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Effects of Machining Parameters on Total Cutting Force in Hard Turning Process of Hardened 90CrSi Steel Using Carbide Insert with MoS_2 Nanofluid MQL

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***Abstract*—Minimum Quantity Lubrication (MQL) is widely used in machining, especially hard machining. However, this method has many limitations regarding cooling and lubrication capabilities. In recent years, nano-cutting oils have been researched and applied in machining to improve the lubrication and cooling efficiency of the MQL method. In this research, the machinability of 90CrSi steel with carbide inserts using nanofluid with different concentrations (1%, 1.5%, and 3%) of molybdenum disulfide (MoS_2) nanoparticles in emulsion oil was evaluated by applying Box-Behnken optimization model. Carbide inserts commonly used to machine the low hardness steel (below 35HRC) have been used to cut hardened steel with high hardness (59-62HRC) by applying the MQL technology with MoS_2 nanofluid. A mathematical model was also used to predict the cutting resultant force value in the hard turning process under MQL conditions using MoS_2 nanofluid. The obtained results indicate that the total cutting force reached the minimum value (328 N) with the MoS_2 nanoparticle concentration of 1.985%, a cutting speed of 80 m/min, and a feed rate of 0.138 mm/rev. In particular, the work has also provided technical guides for different machining conditions.**

***Keywords*—cutting force, Minimum Quantity Lubrication (MQL), hard turning, nanofluid**

I. INTRODUCTION

Metal cutting is a common machining process used to make mechanical products. In these machining processes, various cutting oils are used to lubricate and cool the cutting zone. These fluids are often introduced into the cutting area by overflow method, causing environmental and health problems [1]. Therefore, The Minimum Quantity Lubrication (MQL) is used to minimize the harmful effects of cutting oils in metalworking processes. Furthermore, this method can provide higher lubrication efficiency because the solution is sprayed directly into the cutting area in a mist [2]. The MQL method helps improve the efficiency of the metal machining process. However, this method has many limitations when applied to hard machining processes due to limited cooling capacity [3]. Recently, the solution of using nano-cutting oil combined with the MQL method can improve friction conditions and potentially reduce the cutting zone temperature [4]. Nano-cutting oil is prepared by adding nanoparticles in a suitable ratio to conventional cutting oil [5]. Nanoparticles added to the cutting fluid boost the base fluid's properties such as thermal conductivity, viscosity, wettability, PH value, and tribological features [6]. Hence, using nano-cutting oil with the MQL method can reduce friction, and cutting heat in the cutting area, reduce cutting force, and improve the surface quality and tool life [7]. Sushansu *et al.* made two kinds of nanofluids by adding Al_2O_3 and CuO [8] nanoparticles into Rice oil to improve the thermal properties of rice oil, and applied to the hard turning process with MQL technology. Research results show that using nanofluids can improve surface quality, and reduce cutting force and cutting temperature in the machining process. Especially, using CuO nanofluids gives better surface quality than using Al_2O_3 nanofluids. Rahman *et al.* [9] studied and applied the MQL method using Al_2O_3, MoS_2, and TiO_2 vegetable-based nano cutting oils on the hard turning process of Ti-6Al-4V alloy. Applying nanofluids to the turning process of titanium alloys can improve lubrication and cooling in the cutting zone, thereby improving the efficiency of the cutting process. Research results show that surface quality is better when using 0.5% canola oil-based Al_2O_3 nano cutting oil. The effectiveness of nanofluids with Multi-Walled Carbon Nanotubes (MWCNTs) and Al_2O_3 nanoparticles in the hard turning process of Inconel 718 alloy was analyzed by Hegab *et al.* [10]. Study results show that nanofluids with MWCNTs nanoparticles have a better lubricating effect than nanofluids with Al_2O_3 nanoparticles. In addition to improving lubrication, nanofluids also have the ability to reduce cutting heat during the machining process. Darshan *et al.* [11] investigated the effects of Al_2O_3, MoS_2, and graphite sunflower-based nano cutting oils on the turning of Inconel 800 alloy. The research results showed that the thermal conductivity and lubrication

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performance of cutting oils added graphite and MoS_2 nanoparticles are better than cutting oils mixed Al_2O_3 nanoparticles. The efficiency of hard turning Inconel 800 alloy using MQL technology with nanofluid was also studied and analyzed by Gupta *et al.* [12]. In this study, vegetable oil mixed with nanoparticles was used, thus minimizing harm to the environment. Research results also show that the cooling lubrication effect of nano oil depends on nanoparticle type, size, and nanoparticle concentration. This is also consistent with many previous publications. Al_2O_3 nanoparticles have high hardness, strength, high thermal conductivity, and near-spherical morphology [13]. Therefore, the nanoparticles penetrate into the cutting area and act as rollers, helping to reduce friction in the cutting area, thereby reducing the cutting force and temperature. MoS_2 and graphite nanoparticles have a good lubricating ability due to their layered structure, and they also have a higher thermal conductivity than Al_2O_3 nanoparticles. Therefore, many researchers have used these two types of particles in combination with some conventional cutting oils in the metal machining processes. Zhang *et al.* [14] studied and analyzed the influence of the different vegetable oils mixed MoS_2 nanoparticles on the grinding process with MQL method. This study has shown that using MoS_2 nano cutting oil based on vegetable oil can reduce cutting force and cutting heat during grinding. Furthermore, using minimal amounts of oil and biodegradable vegetable oils can minimize the negative impact on the environment. Ayşegül Yucel *et al.* [15] investigated the influence of nanofluid on the surface quality and the built-up-edge (BUE) formation on the turning aluminum alloy process. Research results show that using nano cutting oil can reduce cutting heat, thereby reducing the BUE formation, reducing tool wear, and improving the surface quality compared to pure MQL and dry machining conditions. Uysal *et al.* [16] analyzed the effects of MQL with vegetable oil mixed MoS_2 nanoparticles on the efficiency of the milling process. This study indicated that using nanofluids can improve the lubricating and cooling conditions in the cutting zone, thereby improving surface quality and reducing tool wear. In addition, the MoS_2 nanoparticles have a layered structure, so they easily tend to form tribo-film between tool and workpiece, reducing friction in the cutting area [17]. However, no study has been found on the machining of the hardened alloy steel with normal carbide insert under MoS_2-based nanofluid. This study focuses on evaluating the efficiency of turning the hardened 90CrSi Tool Steel process using MQL technology with MoS_2 nanofluid through the total cutting force.

II. EXPERIMENTAL SYSTEM AND METHOD

The experiment used workpieces made of the 90CrSi steel, having a diameter of 40 mm with a hardness of 60–62 HRC and the composition shown in Table I. These studies used the tungsten carbide inserts with coating layers of CVD Al_2O_3/TiCN of Tungaloy company with code CNMG120404-TM T9125. The tool is mounted on the kistler force sensor and fixed on the tool table of the lathe, shown in Fig. 1. All trials were performed on the CS-460×1000 Chu Shing lathe (Taiwan). The MQL nozzle (UNIT 264MM-NOGA MiniCool MC1700 of Noga Engineering & Technology) is setup to spray directly onto the flank face of tool. Nano cutting oil is introduced into the machining area in the form of mist by the MQL nozzle with high-pressure air flow. Nano cutting oil is prepared by mixing MoS_2 nanoparticles into emulsion oil, then ultrasonically vibrated with the frequency of 40Khz in usually only 30–45 min using Ultrasons-HD ultrasonicator (JP Selecta, Spain). MoS_2 nanoparticle of China Luoyang company has a layered structure with an average size of 30 nm.

TABLE I. THE CHEMICAL COMPOSITION OF 90CrSi

Elements	Wt (%)
C	0.86
Si	1.32
Mn	0.42
Ni	Max: 0.40
S	Max: 0.03
P	Max: 0.03
Cr	1.12
Mo	Max: 0.20
W	Max: 0.20
V	Max: 0.15
Ti	Max: 0.03
Cu	Max: 0.3

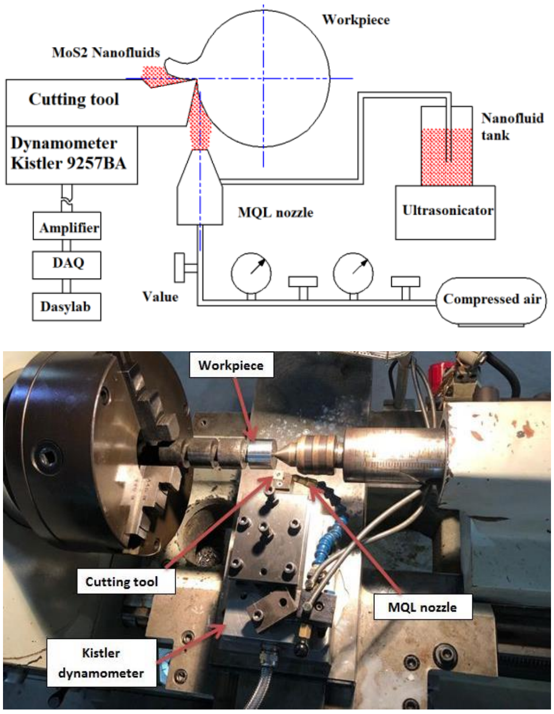


Fig. 1. Experimental set up.

During the experiment, based on preliminary research [18], some parameters were fixed including air pressure 6 Bar and air flow rate 200 L/min; cutting depth 0.15 mm; The dynamometer 9257BA of Kister is used to measure cutting force in the machining process. The signal from the force sensor is transmitted to an amplifier and a signal converter, and displayed on a computer with Dasylab 10.0 data acquisition software installed.

In this study, the efficiency of the MQL method with nano cutting oil was evaluated by analyzing the effects of three input factors (Nanoparticle Concentration (NC); cutting speed (V), and feed rate (f)) on the total cutting force. The level values of the input factor were selected based on analyzing the preliminary research [18], and are shown in Table II.

TABLE II. INPUT MACHINING PARAMETERS

Input machining variables	Symbol	Level		
		Low	Medium	High
Nanoparticle Concentration (NC), wt%	A	1	2	3
Cutting speed (V), m/min	B	80	120	160
Feed rate (f), mm/rev	C	0.1	0.15	0.2

TABLE III. EXPERIMENTAL DESIGN AND MEASURED RESPONSES

Std	Run	A:NC (%)	B:V (m/ min)	C:f (mm/ rev)	Fr (N)
17	1	3	80	0.15	424.3422
19	2	3	160	0.15	373.4419
10	3	2	160	0.1	673.9186
12	4	2	160	0.2	400.0351
3	5	1	160	0.15	415.5911
16	6	1	80	0.15	446.5
29	7	2	120	0.15	384.1323
14	8	2	120	0.15	343.9646
4	9	3	160	0.15	357.3
22	10	1	120	0.2	496.4314
30	11	2	120	0.15	413.4428
18	12	1	160	0.15	397.9111
24	13	2	80	0.1	341.2244
2	14	3	80	0.15	420.6337
5	15	1	120	0.1	546.3108
13	16	2	120	0.15	429.9556
26	17	2	80	0.2	388.4346
8	18	3	120	0.2	412.6
15	19	2	120	0.15	383.5919
28	20	2	120	0.15	348.0185
23	21	3	120	0.2	398.6
21	22	3	120	0.1	523
9	23	2	80	0.1	306.3
7	24	1	120	0.2	476.0967
25	25	2	160	0.1	689.2492
6	26	3	120	0.1	505.3
1	27	1	80	0.15	413.8428
20	28	1	120	0.1	546.55
11	29	2	80	0.2	411.4143
27	30	2	160	0.2	396.4574

This study used the Box-Behnken method with 3 input factors to develop the experimental plan. The experimental matrix including 30 trials was built by using Design Expert 11 software. All trials were carried out according to RunOrder in Table III. Three-component cutting forces (Fx, Fy, Fz) were directly measured during machining process (Fig. 2). The total cutting force Fr is determined by the Eq. (1) below.

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{1}$$

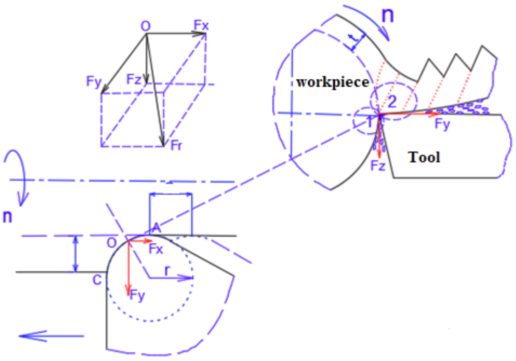


Fig. 2. The cutting forces model in the hard turning process.

III. RESULT AND DISCUSSION

A. Influence of the Input Variables on the Total Cutting Force

The influence of machining parameters on the total cutting force Fr is analyzed on Design Expert software 11. The results of ANOVA analysis for the total cutting force Fr with 95% confidence are shown in Table IV. The Model F-value of 6.8 is very high and implies the model is significant. There is only a 0.02% chance that an F-value the cutting force this large could occur due to noise. That proves that the selected 2nd order model is suitable to evaluate the influence of survey factors on the total cutting force value Fr. The regression model for Fr is given as below:

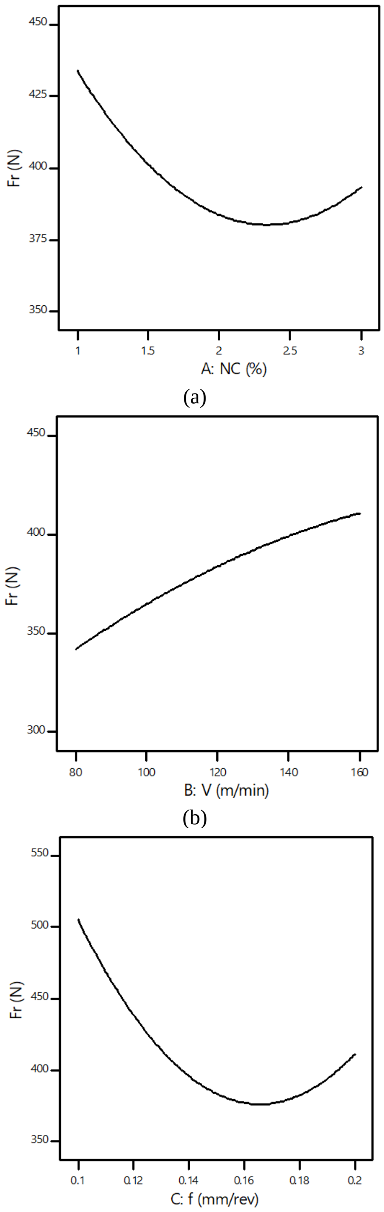
$$Fr = 252.371 - 77.843CN + 9.14V - 4000.036f - 0.21CN \times V - 241.918CN \times f - 44.937V \times f + 29.788CN^2 - 0.0047V^2 + 29788.803f^2$$

TABLE IV. RESULT OF ANOVA ANALYSIS FOR THE TOTAL CUTTING FORCE FR

Source	Sum of	df	Mean	F-value	p-value
Model	174142.6	9	19349.2	6.8	0.000
A-CN	6559.2	1	6559.2	2.3	0.146
B-V	18992.8	1	18992.8	6.6	0.018
C-f	35314.2	1	35314.2	12.3	0.002
AB	567.5	1	567.5	0.2	0.661
AC	1168.8	1	1168.8	0.4	0.530
BC	64625.6	1	64625.6	22.6	0.000
A^2	6555.1	1	6555.1	2.3	0.146
B^2	409.6	1	409.6	0.1	0.709
C^2	40955.7	1	40955.7	14.3	0.001
Residual	57227.4	20	2861.4		
Lack of Fit	49064.1	3	16354.7	1.1	0.000
Pure Error	8163.2	17	480.2		

The fit of the model is also evaluated through the P value. This model is meaningful because P-values less than 0.0500 indicate model terms. In this case the cutting speed (B-V), the feed rate (C-f), the V*f interaction (BC), the interactions B^2 and C^2 are significant model terms.

The other factors have P values greater than 0.1, so they have little influence on the total cutting force. In this case, the coefficient of determination R^2 = 75.3% and the adjusted coefficient of determination R^2 = 64.1% are pretty large, which proves that the regression model is consistent with the experimental data set. And this model can be used to predict the total cutting force Fr. The results show that Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 8.863 indicates that model is suitable to analyze the influence of factors on the total cutting force.



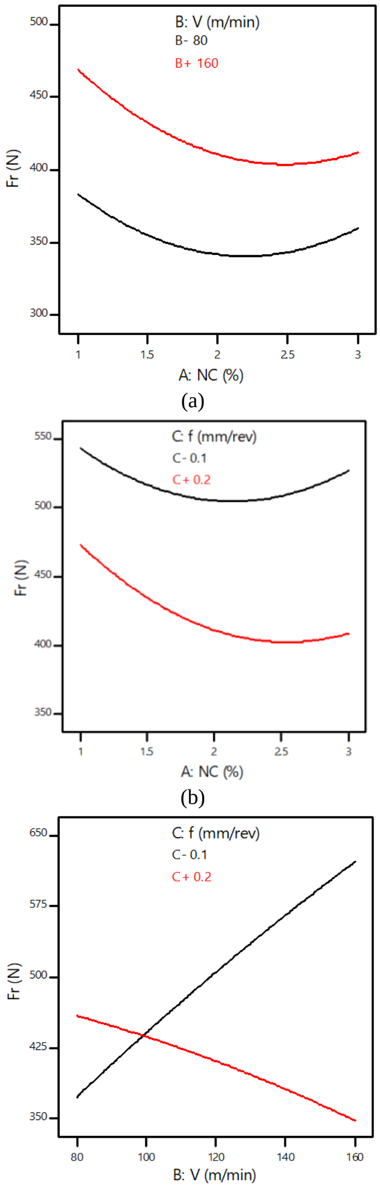
(a)

(b)

(c)

Fig. 3. The influence of the input factors on the total cutting force. (a) The nanoparticle concentration (b) The cutting speed (c) The feed rate.

The effects of input factors on the average value of the total cutting force Fr are shown in Fig. 3 The results show that all three input parameters have a significant influence on the total cutting force Fr. As the particle concentration increased, the total cutting force Fr decreased and when the nanoparticle concentration was greater than 2%, the cutting force started to increase again. The reason is that initially increasing the nanoparticle concentration leads to an increase in the lubricating capacity of the oil, leading to a decrease in the total cutting force Fr. However, when the concentration of nanoparticles continued to increase, the nanoparticles tended to cluster, compress and hinder the cutting process, leading to an increase in the total cutting force Fr. The cutting speed also greatly affects the total cutting force Fr, as the cutting speed increases, the cutting force Fr increases. The results also show that the feed amount also has the strongest influence on the cutting force Fr. The cutting force decreases with increasing feed rate from 0.1 mm/rev to 0.16 mm/rev and decreases with further increase of feed.



(a)

(b)

(c)

Fig. 4. Interaction effects between the input factors on the total cutting force (a) The V*NC interaction (b) The NC*f interaction (c) The V*f interaction.

The influence of the interaction between the input factors on the total cutting force Fr is shown in Fig. 4. The results show that the V*NC interaction has a weak influence on the total cutting force value Fr, while the V*f and NC*f interactions significantly affect the total cutting force value Fr. When machining with a small feed rate (0.1 mm/rev), the nanoparticle concentration has a weak influence on the total cutting force Fr. While machining with a large feed rate (0.2 mm/rev), the cutting force is reduced with increasing particle concentration. The reason is that when the feed rate is small, it is more difficult for MoS_2 nanoparticles to penetrate into the cutting area than when using a large feed rate. The interaction between cutting speed and feed rate has the greatest influence on the total cutting force Fr. When machining with a small feed rate, the total cutting force increases rapidly with increasing cutting speed. However, when machining with a large feed rate, the total cutting force decreases with increasing cutting speed. The reason is that when the feed rate is small, no slip occurs occur during the hard machining process, leading to an increase in the radial force component leading to a rapid increase in the total cutting force.

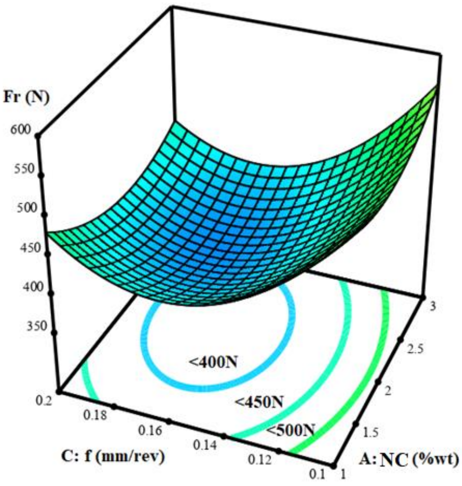


Fig. 5. Effect of f and NC on the total cutting force with V=120 m/ph.

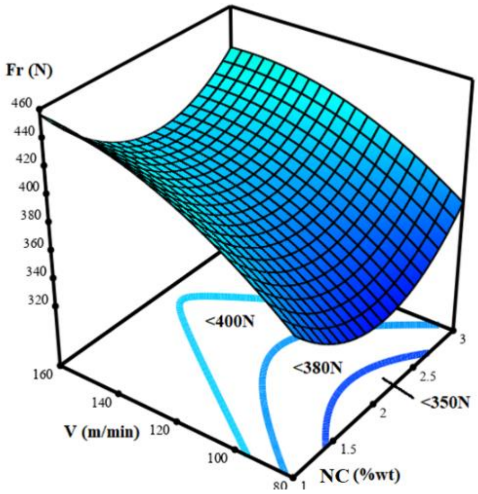


Fig. 6. Effect of V and NC on the total cutting force with f=0.15 mm/rev.

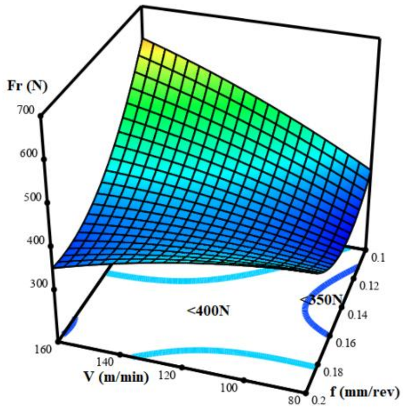


Fig. 7. Effect of V and f on total cutting force with NC= 2 (%wt).

Fig. 5 shows the contour plot and the surface plot, showing the simultaneous influence of the feed rate and the MoS_2 nanoparticle concentration on the total cutting force. The results show that, with a cutting speed of 120 m/min, the total cutting force is less than 400N with a feed rate (0.14–0.18 mm/rev) and a nanoparticle concentration in the range of 1.5–2.5%. The simultaneous effect of cutting speed and grain concentration on the total cutting force with a feed rate of 0.15 mm/rev is shown in Fig. 6. The results show that the total cutting force increases with increasing cutting speed, this problem is consistent with the results of previous studies. The simultaneous influence of cutting speed and feed rate on the total cutting force Fr is shown in Fig. 7. Research results show that the total cutting force Fr reaches a small value (<350N) with a small cutting speed (<100m/min) and medium feed (0.12–0.16 mm/rev).

B. Determination of Optimal Parameters

Using the optimization module on Design Expert 1 software, with the criterion of the smaller total cutting force being better, the optimal set of machining parameters for the total cutting force value when turning 90CrSi steel with Carbide inserts using the MoS_2 NF MQL method determined and shown in Fig. 8. The results showed that the total cutting force Fr reached the minimum value (328 N) with the MoS_2 nanoparticle concentration of 1.985%, a cutting speed of 80 m/min, and a feed rate of 0.138 mm/rev.

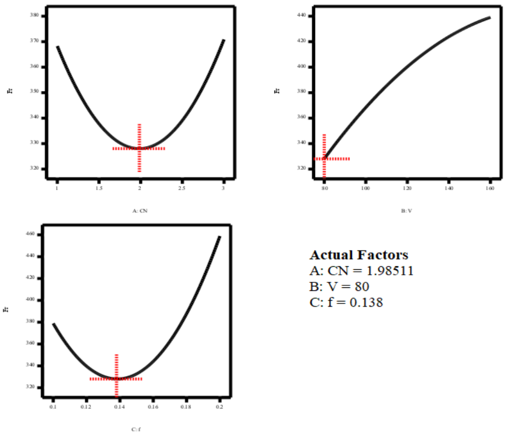


Fig. 8. Optimal results for total cutting force Fr.

IV. CONCLUSION

This research presented an experimental investigation of total cutting force in the hard machining process using MQL technology with MoS_2 nanofluids. ANOVA analysis were performed with Box-Behnken design on Design Expert software 11. The influence of input parameters including MoS_2 nanoparticle concentration, cutting speed, and feed rate on the total cutting force Fr were analyzied. The influence trend and the interaction effects between the input parameters show that the influence of the input factors and their interactions on the output factor is total cutting force. A mathematical model was built to predict and optimize the total cutting force in the hard turning process of 90CrSi steel using MQL method with MoS_2 nanofluid. The cutting force reaches its maximum value when cutting with a particle concentration (1.985%), cutting speed of 80 m/min, and average feed rate (0.138 mm/rev). The surface and contour plots also allow us to determine the appropriate technology mode when assigning the total cutting force value. In further study, more investigations are needed on the microstructure of the machined surface and the lubricating mechanism of MoS_2 nanofluids with the proposed optimal cutting parameters factors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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