International Journal of Industrial Engineering & Production Research December 2024 Vol. 35, No. 4: 1-15
DOI: 10.22068/ijiepr.35.4.2087

RESEARCH PAPER

Influence of Al_2O_3/MoS_2 Hybrid Nanofluid MQL Technique on Cutting Forces and Surface Roughness in Hard Turning Using CBN Inserts

Tran Bao Ngoc[1], Tran Minh Duc[2], Dang Thi Huyen Trang[3], Tran The Long[4] & Minh Tuan Ngo[5]*

Received 6 July 2024; Revised 10 September 2024; Accepted 18 October 2024;

ABSTRACT

Improving hard machining efficiency is a growing concern in industrial production, but environmentally friendly characteristics are guaranteed. Nanofluid minimum quantity lubrication (NF MQL) has emerged as a promising solution to improve cooling and lubrication performance in the cutting zone. This paper utilizes Box-Behnken experimental design to identify the influences of Al_2O_3/MoS_2 hybrid nanofluid MQL hard turning using CBN inserts on surface roughness and cutting forces. Mathematical models were employed to predict thrust cutting force, tangential cutting force, and surface roughness in hard turning under MQL conditions using Al_2O_3/MoS_2 hybrid nanofluid. The study results reveal that the minimum thrust force (F_y) occurs at a nanoparticle concentration of 0.5%, air pressure of 5 bar, and flow rate of 236 l/min. In comparison, the tangential force (F_z) reaches its minimum at a nanoparticle concentration of 0.8%, air pressure of 5 bar, and airflow rate of 227 l/min. The minimum surface roughness was achieved with a nanoparticle concentration of 1%, air pressure of 4.7 bars, and airflow rate of 186 l/min. Additionally, based on the multi-objective optimization, an optimal parameter set of NC=1%, p=5 bar, and Q = 210 l/min was identified to bring out the minimal values of surface roughness (R_a) of 0.218 µm, thrust force (F_y) of 115.9 N, and tangential force (F_z) of 93.3 N.

KEYWORDS: MQL; Surface roughness; Hard turning; Hybrid nanofluids; Cutting force; Lubricant; CBN.

1. Introduction

Over the past few years, the challenges in machining hardened materials have gained much attention in the metal-cutting field. Among hard machining processes, hard turning has been proven to enhance dimensional accuracy, surface quality, and machining productivity as well as reduce manufacturing costs [1]. Due to high cutting forces and cutting temperature in contact faces, the flood condition is the traditional method and has been widely used in production practice. However, the environmental and health problems from the use and treatment of cutting oils are growing concerns and become unsuitable for sustainable development [2]. Consequently, the Minimum Quantity Lubrication (MQL) technique was proposed and developed to address the negative impacts of cutting oils in metalworking processes. This technique exhibits high lubrication efficiency as the cutting fluids in oil mist form are sprayed directly into the cutting area [3]. The MQL technique enhances the cutting effectiveness, yet it faces several constraints when employed in hard machining processes due to its restricted cooling capacity [4]. A recent approach involves the additives of nanoparticles in cutting oil for the MQL method to reduce the friction coefficient and potentially lower the temperature in the cutting zone [5]. Nano-cutting oils are formed by adding nanoparticles in a suitable ratio to conventional cutting oil [6] to enhance various

***Corresponding author: Minh Tuan Ngo**
minhtuanngo@tnut.edu.vn

1. ***Department of Fluids Mechanic, Faculty of Automotive and Power Machinery Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam.***
2. ***Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam.***
3. ***Education Institute - Van Lang University, Vietnam.***
4. ***Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam.***
5. ***Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam.***

properties of the base fluid, including thermal conductivity, viscosity, wettability, pH value, and tribological characteristics [7]. Consequently, the MQL method using nano-cutting oil exhibits effectiveness in the reduction of friction and cutting heat in the cutting area, thereby decreasing cutting force, and enhancing surface quality and tool life [8]. V.K. Pasam et al. [9] explored the impact of nanoparticle size on the machining process and found that smaller grain sizes are better suited for finishing cuts, whereas microparticles prove to be more advantageous and cost-effective for rough cutting or semi-finishing. Additionally, the concentration of nanoparticles serves as a crucial parameter, significantly influencing the lubricating and cooling efficiency of the base cutting oil. Rahman et al. [10] investigated and implemented the Minimum Quantity Lubrication (MQL) method with Al_2O_3, MoS_2, and TiO_2 nano-cutting oils derived from vegetables in the hard turning process of Ti-6Al-4V alloy. The application of nanofluids in the turning process of titanium alloys enhances lubrication and cooling in the contact zone, thereby boosting the overall efficiency of the cutting process. The obtained findings indicate that the use of 0.5% Al_2O_3 nanoparticles enriched in canola oil results in the improvement of surface quality. A. H. Elsheikh et al. suspended Al_2O_3 and CuO nanoparticles in rice oil to enhance the thermal properties of the based oil. These two nanofluids were then employed in hard turning under the MQL method [11]. The study findings reveal that the application of nanofluids contributes to improving surface quality and reducing cutting forces and cutting temperature. Notably, the use of CuO nanofluids yields better surface quality than Al_2O_3 nanofluids. Li et al. conducted a study on the thermal conductivity of vegetable-based nano-cutting oils containing MoS_2, ZrO_2, carbon nanotube (CNT), polycrystalline diamond (PCD), Al_2O_3, and SiO_2 [12]. The results indicate that the thermal conductivity coefficients of these investigated nanofluids were higher than those of pure vegetable oil. In the grinding of Ni alloys, the utilization of nano-cutting oils demonstrates a significant reduction in cutting heat and cutting forces due to their superior lubrication and cooling capabilities. This outcome also extends the feasibility of vegetable oil application in machining difficult-to-cut materials. A. Garg et al. investigated the effect of nanoparticle concentration on micro-drilling performance. The increase of nano concentration from 1.4 wt% to 4.0 wt% led to higher material removal rates (MRR) and lower values of torque and thrust force [13]. Mao et al. studied Minimum Quantity Lubrication grinding of hardened AISI 52100 steels using Al_2O_3 (40 nm) nanoparticles suspended in ethylene glycol at different concentrations of 1%, 3%, and 5%. It was observed that higher nanoparticle concentrations resulted in lower values of grinding force, grinding temperature, and surface roughness [14]. Similar findings were reported in a study involving nano graphite with concentrations of 0.1% and 0.5%, where the growing concentration led to reduced coefficients of friction and average temperature on the contact surfaces [15]. In addition, the investigation on base cutting oils has primarily focused on viscosity, thermal conductivity, and environmental friendliness [16], and vegetable-based oils with inherent biodegradability and environmentally friendly characteristics have emerged as alternative cutting oils [17]. Zhang et al. [18] examined the impact of different vegetable oils mixed with MoS_2 nanoparticles on MQL grinding performance. The study results revealed that the utilization of MoS_2 nano enriched in vegetable oil can effectively decrease cutting forces and grinding heat. Moreover, the usage of the MQL method with vegetable oils can minimize the negative effects on the environment. In a separate investigation, Ayşegül Yucel et al. [19] explored the nanofluid effects on surface quality and built-up-edge (BUE) formation in the turning of aluminum alloy. The findings indicate that the use of nano-cutting oil can diminish cutting heat, thereby reducing BUE formation, minimizing tool wear, and enhancing surface quality when compared to pure MQL and dry machining conditions. Darshan et al. [20] studied the impact of Al_2O_3, MoS_2, and graphite sunflower-based nano-cutting oils on the turning performance of Inconel 800 alloy. The authors concluded that graphite and MoS_2 nano-cutting oils exhibited superior thermal conductivity and lubrication performance compared to Al_2O_3 nanofluid. Gupta et al. [21] investigated the hard-turning efficiency of Inconel 800 alloy under a nanofluid MQL environment. The results demonstrated that the cooling lubrication effectiveness of nano-cutting oil is closely dependent on the type, grain size, and concentration of nanoparticles. Al_2O_3 nanoparticles, characterized by high hardness, strength, thermal conductivity, and near-spherical morphology, penetrate the cutting area and act as rollers, thereby reducing friction, cutting force, and cutting temperature [22]. MoS_2 and graphite nanosheets possess excellent lubricating performance and higher thermal conductivity than

Al_2O_3 nanoparticles. Consequently, the mixture of the two nanoparticle types suspended in cutting oils is a promising topic. Uysal et al. [23] analyzed the effects of MQL using vegetable oil containing MoS_2 nanoparticles on milling efficiency. The authors reported the improvement of the lubricating and cooling performance resulted in the use of MoS_2 nano-cutting oil, 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 the cutting tool and workpiece, which contributes to reducing the friction coefficient in the cutting zone [24]. Nevertheless, there is a notable absence of studies regarding hard machining using CBN inserts under the hybrid nanofluid MQL method. This investigation is dedicated to assessing the effectiveness of hard turning of 90CrSi tool steel under a hybrid nanofluid MQL environment on cutting forces and roughness surface.

2. Experimental System and Method

In this study, 90CrSi tool steel samples with dimensions D40xL200 mm were used and hardened to 60-62 HRC. The experimental setup is shown in Figure 1. The cutting experiments were performed on the CS-460x1000 Chu Shing lathe machine (Pin Shin Machinery Company) using CBN 7025 inserts from Sandvik specialized for the hard turning process. Based on the previous study [25], the fixed cutting parameters (V_c = 160 m/min; f = 0.12 mm/rev; t = 0.12mm) were selected. The NOGA's mini cool MQL nozzle was used for experiments. Al_2O_3/MoS_2 hybrid nanofluids were prepared by mixing a mixture of Al_2O_3 and MoS_2 nanoparticles with a ratio of 8/2 in soybean oil. The grain sizes of Al_2O_3 and MoS_2 nanoparticles are 30 nm. The Kistler 9257BA dynamometer made by Germany (figure 4) was used to measure three components of cutting force (F_x, F_y, F_z) with DQA N16210 A/D data acquisition and Dasylab 10.0 software. After each machining pass, the surface roughness was measured three times by using the Mitutoyo SJ-210 surface roughness tester and taken by the average values.

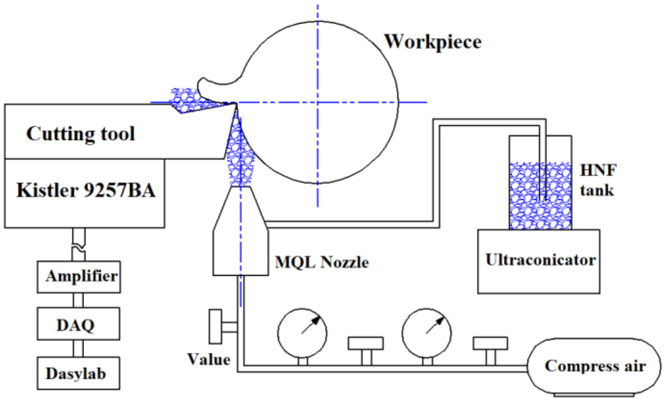

Fig. 1. Experiment set up

The study focuses on evaluating the influence of nanofluid MQL parameters (nanoparticle concentration (NC), air pressure (p), and airflow rate (Q)) on cutting force and surface roughness. Based on the capacity adjustment of the experimental equipment and the results of previous studies [25], the input parameters and their values are selected as shown in Table 1.

Tab. 1. Input parameters and their values

Input parameters	Symbol	Low level	High level
Nanoparticle concentration (%)	NC	0,5	1,5
Air pressure (Bar)	p	4	6
Air flow rate (l/min)	Q	150	250

Many experimental research models are used to analyze, evaluate, and optimize the efficiency of the machining process such as the RSM, Taguchi, factorial, and Central composite... [27, 28]. Each model has its advantages and disadvantages. The box-Behnken model is a complete and stronger model for optimization problems with few experimental points. Therefore, in this study, the Box-Behnken experimental design was used to study the effects of nanoparticle concentration (NC), air pressure (p), and airflow rate (Q) on cutting forces and surface roughness. The experimental matrix is shown in Table 2. All experimental trials were performed by following the run order. The three components of cutting forces were directly measured by using a Kistler 9257BA dynamometer (figure 2). The feed force is the smallest of the three cutting force components, changes little during the machining process, and depends mainly on the cutting parameters. Hence, it was not analyzed in this study. After processing the data, the cutting forces and surface roughness values are given in Table 2.

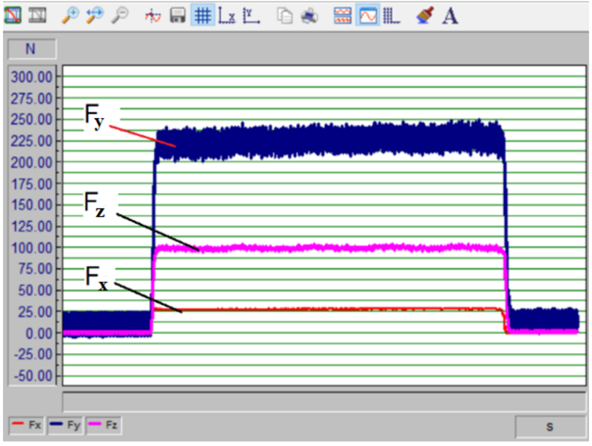

Fig. 2. The measured cutting forces with kistler 9257BA dynamometer

Tab. 2. Experimental matrix and measured results

Std order	Run order	NC (%)	p (Bar)	Q (l/min)	R_a (µm)	F_x (N)	F_y (N)	F_z (N)
1	1	0.5	4	200	0.283	24.1	137.6	113.3
2	9	1.5	4	200	0.277	25.2	141.7	130.3
3	7	0.5	6	200	0.264	24.6	139.2	119.3
4	11	1.5	6	200	0.285	25.7	145.9	128.7
5	14	0.5	5	150	0.269	27.1	159.7	128.8
6	4	1.5	5	150	0.264	23.9	130.3	108.7
7	3	0.5	5	250	0.299	21.3	113.8	99.5
8	10	1.5	5	250	0.284	22.1	125.2	104.1
9	13	1	4	150	0.223	26.9	152.0	134.7
10	12	1	6	150	0.285	27.3	153.1	139.4
11	2	1	4	250	0.252	25.9	148.1	120.1
12	8	1	6	250	0.249	26.4	148.4	119.1
13	15	1	5	200	0.219	22.7	115.4	96.8
14	5	1	5	200	0.213	23.1	117.3	91.7
15	6	1	5	200	0.216	22.8	118.0	95.3

3. Result and Discussion

3.1. Thrust cutting force (F_y) and tangential cutting force (F_z)

3.1.1. ANOVA analysis for F_y and F_z

The influence of the survey factors on F_y and F_z was evaluated by using the ANOVA analysis with significance level α = 5% (95% confidence level), and the results are shown in Tables 4 and 5. If the input factors have a probability value P smaller than the significance level α = 0.05, it proves the influence of survey factors is very significant. If the probability value P is greater than the significance level α, it proves that the survey factor has little effect on the objective function. ANOVA analysis for thrust force F_y (table 3) shows that the airflow rate (Q) has a significant effect. The nanoparticle concentration (NC) and air pressure (p) have little effect. Second-order interactions have great influences on F_y, in which the air pressure interaction (p*p) causes the strongest impact, followed by the interaction of airflow rate (Q*Q) and the interaction effect between nanoparticle concentration and air flow rate (NC*Q). The remaining interaction effects have little impact on the responses.

Tab. 3. Results of ANOVA analysis for the thrust force F_y

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2956.98	328.55	4.91	0.047
Linear	3	456.98	152.33	2.28	0.197
NC(%)	1	6.48	6.48	0.1	0.768
p (bar)	1	6.48	6.48	0.1	0.768
Q(l/min)	1	444.02	444.02	6.64	0.05
Square	3	2081.99	694	10.38	0.014
NC*NC	1	33.79	33.79	0.51	0.509
p*p	1	1655.56	1655.56	24.75	0.004
Q *Q	1	560.88	560.88	8.39	0.034
2-Way Interac.	3	418.01	139.34	2.08	0.221
NC*p	1	1.69	1.69	0.03	0.88
NC *Q	1	416.16	416.16	6.22	0.055
p*Q	1	0.16	0.16	0	0.963
Error	5	334.44	66.89		
Lack-of-Fit	3	330.82	110.27	60.92	0.016
Pure Error	2	3.62	1.81		
Total	14	3291.42			

Tab. 4. Results of ANOVA analysis for the main cutting force F_z

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	3085.93	342.88	7.35	0.02
Linear	3	614.73	204.91	4.39	0.072
NC (%)	1	14.85	14.85	0.32	0.597
p (bar)	1	8.2	8.2	0.18	0.692
Q(l/min)	1	591.68	591.68	12.68	0.016
Square	3	2296.11	765.37	16.4	0.005
NC*NC	1	96.98	96.98	2.08	0.209
p*p	1	1983.07	1983.07	42.49	0.001
Q*Q	1	410.96	410.96	8.8	0.031
2-Way Interac.	3	175.09	58.36	1.25	0.385
NC*p	1	14.44	14.44	0.31	0.602
NC*Q	1	152.52	152.52	3.27	0.13
p*Q	1	8.12	8.12	0.17	0.694
Error	5	233.38	46.68		
Lack-of-Fit	3	219.64	73.21	10.66	0.087
Pure Error	2	13.74	6.87		
Total	14	3319.3			

From the results of the ANOVA analysis (table 4), the airflow rate (Q) strongly influences the tangential force F_z. The nanoparticle concentration (NC) and air pressure (p) have little effect. For the second-order interactions, the interactions of air pressure (p*p) and air flow rate (Q*Q) have a significant influence on the main cutting force F_z, in which the second-order interaction of air pressure is the greatest influence.

The degree of agreement of the experimental model with the measured experimental data is evaluated through the coefficient of determination R^2. From here, it can be seen that R^2 for thrust force F_y and main cutting force F_z are 89.85% and 92.93%, respectively, proving that the experimental model is very consistent with the experimental results. The regression models of cutting force components are given in the following equations:

F_y=967–114.3NC–211.2P-2.513Q +12NC*NC + 21.16 P*P +0.00494 Q*Q +1.34NC*P + 0.409 NC *Q -0.0040 P *Q

F_z=892 -68.7 NC-221.1 P-1.970 Q+20.4 NC*NC+23.15P*P+ 0.00423 Q*Q - 3.79 NC*P + 0.248 NC*Q - 0.0284 P *Q

3.1.2. The influence of survey variables on the objective functions F_y and F_z

The main effects of the investigated variables on the objective functions Fy and Fz are shown in Figures 2 and 3. The influence trends of the survey parameters on Fy and Fz are similar. The inflection points can be observed from the graphs of investigated variables for the objective functions to reach the optimal values (the smallest value), so the selected ranges of the survey variables are reasonable. The objective functions F_y and F_z reach small values when the nanoparticle concentration is about 1.0%. It means that the concentration of Al_2O_3 nanoparticles of 0.8%, and a concentration of MoS_2 nanoparticles of 0.2% because Al_2O_3/MoS_2 hybrid nano cutting oil is mixed at a ratio of 8:2. Hence, it is possible to maximize the effectiveness of two types of Al_2O_3 and MoS_2 nanoparticles in hard turning under NF MQL condition [26].

The figures 2 and 3 also indicate that the objective functions F_y and F_z reach small values when the air pressure p is about 5 bars. The reason behind this is that air pressure largely affects the ability to form the droplets of nano-cutting oil, penetrate the cutting area, and create the tribe film on contact faces [26]. External cylindrical turning belongs to the group of open machining methods, so if the air pressure is small, the ability to create oil drops and bring them into the cutting area is limited. When the air pressure is high, the ability to create oil droplets and bring them into the cutting area is better. However, if the air pressure is too high, the oil droplets are easily pushed out of the cutting area, thus limiting the lubrication efficiency. For the average air pressure of about 5 bar, although the ability to create oil mist and bring it into the cutting area is not the best, the ability to keep oil droplets in the cutting area is better than when the higher air pressure is used. Accordingly, the cooling lubrication performance is more effective.

For air flow rate Q is at 150 l/min, F_y and F_z reach their maximum values. When the air flow rate increases, the cutting force components decrease. For Q at about 220 l/min, the objective functions reach the smallest values, and they increase with the growing flow rate. It can be explained that the increase in the airflow rate will increase the amount of cutting oil as well as the number of Al_2O_3 and MoS_2 nanoparticles in the cutting zone. For Q at about 220 l/min, the number of nanoparticles in the cutting area is appropriate, so it contributes to making objective functions reach the minimum values. If the airflow rate continues to increase, more nanoparticles will present in the cutting area, causing compression and impedance resulting from Al_2O_3 nanoparticles and the adhesion to the cutting edge and machined surface resulting from MoS_2 nanoparticles. They cause the values of the objective functions F_y and F_z to increase [26].

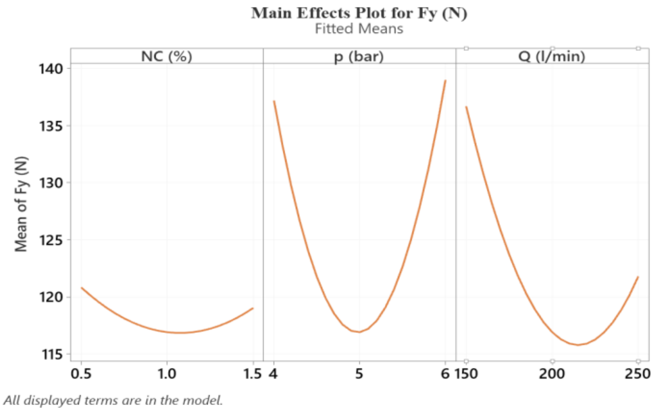

Fig. 2. Main effects of input parameters on the thrust force F_y

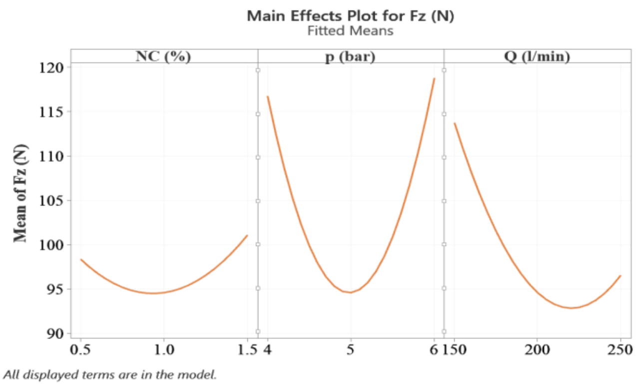

Fig. 3. Main effects of input parameters on the tangential cutting force F_z

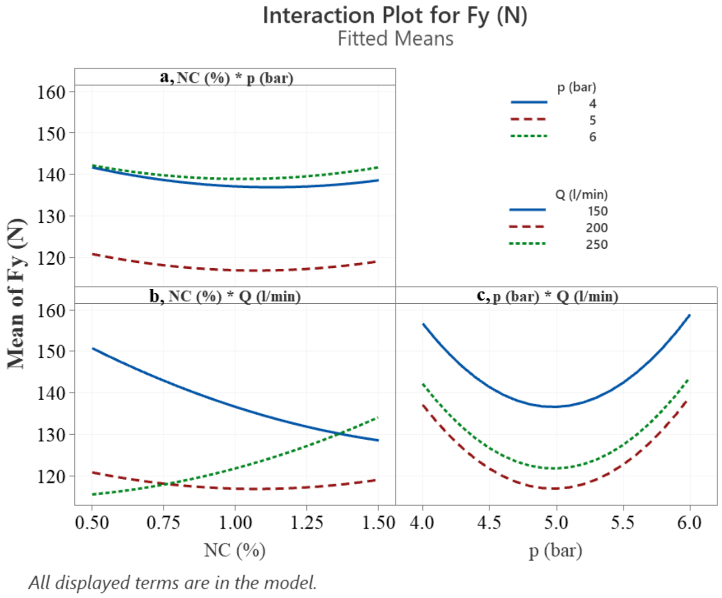

Fig. 4. Interaction plot of influences of survey factors on thrust force F_y

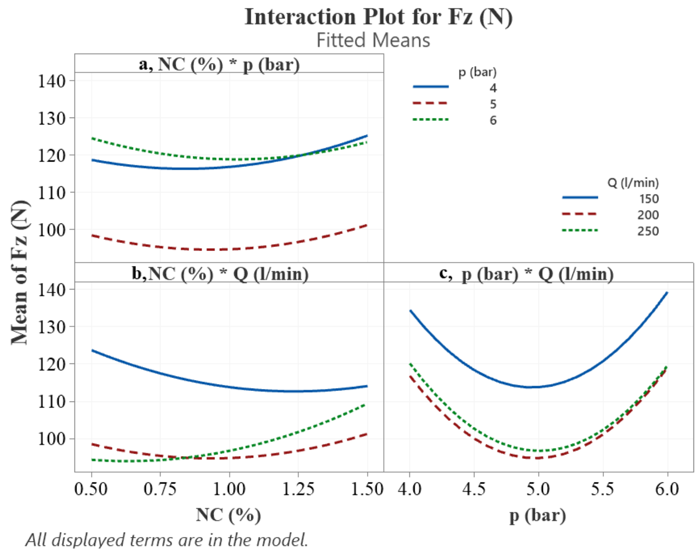

Fig. 5. Interaction plot of influences of survey factors on the main cutting force F_z

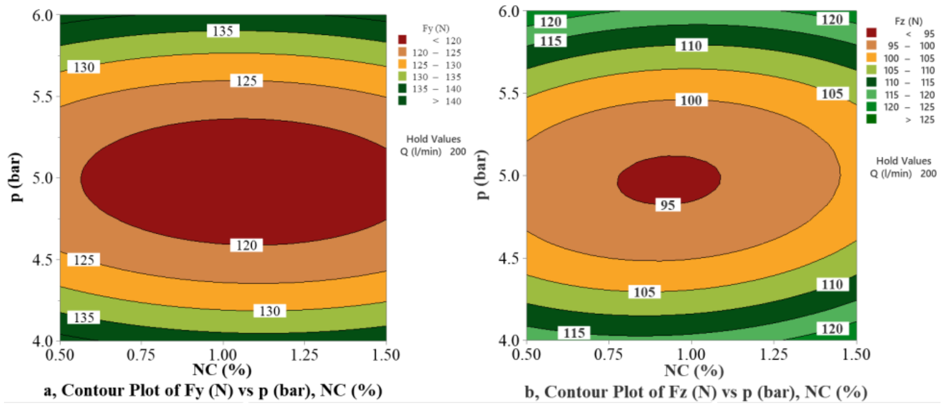

Fig. 6. Contour plot of effects of p and NC on cutting forces F_y and F_z

Figures 4c and 5c depict the interaction effect between air pressure and airflow rate (p*Q) on the cutting forces F_y and F_z. The results also show that the interaction p*Q has little effect on F_y and F_z. When the flow rate rises from Q=150 l/min to 200 l/min, the cutting forces are reduced and are less affected by air pressure p. However, the cutting forces are almost unchanged when the airflow rate increases from 200 l/min to 250 l/min. The reason may be that when the high level of air pressure and airflow rate are used, the number of nanoparticles in the cutting zone will increase, promoting the mechanical scratching and adhesion of nanoparticles to the machined surface. Figure 8 also clearly describes the influence of the interaction p*Q on F_y and F_z with NC=1%.

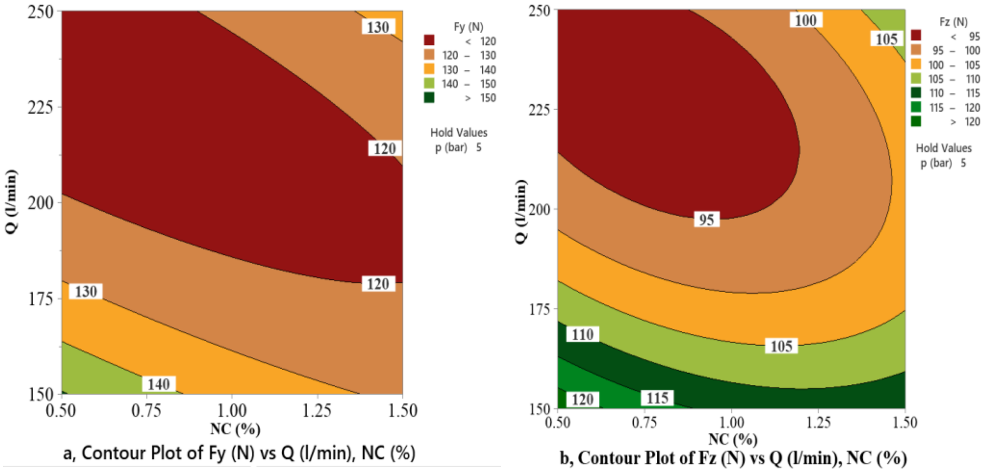

Fig. 7. Contour plot of effects of Q and NC on cutting forces F_y and F_z

The interaction effects between survey variables on the objective functions F_y and F_z are shown in Figures 4 and 5. For the three levels of air pressure, the change in nanoparticle concentration causes little influence on F_y and F_z. At p = 5 bar, the smallest cutting force components are reported. The interaction effect of NC*p with cutting force F_y, F_z is clearly shown in Figure 6 when Q is fixed at 200 l/min. F_y is less than 120N and force F_z is less than 95 N with p = 5 bar and NC =1%.

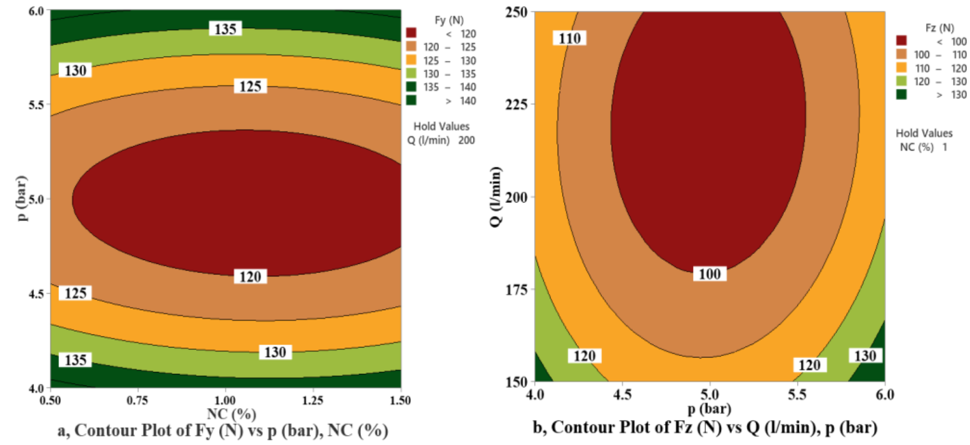

Fig. 8. Contour plot of effects of p and Q on cutting forces F_y and F_z

The interaction effect between nanoparticle concentration and flow rate on thrust cutting force F_y and main cutting force F_z is shown in Figures 4b and 5b. The results also show that the NC*Q interaction significantly affects the two cutting force components F_y and F_z. At flow rates of 150 l/min and 200 l/min, the cutting forces F_y and F_z both decrease gradually when increasing the nanoparticle concentration in the investigated range. However, at a flow rate of 250 l/min, F_y and F_z cutting forces tend to increase progressively when the nanoparticle concentration increases. It can be explained that for the small air flow rate, the growing nanoparticle concentration will increase the number of nanoparticles in the cutting zone. At the same time, for the large air flow rate, if the nanoparticle concentration increases, the number of nanoparticles entering the cutting zone becomes larger. Too large nanoparticles in the cutting area will increase adhesion and cause compression and impedance phenomena in the cutting area, thereby increasing cutting force and causing surface scratches. In addition, the contour plot in Figure 7 also clearly describes the influence of the interaction NC*Q on the two cutting force components with p=5. From here, technologists can easily choose a reasonable set of NC and Q parameters to reach the smallest cutting forces. For the smaller F_y and F_z, a small level of nano concentration (<1%) and a large air flow rate (>200 l/min) should be suggested.

3.2. Surface roughness Ra

3.2.1. ANOVA analysis for surface roughness

ANOVA analysis for surface roughness was performed on Minitab 19 software with a significance level of 0.05 and the results are shown in table 4.

Tab. 6. ANOVA analysis results for surface roughness R_a

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	0.010447	0.001161	4.88	0.048
Linear	3	0.000522	0.000174	0.73	0.576
NC (%)	1	0.000003	0.000003	0.01	0.913
p (bar)	1	0.000288	0.000288	1.21	0.321
Q(l/min)	1	0.000231	0.000231	0.97	0.37
Square	3	0.008661	0.002887	12.13	0.01
NC*NC	1	0.007148	0.007148	30.04	0.003
p*p	1	0.001099	0.001099	4.62	0.084
Q*Q	1	0.001333	0.001333	5.6	0.064
2-Way	3	0.001263	0.000421	1.77	0.269
NC*p	1	0.000182	0.000182	0.77	0.422
NC*Q	1	0.000025	0.000025	0.11	0.759
p*Q	1	0.001056	0.001056	4.44	0.089
Error	5	0.00119	0.000238		
Lack-of-Fit	3	0.001172	0.000391	43.4	0.023
Pure Error	2	0.000018	0.000009		
Total	14	0.011636			

The survey model is appropriate because p-value is less than 0.05 and a coefficient of determination R2 = 89.78%. The analytical results also show that all investigated factors affect surface roughness, in which the second-order interaction NC*NC has the greatest influence. The regression function of Ra is given in the following equation:

Ra=0.8-0.401 NC-0.115 P-0.00121 Q +0.176 NC*NC+0.01725 P*P+0.000008 Q*Q+0. 0135 NC*P-0.0001 NC*Q-0.000325 P*Q

3.2.2. The influence of survey variables on surface roughness Ra

Figure 9 shows the main effects of survey variables on Ra. It can be observed that Ra can reach the optimal value (the smallest value) in the survey area, so the selected value ranges are reasonable. The smallest value (0.215÷0.26μm) can be achieved with NC = 1.0%, air pressure p = 5 bar, and airflow Q =200 ml. In this case, the oil droplets are introduced and retained appropriately in the cutting zone.

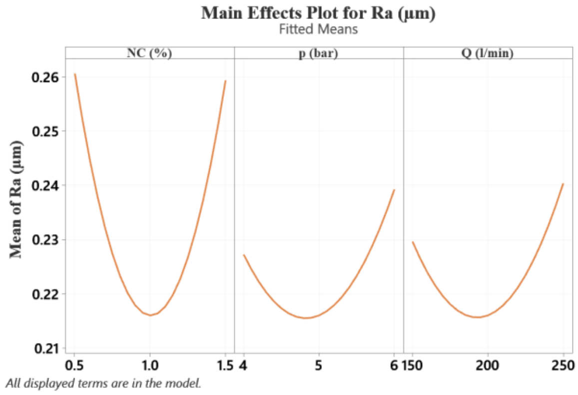

Fig. 9. Main effects of investigated factors on R_a

The interaction effects between survey factors are shown in Figure 10. For the interactions (NC*p) and (NC*Q), the best results can be obtained with p = 5 bar, Q = 200 l/min, NC =1.0% gives. For the interaction effect (p*Q), with Q = 150 l/min, the increase of air pressure (p = 6 bar) contributes to reducing surface roughness Ra. For Q = 250 l/min, the growing air pressure (p = 6 bar) negatively influences on surface quality (Ra increases).

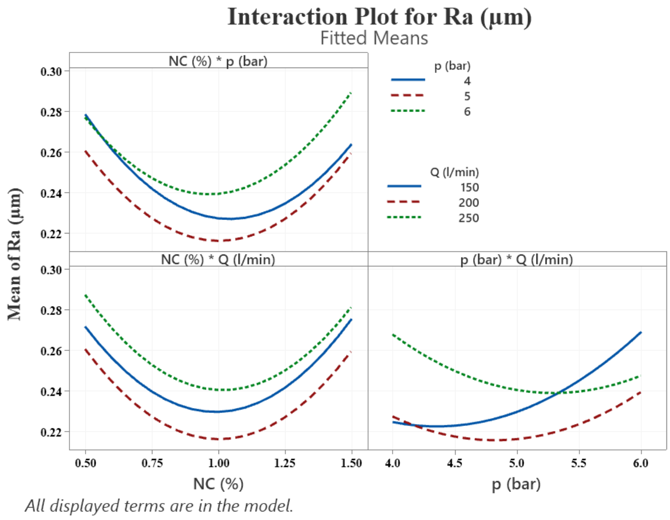

Fig. 10. Effect of interaction between variables on surface roughness R_a

The contour plots depict the influence of the survey variables on the objective function Ra (Figure 11). They have great practical significance because they will help technical staff quickly evaluate the rules as well as the influence level of the survey variables on Ra. Therefore, it is possible to select the reasonable values of survey variables for the required surface roughness Ra.

3.3. Determination of the optimal set of technological parameters

The optimization results for each response are shown in Figures 12-14. The main cutting force Fz reaches the smallest values with NC= 0.8%, p=5 bar, and Q= 227 l/min. The thrust cutting force Fy reaches the smallest values with NC= 0.5%, p= 5 bar, and Q= 236 l/min. The minimal surface roughness value of 0.214µm can be achieved with NC= 1%, p= 4.7 bar, and Q=186 l/min.

Figure 15 shows the multi-response optimization for Fy and Fz. The results show that under hybrid nanofluid MQL conditions NC= 0.7%, p =5 bar, and Q =228 l/min should be chosen for the smallest values of Fy (114 N) and Fz (92 N).

The results of multi-response optimization for Ra, Fy, and Fz are shown in Figure 16. The optimal set of NC=1%, p=5 bar, and Q=210 l/min is specified for smallest values of Ra (0.218 µm), Fy (115.9 N) and Fz (93.3 N).

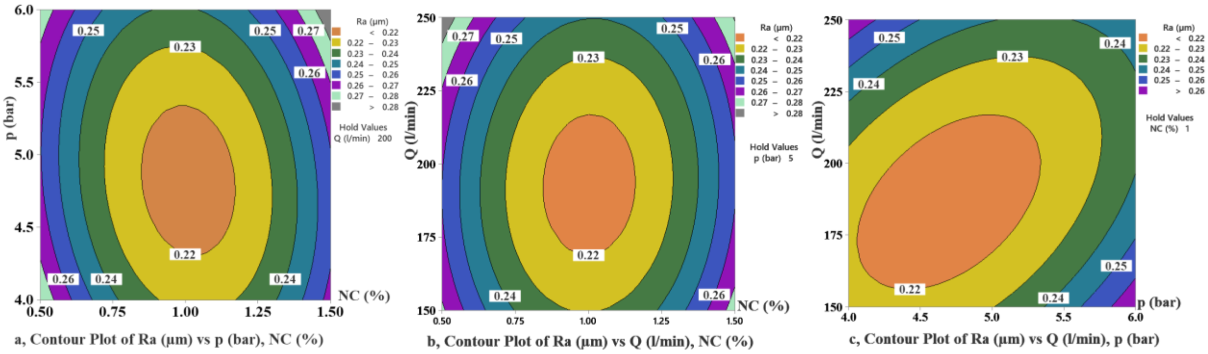

Fig. 11. Simultaneous influence of the input factors on surface roughness

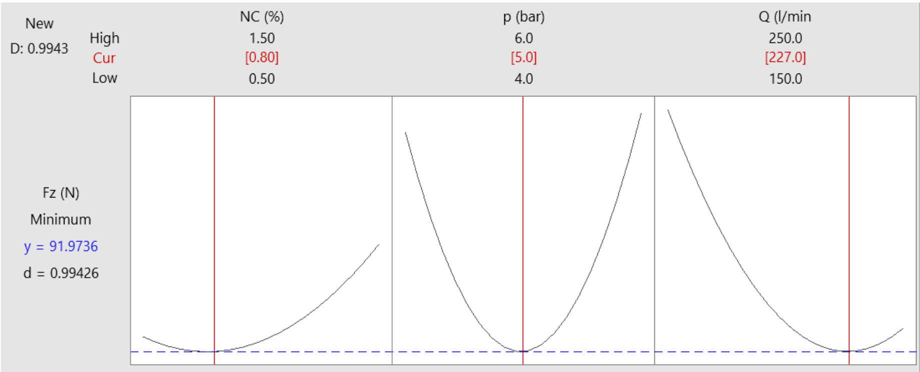

Fig. 12. Optimal results for the main cutting force F_z

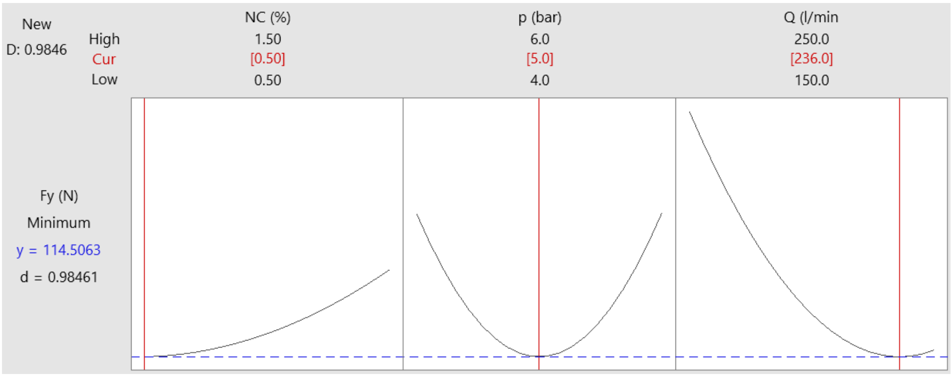

Fig. 13. Optimal results for the thrust cutting force F_y

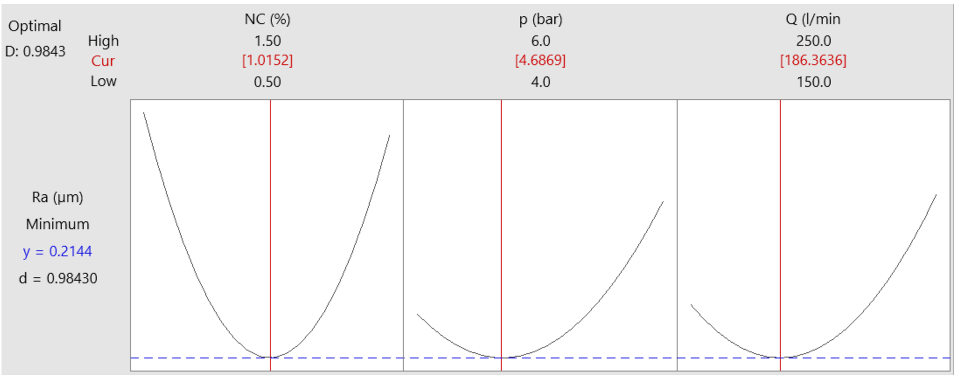

Fig. 14. Optimal results for surface roughness F_z

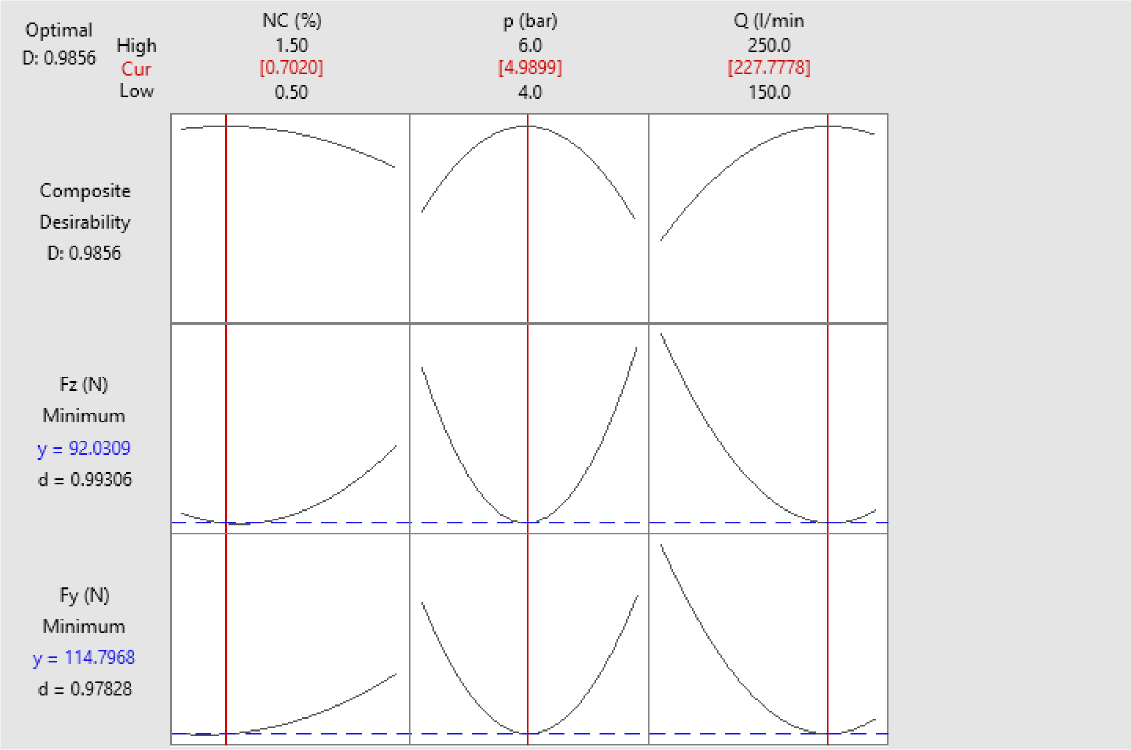

Fig. 15. Multi-objective optimization results with objective function F_y and F_z

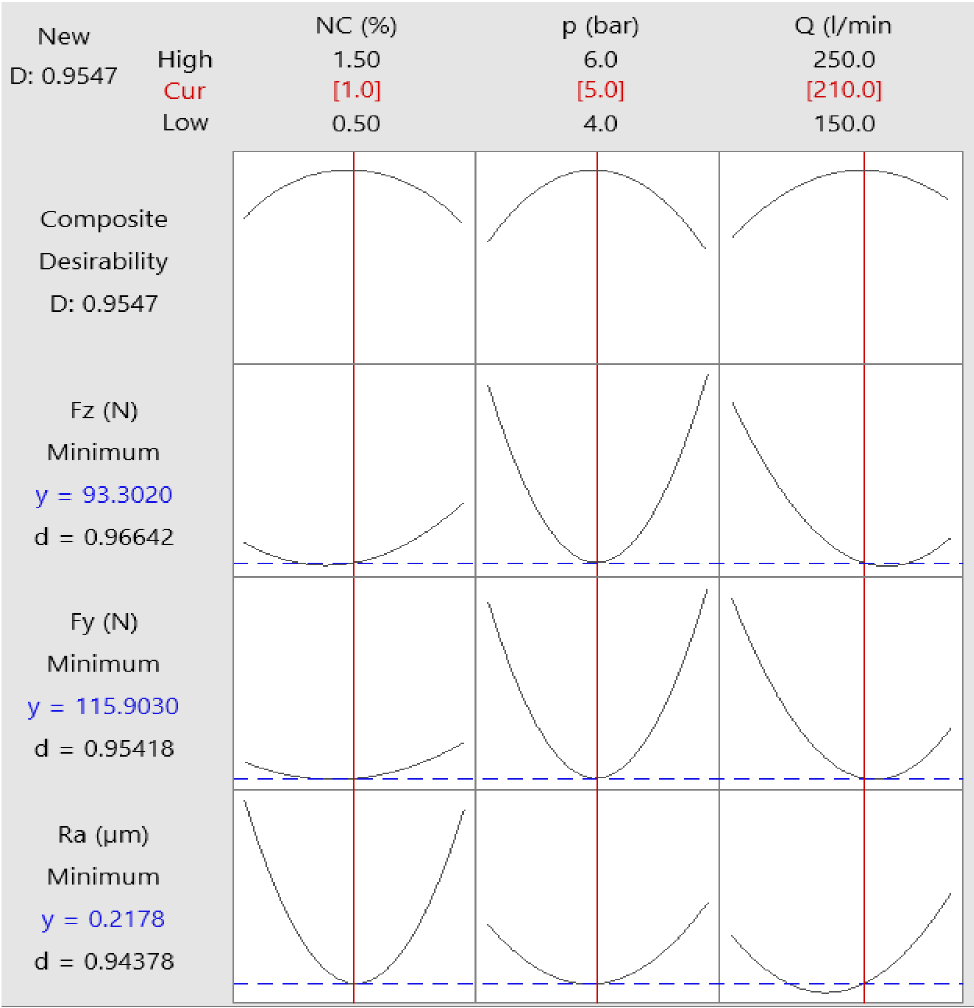

Fig. 16. Multi-objective optimization results with objective function R_a, F_y and F_z

4. Conclusion

This article assesses the efficacy of HFMQL technology in machining hardened 90CrSi steel with CBN inserts, focusing on cutting force and surface roughness. Three distinct hybrid nanofluid concentrations were formulated by blending MoS_2 and Al_2O_3 nanoparticles with soybean oil. The impacts of particle concentration, pressure, and airflow were scrutinized using the Box-Behnken method. Regression models were developed via the Box-Behnken method to examine the influence of hybrid nanofluid concentration, alongside other MQL parameters like pressure and airflow, on key factors such as main cutting force (F_z), thrust force, and surface roughness. The findings are summarized as follows:

In the hard turning of 90CrSi steel with Hybrid nano-cutting oil and MQL technology, the main cutting force and thrust cutting force are significantly influenced by airflow and pressure. Additionally, variations in particle concentration led to distinct effects on cutting forces F_y and F_z depending on the flow rate. The minimum value for thrust cutting force F_y is attained at a nanoparticle concentration of 0.5%, air pressure of 5 bar, and flow rate of 236 l/min. On the other hand, the main cutting force F_z reaches its minimum at a nanoparticle concentration of 0.8%, air pressure of 5 bar, and airflow rate of 227 l/min. In the hard turning of 90CrSi steel with Hybrid nano-cutting oil and MQL technology, the main cutting force and normal cutting force are significantly influenced by airflow and pressure.

Likewise, in the hard turning of 90CrSi steel, the quadratic interaction of nanoparticle concentration and the interplay between pressure and airflow exert the most significant influence on surface roughness. Variations in airflow also result in differential effects on surface roughness depending on air pressure. The minimum surface roughness is achieved with a nanoparticle concentration of 1%, air pressure of 4.7 bar, and airflow rate of 186 l/min.

Through the simultaneous optimization of three objectives (cutting forces F_y, F_z, and surface roughness), an optimal parameter set (1%, p 5 bar, and Q 210 l/min) was identified. Machining with these optimal parameters yields a surface roughness (R_a) of 0.218 µm, a thrust cutting force (F_y) of 115.9 N, and a main cutting force (F_z) of 93.3 N.

In further study, more investigations are needed on the microstructure of the machined surface and the lubricating mechanism of hybrid nanofluids with the proposed optimal cutting parameters factors.

5. Conflict

The authors declare no conflict of interest

6. Funding

This research received no specific financial support from any funding agency.

7. Acknowledgment

The study had the support of Thai Nguyen University of Technology, Thai Nguyen University

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