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An Investigation of Nanofluid MQL on Surface Roughness and Total Cutting Force in Hard Turning Process Using CBN Inserts

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Abstract
The growing demand for environmentally friendly solutions for improving hard machining performance is considered an urgent issue in modern manufacturing. Nanofluid minimum quantity lubrication (NF MQL) has emerged as a promising technique to enhance cooling and lubrication effectiveness in cutting zone, thereby improving hard cutting performance. This paper aims to study the effects of Al_2O_3 nanofluid MQL hard turning using CBN inserts on surface roughness and total cutting force. Box–Behnken experimental design for response surface methodology was used to investigate the influences of nanoparticle concentration, air flow rate, and air pressure on the responses. The obtained results revealed that the performance of hard turning process were improved by using Al_2O_3 nanofluid MQL environment. The technological guides were provided for the specific cutting conditions. Specifically, nanoparticle concentration of 0.5%, air pressure of 4.9 bar, and flow rate of 150 L/min is determined as the optimal set for lowest total cutting force (F_r =153.36 N). Besides, nanoparticle concentration NC = 0.54%, air pressure p = 5.1 bar, and air flow rate Q = 250 L/min should be used for the minimum surface roughness (R_a = 0.288 µm). Furthermore, based on the multi-optimization results, an optimal parameter set (NC = 0.53%, p = 4.79 bar, and Q = 193.4 L/min) should be suggested to achieve the minimal values of R_a=0.2987 µm and F_r =169.16 N.
Keywords: *Hard turning, Nanofluid, MQL, Al_2O_3 Nanoparticles, Surface roughness, Total cutting force.*

1. INTRODUCTION

In recent years, hard turning has become increasingly popular in manufacturing industry as an alternative or supplement solution to grinding. It involves machining hardened materials with a hardness range of 45–68 HRC using various cutting inserts. Despite using small depths of cut and feed rates, hard turning can reduce machining time by up to 60% compared to grinding [1]. This efficiency makes it increasingly favored in manufacturing. Research has shown that, when applied correctly, hard turning can produce better surface quality than that achieved by grinding. However, machining of hard materials generates high cutting forces and temperatures, so the use of cutting tool materials with superior hardness, heat resistance, and wear resistance is always required. In recent years, Cubic Boron Nitride (CBN) has become a popular choice for hard turning due to its excellent hardness, heat resistance, and abrasion resistance [2].

To reduce friction and cutting temperature during hard machining, various advanced cooling lubrication methods have been proposed and studied. However, the introduction of cutting fluids under flood condition during machining operations raises environmental and health concerns [2]. Consequently, the adoption of the Minimum Quantity Lubrication (MQL) technique aims to minimize the adverse impacts of cutting oils in metalworking processes. Moreover, this approach has been proven to enhance lubrication efficiency as the cutting oil in mist form is sprayed directly into the cutting area [3]. However, the use of MQL has been shown to be effective when machining steels before heat treatment or materials with low hardness. When machining hard materials, MQL shows the poor performance due to limited cooling capacity [4]. To overcome this drawback, NF-MQL technology was developed to improve the cooling efficiency. There have been many studies using cutting oils with good cooling properties such as emulsion oil to produce cooling effect for MQL technology [5]. Rahman et al. [6] studied on turning process of Ti-6Al-4V alloy with MQL environment using Al_2O_3, MoS_2 and TiO_2 vegetable-based nano cutting oils. The obtained results showed that the machining efficiency was improved due to the enhanced lubricating and cooling capacity resulted from nano cutting oils. The analysis of machined surface microstructure indicated that the higher surface quality was achieved by using 0.5% Al_2O_3 nanofluid based on rapeseed oil. Hegab et al. [7] investigated the MQL turning of Inconel 718 using Multi-Walled Carbon Nanotubes (MWCNTs) and Al_2O_3 nanoparticles suspended in rapeseed oil. The authors concluded that the tribological characteristics of MWCNTs nano cutting oil were better than that of Al_2O_3 nanofluid. Besides, the presence of nanoparticles has contributed to improve the lubrication and cooling efficiency in the cutting zone. Darshan et al. [8] studied the effects of Al_2O_3, MoS_2 and graphite sunflower-based nano cutting oils on turning performance of Inconel 800 alloy. From the experimental results, the authors pointed out that graphite and MoS_2 nano-cutting oils showed the better results than Al_2O_3 nano cutting oil due to their better thermal conductivity and lubrication properties. Gupta et al. [9] also recorded the improvement of machining performance of the turning process of Inconel 800 alloy, under nanofluid MQL environment. Due to the very small amount of vegetable oil used, it contributes to reduce negative impacts on the environment.

Each nanoparticle type has different properties and shapes, so its characteristics and concentration in the base cutting oil are very important parameters, strongly affecting lubricating and cooling efficiency. Al_2O_3 nanoparticles are reported to have high hardness, strength and near-spherical morphology [10]. Therefore, when they penetrate into the cutting zone, they will act as “ball rollers” to convert the sliding friction into rolling friction, thereby reducing the friction coefficient and cutting forces. On the other hand, MoS_2 and graphite nanoparticles possess layered structures and high thermal conductivity coefficient [11], and they have good lubricating properties. Therefore, these types of nanoparticles have been widely used to formulate nano cutting oils in metal cutting. Zhang et al. [12] investigated the efficiency of different vegetable oils containing MoS_2 nanoparticles in MQL grinding. The reduction of grinding heat and force was reported, which proves the better lubricating effect. This means that the application of vegetable oils is expanded in machining, and the adverse effects resulted from the usage of cutting fluids on the environment are minimized. Uysal et al. [13] made a study on milling process under MQL environment using MoS_2 vegetable-based nano cutting oil. The obtained results show that the machined surface quality and tool life were improved due to the excellent lubricating and cooling effects of MoS_2 nano cutting oil. Yucel et al. [14] conducted an investigation on the effects of MoS_2 nanofluid based on mineral oil for turning AA 2024 T3 aluminum alloy. The authors found out the enhancement of surface roughness and surface topography as well as the significant reduction in the built-up-edge (BUE) formation when compared with dry turning. Furthermore, cutting temperature and tool wear were reduced in comparison with dry and pure MQL conditions. Moreover, an outstanding property of MoS_2 nanoparticles is that they have a large surface area, which tends to form tribo-film when using reasonable concentration, air pressure and air flow rate in MQL/MQCL environment [15,16].

Sharma et al. [17] pointed out the four main mechanisms of nanoparticles in cutting zone including rolling, sliding, polishing and filming, leading to the difference in cooling and lubricating effects. Maruda et al. [18] investigated the copper nanoparticle sizes and concentrations in turning process of 316L stainless steel under MQL condition. The obtained results revealed the smaller nanoparticle size for the better machined surface topography. In addition, the 0.5% copper nano concentration was appropriate for achieving the better surface quality and lower power consumption [19]. The study reveals that Al_2O_3 nanoparticles are among the most common usages due to the high harness and strength, nearly spherical morphology, and good thermal conductivity [20]. The improvement in grinding performance due to the significant reduction of friction coefficient was reported in [21]. On the other hand, the good thermal resistance makes Al_2O_3 nanoparticles suitable for hard machining [22]. The improvement of cooling and lubricating effects has been proven by adding Al_2O_3 nanoparticles in the vegetable oils [23], which enlarge their applicability [24]. Eltaggaz et al. [25] concluded that Al_2O_3 nanofluid MQL contributed to achieve the higher cutting performance than dry and flood conditions. Hegab et al. [26] claimed the tight relationship between Al_2O_3 nanoparticles and multi-walled carbon nanotubes (MWCNTs) concentrations and the machining outputs. Cheraghian [27] concluded that the additives of nano particles helped improve the drilling performance. Günan et al. [28] made an extensive study on Al_2O_3 nanoparticle concentrations in MQL milling process of Ni alloy. The results indicated that the rise of nanoparticle concentration resulted in the cutting force reduction, but the agglomeration phenomenon was reported in case of high nano concentration, negatively affecting the surface quality. Madanirad et al. [29] pointed out that the smaller sizes of nanoparticles and the higher concentration bring out the larger contact angle.

However, through the literature review, it can be clearly seen that the studies on the technological parameters of nanofluid MQL technique are still very limited, especially for hard turning process. Therefore, the authors aim to make a study on the influence of Al_2O_3 nanoparticle concentration, air pressure and air flow rate in hard turning of 90CrSi steel (60-62 HRC) under MQL condition using CBN inserts.

2. MATERIAL AND METHOD

In this study, the experimental trials were conducted to investigate the effects of three input parameters on surface roughness and total cutting force in hard turning process under Al_2O_3 NF-MQL condition. This research aimed to gain a better understanding of how the surveyed parameters (Al_2O_3 nanoparticle concentration, air pressure, and air flow rate) influence the surface roughness and total cutting force. The experimental model is illustrated in Figure 1. The cutting trials were carried out on a CS-460x1000 Chu Shing lathe machine (manufactured by Pin Shin Machinery Company). The workpieces used in the experiments were 90CrSi steel, with the dimension of D40xL200 and hardness of 60-62 HRC. The chemical composition of the 90CrSi steel is shown in Table 1.

The experiments utilized CBN inserts (CCGW09T308S01020FWH7025) manufactured by Sandvik, along with an NOGA MQL nozzle. For the preparation of nanofluid, aluminum oxide (Al_2O_3) nanoparticles with purity of 99.5%+ and the grain size of 30 nm were added to the vegetable-based cutting oil (rice oil) in different concentrations of 0.5%, 1.0%, and 1.5%. Surface roughness measurements were taken three times after each cutting trial using Mitutoyo SJ210 Portable Surface Roughness Tester (Japan), and the average values were recorded. Kistler 9257BA dynamometer (Germany) with A/D data collection and Dasylab 10.0 software was employed to directly measure the three components of cutting forces (F_x, F_y, F_z). F_x is the feed force, F_y is the thrust force, and F_z is the tangential force. The total cutting force F_r was then determined using the equation (1) below.

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

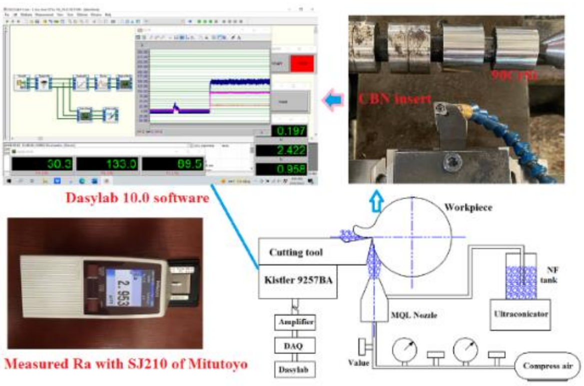


Figure 1. *Diagram of the experimental set-up*

In this study, based on the manufacturer's recommendations and the previous publication [30], the cutting parameters were fixed at V_c=160m/min; f = 0.12 mm/rev.; a_p = 0.12mm. The input variables including nanoparticle concentration (NC), air pressure (p), and air flow rate (Q) were investigated in terms of the total cutting force and surface roughness. The symbols and value levels of the surveyed variables are shown in Table 2.

The Box-Behnken method was used to build an experimental planning diagram for the influence of nanoparticle concentration (NC), air pressure (p) and air flow rate (Q) on surface roughness and the total cutting force (Table 3). The cutting experiments were conducted by following RunOrder.

Table 1. *Chemical composition in wt% of 90CrSi steel.*

C	Si	Mn	Ni	S	P	Cr	Mo	W	V	Ti	Cu
0.85–0.95	1.20–1.60	0.30–0.60	Max 0.40	Max 0.03	Max 0.03	0.95–1.25	Max 0.20	Max 0.20	Max 0.15	Max 0.03	Max 0.3

Table 2. *Surveyed parameters and their levels.*

No.	Parameters	Symbols	Low	High
1	Nanoparticle concentration (%)	NC	0.5	1.5
2	Air pressure (Bar)	p	4	6
3	Air flow rate (L/min)	Q	150	250

Table 3. *Experimental matrix and measured results.*

Std. Order	Run Order	PtType	NC (%)	p (Bar)	Q (L/min)	F_x (N)	F_y (N)	F_z (N)	F_r (N)	R_a (µm)
7	1	2	0.5	5	250	28.7	157.0	100.5	188.6	0.306
13	2	0	1	5	200	27.5	105.6	92.5	143.1	0.303
4	3	2	1.5	6	200	29.6	171.0	110.4	205.7	0.390
15	4	0	1	5	200	23.8	145.9	94.8	175.6	0.295
5	5	2	0.5	5	150	28.9	109.9	92.2	146.3	0.317
10	6	2	1	6	150	30.1	118.9	98.5	157.3	0.375
8	7	2	1.5	5	250	26.3	248.0	116.6	275.3	0.365
14	8	0	1	5	200	25.7	262.0	122.0	290.1	0.301

Std. Order	Run Order	PtType	NC (%)	p (Bar)	Q (L/min)	F_x (N)	F_y (N)	F_z (N)	F_r (N)	R_a (µm)
1	9	2	0.5	4	200	19.4	135.4	115.8	179.2	0.313
9	10	2	1	4	150	28.1	236.8	121.8	267.7	0.302
11	11	2	1	4	250	30.3	266.8	130.5	298.5	0.305
3	12	2	0.5	6	200	12.1	213.3	111.0	240.7	0.315
6	13	2	1.5	5	150	30.6	230.6	134.7	268.8	0.313
2	14	2	1.5	4	200	27.4	280.8	148.9	319.0	0.353
12	15	2	1	6	250	26.4	188.0	113.1	221.0	0.328

3. RESULTS AND DISCUSSION

3.1. Effects of Investigated Parameters of Nanofluid MQL Method on Surface Roughness

ANOVA analysis with a significance level of 0.05 was carried out for surface roughness. The results are shown in Figure 2. The analysis indicates that the regression model is appropriate, with the p-value less than 0.05 and a coefficient of determination (R^2) of 85.77%. The empirical regression function for surface roughness (R_a) is given in Equation 2.

$$R_a\ (\mu m) = 0.866 - 0.332*NC - 0.176*p - 0.00023*Q + 0.0817*NC*NC + 0.02254*p*p + 0.000002*Q*Q + 0.0173*NC*p + 0.000625*NC*Q - 0.000250*p*Q \quad (2)$$

The residual plots for surface roughness in Figure 2 provide further insights into the regression model. The Normal Probability Plot compares the distribution of the residual values (represented by the data points) against the normal distribution (represented by the straight line). The close alignment of the residual values in the Normal Probability Plot compares the distribution of the residual values (represented by the data points) against the normal distribution (represented by the straight line). The close alignment of the residual values with the normal distribution line indicates that the residuals follow a normal probability distribution. The histogram graph depicts the frequency distribution of the residual values, which are centered. The Versus Fits graph illustrates the relationship between the residuals and their corresponding predicted values from the regression model. The random scatter of points around the zero line suggests that the residuals have a constant variance, satisfying the assumption of homoscedasticity.

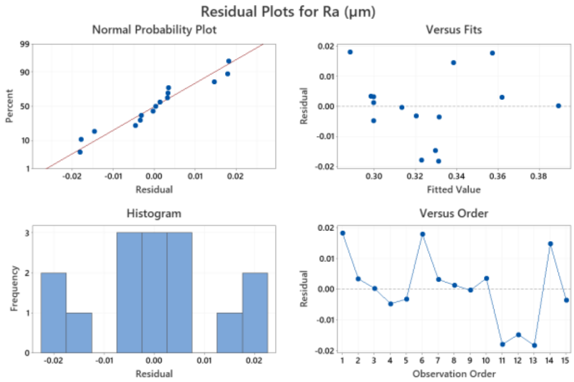


Figure 2. *The residual plots for surface roughness.*

The influences of NF-MQL parameters on the surface roughness in hard turning of 90CrSi steel are depicted in Figure 3. The results show that nanoparticle concentration has the strongest influence, followed by air pressure, and finally air flow rate. When the nanoparticle concentration ranges from 0.5% to 1.0%, the surface roughness reaches its minimum value. However, as Al_2O_3 nanoparticle concentration continues to increase beyond this range, the surface roughness increases rapidly. Hence, the concentration of Al_2O_3 nanoparticles from 0.5% to 1.0% is appropriate [28], because they have the spherical structure, acting as rollers to help reduce friction in the cutting zone and improve surface quality. However, when NC increases to 1.5%, Al_2O_3 nanoparticles in the base oil tend to cluster and prevent the chip formation, and they also scratch the machined surface, making the surface roughness values increase [24].

The results in Figure 3b indicate that air pressure significantly impacts surface roughness. The lowest surface roughness is achieved when air pressure is within 4-5 bar. But it rises rapidly with the growing air pressure from 5 to 6 bar. This may be due to the proper air pressure to form oil droplets containing nanoparticles that are effectively delivered into the cutting area, thereby improving surface roughness. Conversely, higher air pressure might push nano oil droplets out of the cutting area, so the lubricating performance is reduced, and surface roughness R_a values grow [16]. Figure 3c shows that air flow rate (Q) has an insignificant effect on R_a.

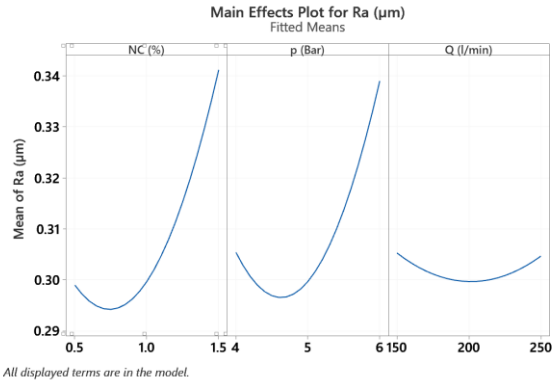


Figure 3. *Influences of survey variables on the average values of surface roughness R_a.*

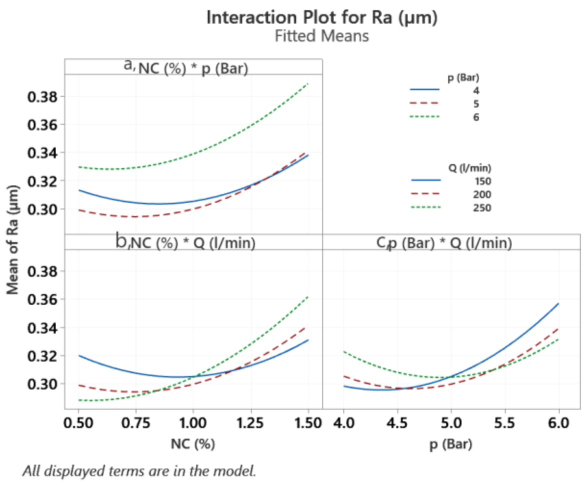
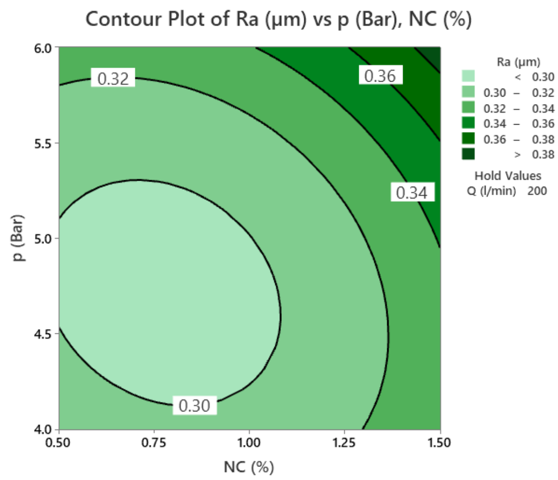


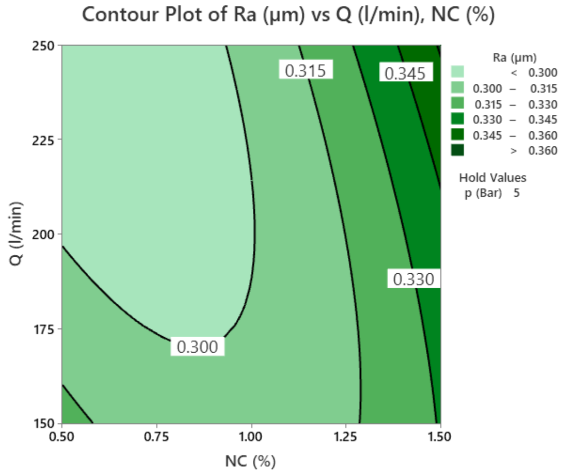
Figure 4. *Interaction effects of Al_2O_3 NF-MQL factors on the mean values of surface roughness R_a.*

Figure 4 illustrates the interaction effects of Al_2O_3 NF-MQL parameters on surface roughness in hard turning. In Figure 4a, the surface roughness reaches the minimum value at air pressure of 5 bar and nanoparticle concentration in the range of 0.5-1.0%. In Figure 4b, the interaction effect between nanoparticle concentration (NC) and air flow rate (Q) has a significant influence on surface roughness. The smallest surface roughness is achieved when using a high level of air flow rate combined with low nanoparticle concentration. In contrast, the interaction between air pressure (p) and air flow rate (Q), as depicted in Figure 4c, has relatively little impact on surface roughness.

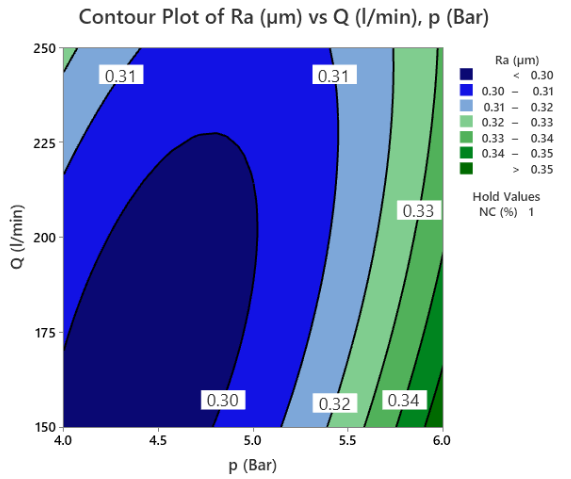
The interaction influences of the input parameters on surface roughness are illustrated in Figure 5. The contour plots provide valuable guides for technologists to select the appropriate NF-MQL input parameters to achieve desired surface roughness requirements. For instance, as shown in Figure 5c, for NC = 1.0%, the air pressure of less than 5 bar and air flow rate of less than 225 L/min should be used to attain surface roughness values $R_a < 0.3$ µm.



(a) *Effects of air pressure and nanoparticle concentration on R_a for Q=200 l/min*



***(b)** Effects of air flow rate and nanoparticle concentration on R_a for p = 5 bar*



***(c)** Effects of air flow rate and air pressure on R_a for NC=1.0%*

***Figure 5.** Contour plots of effects of surveyed variables on surface roughness.*

3.2. Effects of Al_2O_3 NF-MQL Parameters on the Total Cutting Force

Analysis of Variance with a significance level of 0.05 was conducted for the total cutting force F_r (Figure 6). The ANOVA analysis indicated that the experimental model was suitable, as the p-value was less than 0.05, and the coefficient of determination R^2 = 67.42%. This suggested that the model can explain 67.42% of the variability in the total cutting force F_r. The experimental regression function of the total cutting force F_r is given in Equation 3.

$$F_r\ (N) = 646 + 520*NC - 223*p - 1.45*Q + 34*NC*NC + 24.8*p*p + 0.0034*Q*Q - 87.4*NC*p - 0.36*NC*Q + 0.165*p*Q \quad (3)$$

The Versus Order chart (Figure 6) demonstrates the relationship between the residuals and the order of the data points. The random distribution of these points around the zero line confirms that the output F_r is not affected by the time factor. The Histogram chart in Figure 6 shows that the frequency of the residual values is concentrated around the center of the distribution, which aligns with the expected normal distribution pattern. Collectively, these diagnostic plots validate the appropriateness of the experimental model and the lack of systematic biases in the data for the total cutting force F_r.

The influence of NF-MQL technological factors on the average values of total cutting force F_r. For increasing the nanoparticle concentration from 0.5 to 1.5%, the total cutting force gradually increases. Meanwhile, F_r gradually decreases if the air pressure rises. The results also show that air flow rate Q causes little effect on the total cutting force F_r.

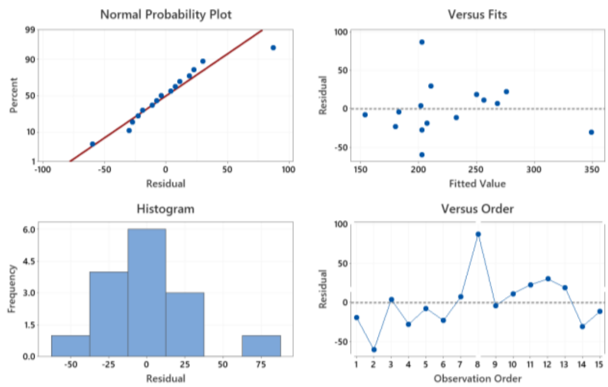


***Figure 6.** Residual plots for the total cutting force F_r.*

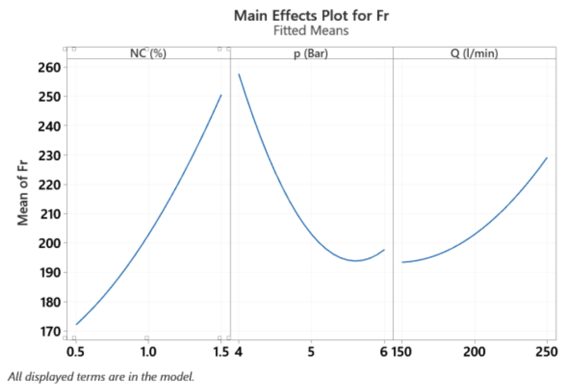


Figure 7. *Main effects of investigated parameters on total cutting force.*

Figure 8 illustrates the interaction effects between the investigated factors on the total cutting force F_r. At the low air pressure of 4 bar, the cutting force rapidly increases with the increase in nanoparticle concentration. At the medium level p= 5 bar, the total cutting force still increases with higher nanoparticle concentration, but with lower rate. Conversely, at p= 6 bar, the increase in nanoparticle concentration has minimal impact on F_r. The interactions between NC and Q, as well as p and Q, have negligible effects on F_r.

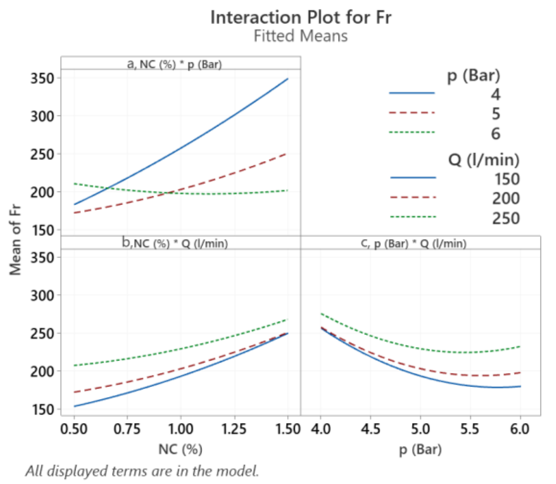
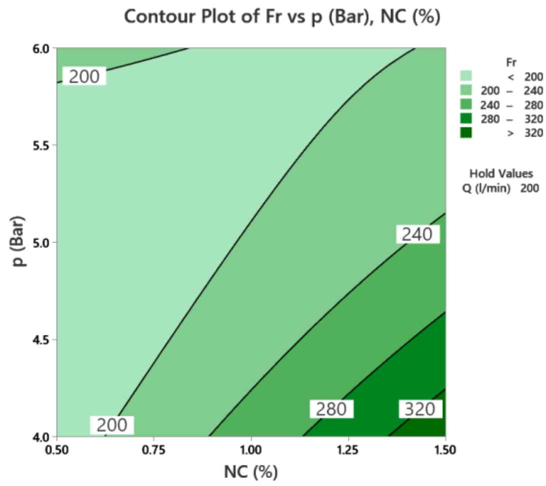


Figure 8. *Interaction plot of effects of input variables on the total cutting force F_r.*

Figure 9 demonstrates the interaction effects of NF-MQL parameters on F_r. For Q=200 L/min, F_r is minimal with the low nanoparticle concentrations. As the nanoparticle concentration increases, the total cutting force remains low with the growing air pressure.For p= 5 bar, the cutting force is minimized when both the nanoparticle concentration and airflow rate are reduced (Figure 9b). For NC equal to 1.0%, the total cutting force decreases with the reduction of p and Q (Figure 9c).

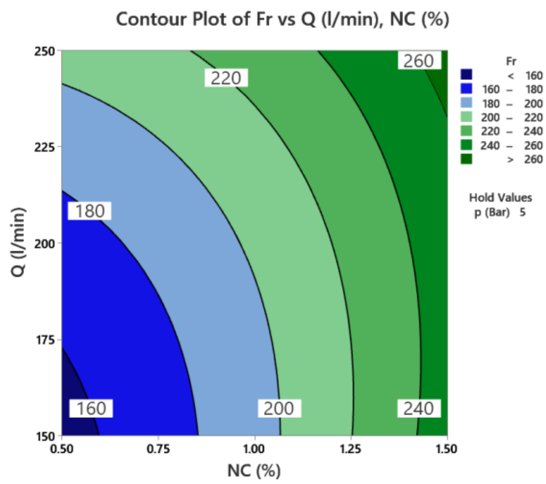
3.3. Optimization for Surface Roughness and Total Cutting Force

If the primary concern is the quality of the machined surface in finishing process, the

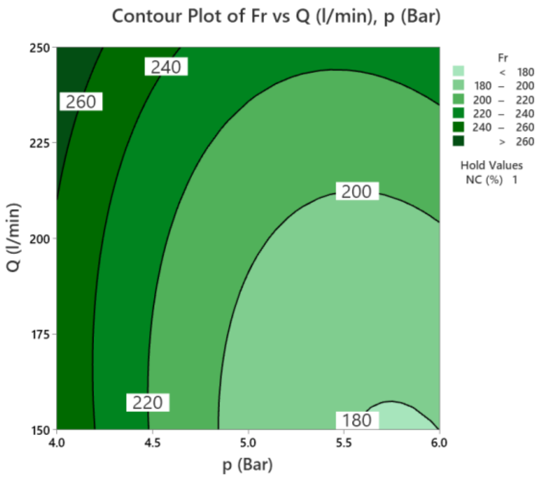


(a) *Effects of air pressure and nanoparticle concentration on F_r for Q=200 L/min*

single-objective optimization with the objective function R_a will be used. The minimum surface roughness R_a = 0.288µm could be achieved with the parameter set NC = 0.54%, p = 5.1 bar, and Q = 250 L/min (Figure 10). In order to reach the smallest total cutting force F_r =153.36N, the optimal set of parameters is NC = 0.5%, p = 4.9 bar, and Q = 150 L/min (Figure 11). For the smallest value of both surface roughness R_a and total cutting force F_r, the multi-objective optimization with the objective functions R_a and F_r was done and the result is shown in Figure 12. The optimal set of parameters NC = 0.53%, p = 4.79 bar and Q = 193.4 L/min is recommended to achieve the minimal Fr = 169.16 N and R_a= 0.2987 µm.



(b) *Effects of air flow rate and nanoparticle concentration on F_r for p=5 bar*



***(c)** Effects of air flow rate and air pressure on F_r for NC=1.0%*

***Figure 9.** Contour plots of effects of input variables on the total cutting force F_r.*

4. CONCLUSION

In this work, the machining performance of hard turning process of 90CrSi steel using CBN inserts under Al_2O_3 NF-MQL was analyzed using the Box–Behnken experimental model. The effects of nanoparticle concentration, air pressure, and air flow rate on surface roughness and total cutting force were investigated. The main contributions are summarized as follows:

- The results of ANOVA analysis show that a second-order model is suitable for analyzing and predicting the values of surface roughness and total cutting force. The regression models for surface roughness and total cutting force have been determined.
- The influences of surveyed factors and their interactions on surface roughness and total cutting force F_r were studied. The nanoparticle concentration (NC), air pressure (p) and the interactions NC*p, NC*Q have a strong influence on surface roughness. Meanwhile, the air pressure and the interactions NC*p have great impacts on the total cutting force. From the obtained results, it is possible to select the reasonable value ranges for the investigated parameters to achieve the smaller R_a or F_r.
- The optimal set of parameters including Al_2O_3 nanoparticle concentration of 0.54%, air pressure of 5.1 bar, and air flow rate of 250 L/min will bring out the minimal surface roughness R_a = 0.288 µm. The smallest value F_r =153.36 N could be achieved by using NC=0.5%, p=4.9 bar, and Q=150 L/min. Furthermore, based on the multi-objective optimization, the optimal set NC = 0.53%, p=4.79 bar and Q=193.4 L/min should be used to obtain the smallest R_a or F_r values (R_a= 0.2987 µm and F_r=169.16 N).

In further work, more investigations should be focused on surface microstructure, tool life and tool wear in Al_2O_3 NF-MQL hard turning.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

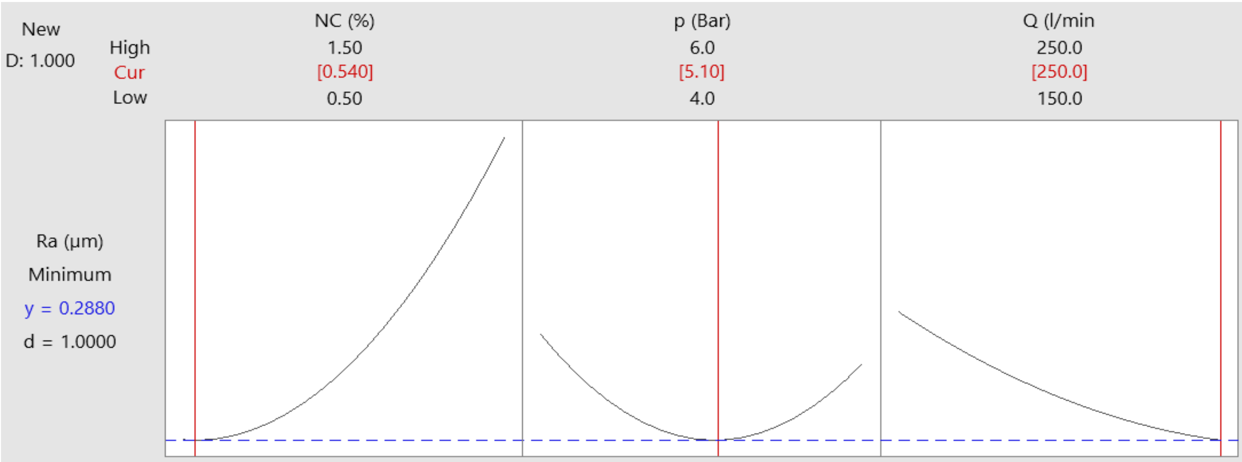

Figure 10. *Optimization for* R_a

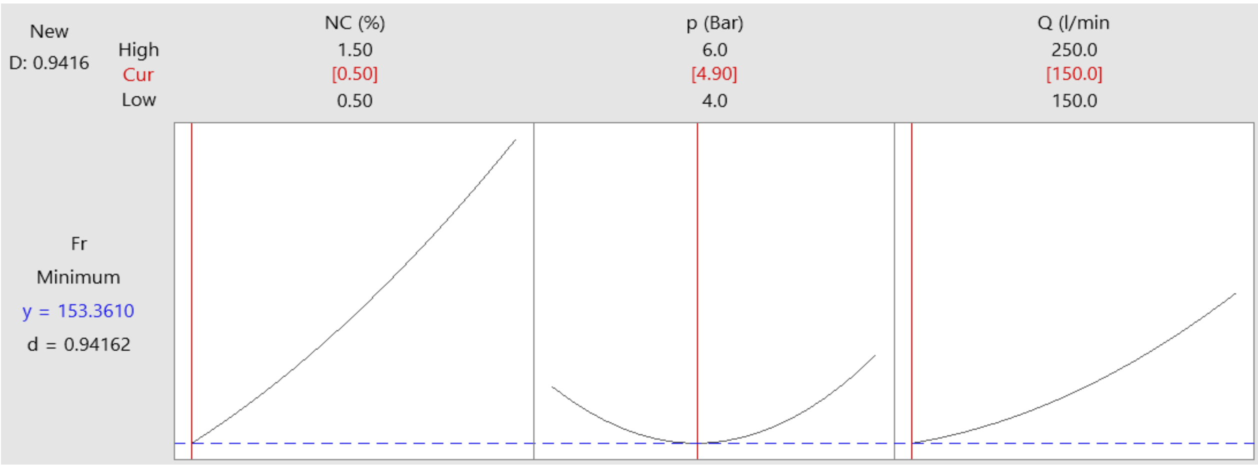

Figure 11. *Optimization for* F_r

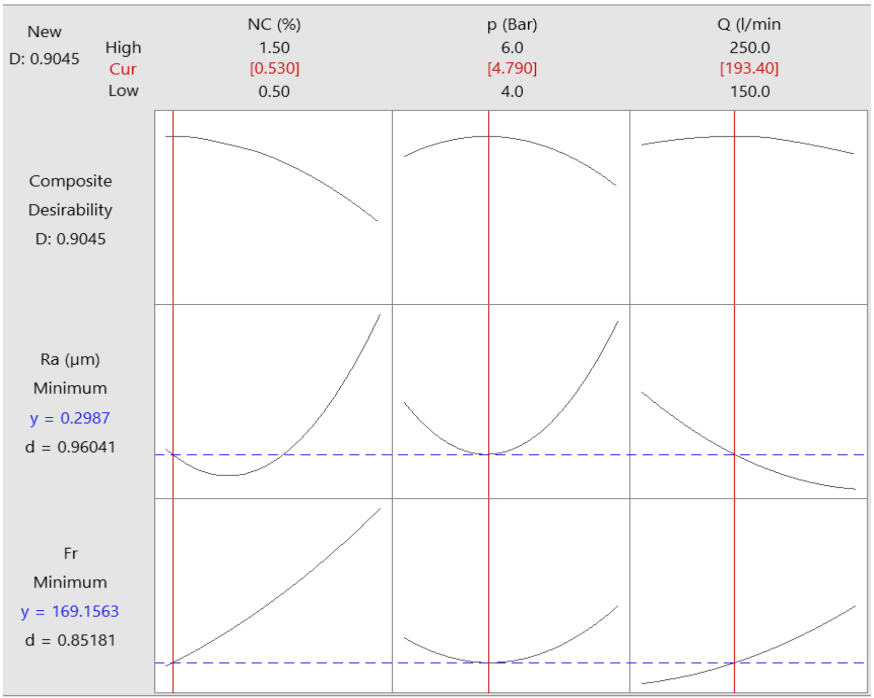

Figure 12. *Multi-objective optimization for* R_a *and* F_r.

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