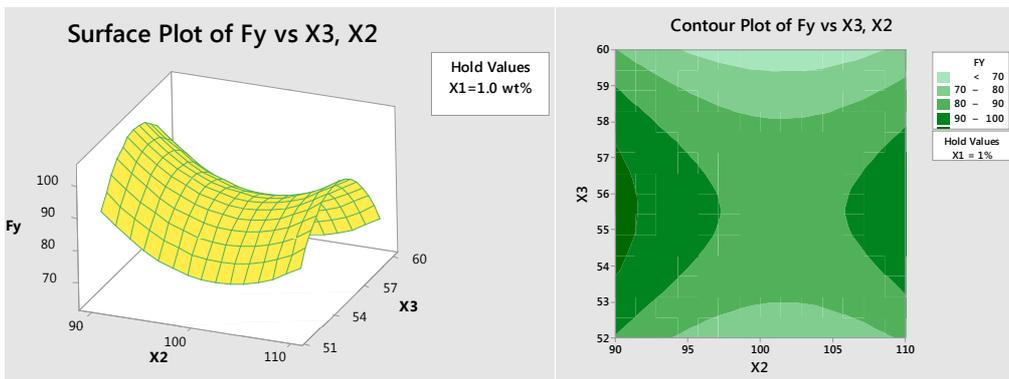


Figure 14. The effects of hardness and cutting speed on cutting force F_y .

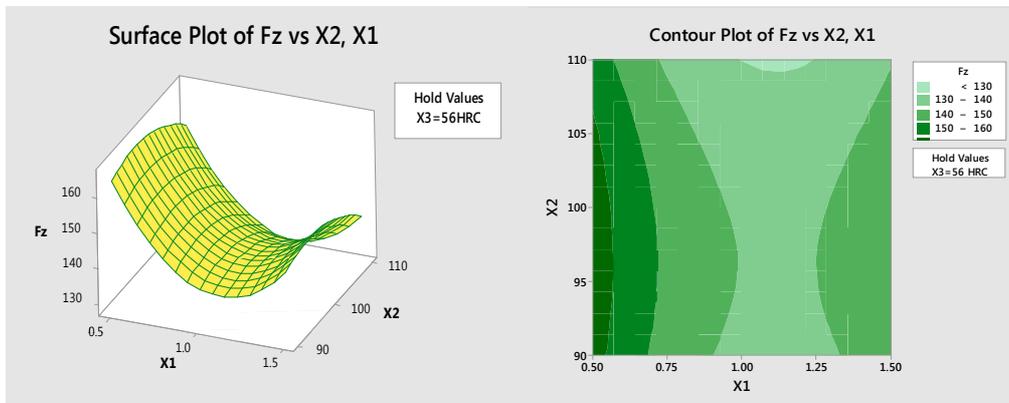


Figure 15. The effects of cutting speed and nanoparticle concentration on cutting force F_z .

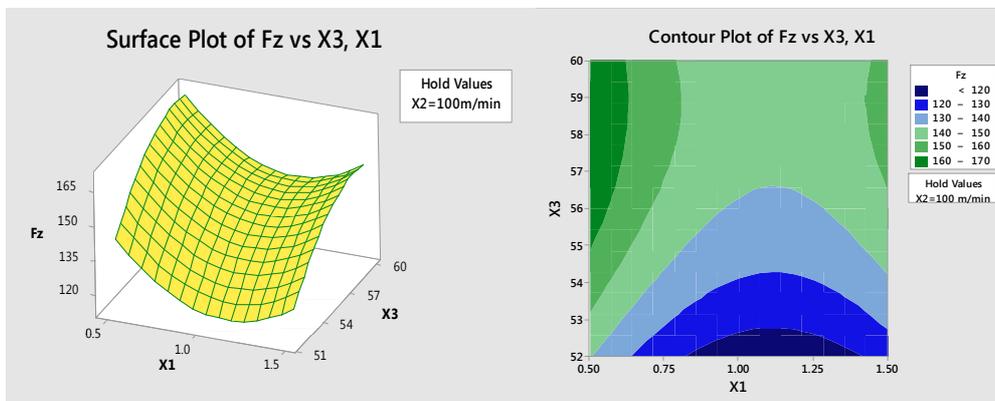


Figure 16. The effects of hardness and nanoparticle concentration on cutting force F_z .

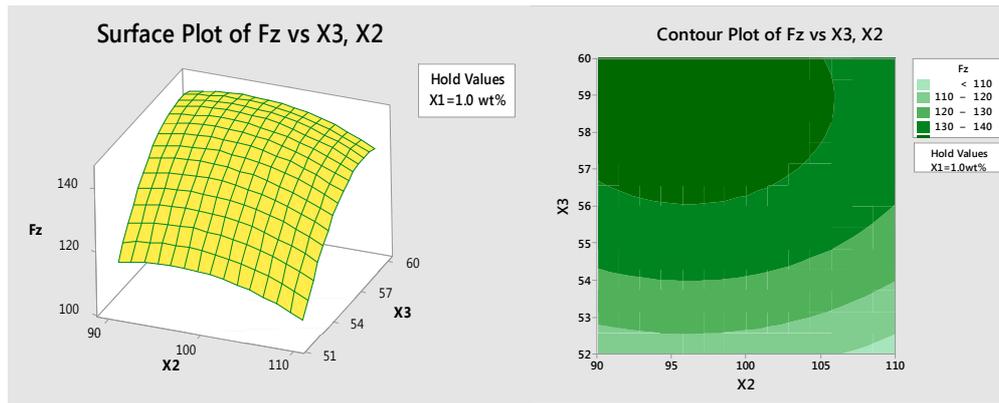


Figure 17. The effects of hardness and cutting speed on cutting force F_z .

The interaction effects of nanoparticle concentration, cutting speed, and hardness on cutting force F_y are shown in the surface plots and contour plots (Figures 12-14). The lowest values of F_y occur in the concentration range of 1.0-1.25 wt% (Figures 12-13) and the cutting speed of 95-105 m/min (Figures 12-14). The cutting force F_y is largest at the hardness of 54-57HRC, which is the distinguishing characteristic of hard machining and is suitable to the previous study [2, 33]. The similar observation can be made with the cutting force F_z , and the difference is only the level and value (Figures 15-17).

4. Conclusion

The effects of nanoparticle concentration, cutting speed and hardness on cutting forces are investigated by using ANOVA analysis applied for the Box-Behnken experimental design. The study provides the necessary directions of further studies in MQCL hard milling process. The interaction effects of hardness and nanoparticle concentration show the strongest influence on the investigated function. The influence of each input machining parameter on the cutting force components F_x , F_y , F_z is studied to propose the usage suggestion of MoS₂ nanofluid in MQCL technique.

The cutting performance of normal carbide inserts is significantly improved by using MoS₂ additives in emulsion-based fluid with MQCL technique in terms of cutting forces. The significant improvement of cooling and lubricating is observed and gives out a promising alternative solution for dry, wet, MQL conditions, from which the applicability of machining difficult-to-cut materials is enlarged. In addition, using MQCL technique can overcome the low cooling effect of MQL.

The concentration of MoS₂ nanoparticles is investigated and should be used in the range of 1.0 - 1.1 wt%, which provides the very important guide for using MoS₂ nanofluid efficiently with the target of low cutting forces. The cutting forces should be chosen at the high level of 110 m/min to achieve the productivity.

In further research, more investigations need to focus on the influences of other parameters like nanoparticle

morphology, nanoparticle size, MQCL parameters in order to bring it to industrial practice.

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