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Performance Investigation of MQL Parameters Using Nano Cutting Fluids in Hard Milling

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Abstract: Machining difficult-to-cut materials is one of the increasingly concerned issues in the metalworking industry. Low machinability and high cutting temperature generated from the contact zone are the main obstacles that need to be solved in order to improve economic and technical efficiency but still have to ensure environmental friendliness. The application of MQL method using nano cutting fluid is one of the suggested solutions to improve the cooling and lubricating performance of pure-MQL for machining difficult-to-cut materials. The main objective of this paper is to investigate the effects of nanofluid MQL (NFMQL) parameters including the fluid type, type of nanoparticles, air pressure and air flow rate on cutting forces and surface roughness in hard milling of $60Si_2Mn$ hardened steel (50–52 HRC). Analysis of variance (ANOVA) was implemented to study the effects of investigated variables on hard machining performance. The most outstanding finding is that the main effects of the input variables and their interaction are deeply investigated to prove the better machinability and the superior cooling lubrication performance when machining under NFMQL condition. The experimental results indicate that the uses of smaller air pressure and higher air flow rate decrease the cutting forces and improve the surface quality. Al_2O_3 nanoparticles show the better results than MoS_2 nanosheets. The applicability of soybean oil, a type of vegetable oil, is proven to be enlarged in hard milling by suspending nanoparticles, suitable for further studies in the field of sustainable manufacturing.

Keywords: hard milling; hard machining; MQL; nanoparticles; nanofluid; nano cutting fluid; difficult-to-cut material; air pressure; air flow rate

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1. Introduction

In recent years, the effects of climate change not only span the physical environment, ecosystems and human societies but also include the economic and social changes. Human-caused climate change is one of the threats to sustainability. In metal cutting industry, environmentally friendly machining is a topic of increasing interest in the world. The reduction of cutting fluids is considered the most effective solution to minimize negative impacts on the environment and human health. Research has shown that up to 85% of cutting fluids in use are derived from mineral oil [1], so the discharge into the environment without going through recycling will destroy the environment. On the other hand, the very expensive treatment for the used oil puts the more pressure on the manufacturing expenses.

Therefore, reducing the use of these oil types and replacing them with biodegradable oils, such as vegetable oils, are potential approaches that have gained the growing concerns of the researchers all around the world. Along with this trend, the cooling and lubricating technology is also an important issue, in which the cutting fluids deeply delivered into the cutting zone combined with the use of small oil flow rate will bring about not only technical efficiency but also economic benefits. In particular, MQL is a technology that was born as a matter of course. This technology uses the nozzles combined with high-pressure air flow and directly spray the cutting fluid into the cutting zone with very small oil flow rate (5–500 mL/h) [2], which brings out very high lubrication efficiency. On the other hand, the very small amount of used cutting fluids makes MQL technique suitable for environmental friendliness.

For the last four decades, there have been a lot of studies on MQL technology used in machining. Most authors claimed that the cutting performance and surface quality under MQL condition were better than those under dry and flood condition. In order to successfully apply MQL, its parameters should be used with the appropriate values. MQL parameters such as: type of cutting fluids, oil flow rate, air pressure, air flow rate, nozzle position, spray angle, number of nozzles, etc. have been studied and reported in many studies. Some commonly used oils are oil-in-water emulsion [3,4], vegetable oil [5], synthetic ether [6] and so forth. Among these cutting fluids, vegetable oils have suitable lubricating properties due to their higher molecular weight than that of mineral oil, which gives vegetable oils outstanding lubricating properties. In addition, these oils are derived from plants, so they are biodegradable, non-toxic to users and non-polluting [7,8]. Therefore, vegetable oils are very suitable for MQL technology because they not only ensure proper cooling lubrication, but also retain environmental-friendly properties, suitable for modern machining industry nowadays. Therefore, this research direction attracts a lot of attention from researchers and manufacturers as well [1–3,9,10].

Among those, the air pressure plays a very important role in MQL, and it has a great influence on the machining process. If the applied air pressure is too low, the penetration of coolant to contact zone is limited, resulting in low cooling lubricating efficiency. In addition, the generated chip will not be ejected from the machining area, adversely affecting surface quality and tool life. On the other hand, if the applied air pressure is too high, the chip will be pushed out of the cutting zone smoothly and deeply brought the cutting oil into the cutting zone, but not in time to form the oil film, it will be blown out of the cutting zone. Hence, the lubricating effect is limited. This raises the problem of choosing the appropriate air pressure value and optimizing this parameter for each specific cutting condition. The initial research results are presented in [11].

The very detailed study of MQL parameters such as spray angle, flow rate, air pressure and nozzle position is reported in [12]. The study results showed the relationship between injection pressure, nozzle position and size and distribution of droplets. The oil film formation acts as a hydrodynamic lubrication layer between the contact faces including the rake face and chip, flank face and machined surface. This is one of the very special features of MQL technology in metal cutting. The results indicated that the nozzle position was an important factor related to the efficiency of the formation of oil film. In addition, there is also a relationship between the movement of droplets to the cutting zone and the flow rate [13]. Recently, there have been initial studies on the number of nozzles in MQL technology to improve cooling lubrication efficiency [14].

In addition, MQL technology has been initially researched and applied to the machining processes of difficult-to-cut materials and has brought about economic and technical effectiveness. In the study of hard turning of AISI 4340 alloy steel (54–57 HRC) using coated carbide tools with MQL technology [15], the results showed that the lubrication efficiency in cutting zone was improved. thereby reducing cutting heat and tool wear and increasing tool life by 20–25% when compared to dry machining. Another study on hard turning of AISI 1060 steel under MQL condition using vegetable oil [16] has also shown that adhesion wear and crater wear are dominant. Compared to dry condition, MQL machining contributes to reduce tool wear and cutting forces [17,18]. However, the enormous heat generated from hard machining process is still a huge challenge, so the application of MQL is still very limited due to the low cooling efficiency, especially for difficult-to-cut materials such as hardened steel, Ni alloy, Ti alloy and so forth [19]. Hence, the selection of the cutting tools and cooling lubrication condition plays the crucial roles.

In recent years, there have been a number of solutions to overcome the low cooling capacity, which is the main disadvantage of MQL technology. There have been some approaches to overcome this problem. O. Pereira et al. [20] combined CO_2 cryo-genic with

MQL (CryoMQL) used for milling process of Inconel 718. The author pointed out that the cooling efficiency was much improved by using CO_2 cryo-genic, which contributed to reduce cutting forces and prolong the tool life compared with MQL alone. The external and internal CO_2 cryogenic cooling were also studied and compared in term of tool life. The experimental results indicated that the thickness of the deformed layer and sub-surface microhardness under CryoMQL technique was much smaller than that under dry condition. They proved the superior cooling and lubricating effects of CryoMQL technique [21–24]. In addition, minimum quantity cooling lubrication (MQCL) has been considered the new solution and was also investigated and applied for hard machining processes. Pervaiz et al. [24] studied the turning process of Ti6Al4V alloy under MQCL condition. The results indicated the better cooling and lubricating effects when compared to dry and flood cutting. Maruda et al. [25,26] investigated the MQCL parameters used for hard turning of AISI 1045 steel. The formation of emulsion oil mist contributed to improve the cooling and lubricating performance, which reduces the friction and tool wear. However, the cooling effect of MQCL in these studies is based on the cooling property of oil-in-water emulsion.

Recently, the application of nano cutting fluids as the based fluids for MQL hard machining has been considered a promising solution and gained much attention of the researchers. Nano cutting fluids are formed by suspending nanoparticles such as: Al_2O_3, SiO_2, MoS_2, TiO_2, CuO, etc. into the based fluids at the reasonable ratio. The presence of nanoparticles has improved the lubricating and cooling performance of the base oils. Hence, the reduction of cutting forces, tool wear and the improvement of tool life and surface quality were reported in [27–29]. A. Das et al. [30] studied on emulsion water-based oil with/without Al_2O_3 nanoparticles used for MQL technology applied to hard turning of AISI 4340 alloy steel. The study also investigated the machining process under air cooling condition. The obtained results revealed that the cutting forces under MQL condition using nanofluid were smallest, followed by air cooling and then MQL with emulsion without Al_2O_3 nanoparticles. In addition, the stability of cutting forces under Al_2O_3 nano cutting fluid can be clearly observed to demonstrate the improvement of lubricating and cooling performance of Al_2O_3 nanofluid. M.K. Gupta et al. [31] optimized the cutting condition of turning process of titanium alloy with MQL technology using nanofluid. The authors investigated three types of nanofluids including Al_2O_3, MoS_2 and Graphite. The results show that the use of nanofluids improves the lubrication and cooling effects, thereby enhancing the machining performance. Among the three types of nanoparticles, the graphite nanofluid shows the highest lubricating effect, thereby reducing cutting temperature and cutting forces, and improving surface quality. P. Sharma et al. [32] studied on the effect of carbon nanotubes (CNTs) nanoparticles on hard turning of AISI D2 steel under MQL condition, and they also found that the effectiveness in reducing cutting temperature due to the improved thermal conductivity of CNTs nanofluid when compared with the based fluid without nanoparticles. From there, the surface quality also improved and tool wear reduced. V. Vasu et al. [33] applied the vegetable oil with Al_2O_3 nanoparticles as the base fluid for MQL used for turning process of Inconel 600 alloy, a difficult-to-cut material. Experimental results revealed that cutting temperature, surface roughness, tool wear and cutting forces were significantly reduced. Using nano cutting fluids shows the outstanding efficiency in lubrication and cooling in the cutting zone when compared with dry turning. Compared with MQL using the based fluid without nanoparticles, it can be clearly seen that the lubrication ability and especially the cooling ability have been improved by using Al_2O_3 nanofluid. Moreover, increasing the concentration of Al_2O_3 nanoparticles from 4% to 6% helped improve the lubrication and cooling. H. Hegab et al. [34] investigated the effects of nano cutting fluids on tool life, tool wear and chip morphology in turning of Inconel 718. Two types of nanoparticles including Al_2O_3 and carbon nanotubes (CNTs) were studied in order to improve the machinability of Inconel 718. The results indicated that the better cutting performance and lower deformed chip thickness were reported in case of using nanofluids when compared to the case without nano additives. The main reason is the increase in the shear angle and effective heat dissipation. The authors also made the research on the nanoparticle concentration of CNTs nanofluid in term of surface quality [35]. The improvement of surface quality was observed. For the other machining processes such as grinding and drilling under MQL condition using nano cutting fluids, the better machining performance has been reported [27–29,36–41]. The suspension of nanoparticles in vegetable oil has improved the lubricating and cooling ability of the base oil, thereby expanding its application in machining processes, especially for difficult-to-cut materials. This is a promising and environmentally friendly research direction, suitable for sustainable production, so many studies have been focused on in order to bring the novel technology into practice. A. Gupta et al. [42] compared the performance of pure vegetable oil and Al_2O_3 vegetable oil-based nanofluid in turning of AISI 4130 for sustainable manufacturing. The author found that the turning performance under Al_2O_3 nanofluid was better and the surface quality improved about 27.3% when compared to pure vegetable oil. G. Gaurav et al. [43] newly made the study on jojoba oil, a new type of vegetable oil applied to MQL, in hard turning of Ti-6Al-4V using MoS_2 nanosheets. They compared the results with the commercially mineral oil (LRT 30) and investigated the five different turning environments. The improvement in machining performance was observed because jojoba oil has long chain fatty acidic structure, excellent thermal oxidative stability and high viscosity combined with lamellar structure of MoS_2 nanosheets. The authors pointed out that the significant reduction in cutting forces, surface roughness and tool wear was reported about 35–37% under MQL using jojoba oil with MoS_2 nanosheets. Moreover, the commercially mineral oil (LRT 30) could be completely replaced by vegetable oil in order to retain the environmental friendliness. A. Pal et al. [44] used nano-graphene enhanced vegetable oil-based cutting fluid for MQL drilling of AISI 321 stainless steel. The authors found that the formation of thin layer (tribo film) of nano graphene contributed to reduce the friction, tool wear, thrust force and torque. The sufficient amount of nanoparticles in sunflower oil can enhance the formation of thin protective tribo film and increase the coefficient of heat transfer. In addition, nano-graphene enhanced vegetable oil-based cutting fluid can replace the conventional mineral oil for MQL system. These authors also studied Al_2O_3 vegetable oil-based nanofluid and found the similar observation for the reduction in thrust force, torque, surface roughness and drilling temperature when compared to flood condition. Moreover, the tool wear significantly decreased [45]. The main reason is that Al_2O_3 sunflower oil-based nanofluid showed the higher cooling and lubricating effects due to the characteristics of Al_2O_3 nanoparticles. These findings fulfill the cleaner manufacturing demands [46,47].

In MQL technique, two parameters consisting of air pressure and air flow rate are very important, and they directly affect the lubrication efficiency in the cutting zone. Moreover, the choice of the types of based fluid type and nanoparticles are two key parameters, which strongly influence the effectiveness of using nanofluids as the based fluids for MQL to improve cooling and lubricating capabilities. However, from the literature review, it can be seen that the studies on these parameters are still very limited, especially for MQL hard milling. Therefore, the authors are motived to study and evaluate the general effects of fluid type, nanoparticle type, air pressure and air flow rate on the machining performance of MQL hard milling process of $60Si_2Mn$ hardened steel. From the obtained results, the technical guides will be provided for further research on the selection and optimization for MQL parameters.

2. Material and Method

Experimental Set Up

The experimental set up for hard milling process is shown in Figure 1 and was conducted on Maximart VMC 85S milling center (Tan Tsu Dist., Taichung City, Taiwan). The workpiece samples are $60Si_2Mn$ hardened steels (50–52 HRC) with the size of 150 mm × 100 mm × 15 mm. The designation of cutting tools is Lamina APMT 1604 PDTR LT30 PVD submicron carbide insert (made in Switzerland). Kistler quartz three-component dynamometer (9257BA) was used for directly measuring cutting forces. SJ-210 Mitutoyo, Japan was used for surface roughness with cut-off length of 0.08 mm. The A/D DQA N16210 (National Instruments, Austin, TX, USA) and DASYlab 10.0 software were used for data acquisition. The MQL system is NOGA MiniCool MC1700. Pressure regulator and air flow control valve were used for controlling the flowrate and air pressure. The two different cutting fluids including oil-in-water emulsion (called emulsion) and soybean oil were used for MQL system [27,38]. Al_2O_3 and MoS_2 nanoparticles made by Soochow Hengqiu Graphene Technology Co., Ltd. (Suzhou, China) and Luoyang Tongrun Info Technology Co., Ltd. (Luoyang, China) with the size of 30 nm (average), respectively, were suspended in emulsion and soybean oil to form nano cutting fluids. Ultrasons-HD ultrasonicator (JP SELECTA, Abrera, Spain) generating 600W ultrasonic pulses at 40 kHz was used for 30 min and the obtained Al_2O_3 and MoS_2 nano cutting fluids were directly used for MQL system.

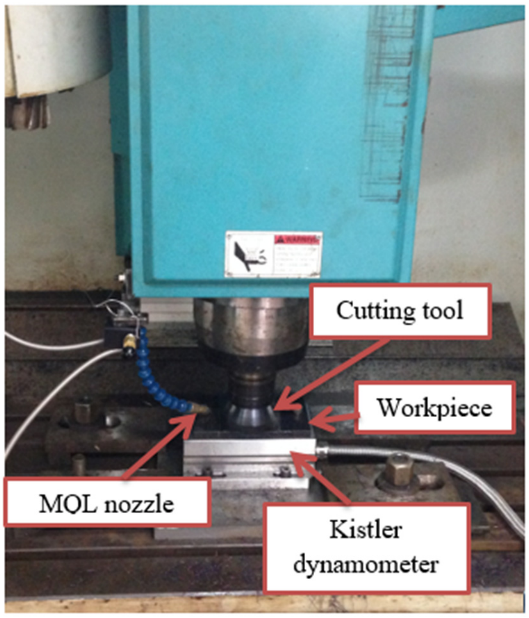

Figure 1. Experimental set up.

The experiment is carried out according to the factorial design 2^{k-p} with four variables (k = 4) with the help of Minitab 18 software. The factorial design $N = 2_{IV}^{k-p}$ is chosen, and N = 2^{4-1} = 8. The input machining parameters and their types or levels are given by Table 1, which are based on the other studies [20,38]. A total number of 24 trials are employed and are performed independently in triplicates. Each experimental trial is repeated by 3 times under the same cutting parameters, and the average values are taken. The cutting condition was fixed at cutting speed of 110 m/min, feed rate of 0.12 mm/tooth, cutting depth of 0.2 mm [38,48]. The Al_2O_3 and MoS_2 nanoparticle nano concentration was fixed at 1.0 wt% [45,48,49].

Table 1. Input machining parameters and their types/levels.

Input Machining Parameters	Unit	Symbol	Type/Level	
Fluid type		*FT*	Emulsion	Soybean
Nanoparticle		*NP*	Al_2O_3	MoS_2
Air pressure	MPa	*P*	5	7
Air flow rate	l/min	*Q*	100	200

3. Results and Discussion

The experiments are carried out by following the design. The measured values of cutting forces F_x, F_y, F_z and surface roughness R_a are reported and taken by the average values. Since this work is an overall investigation, the resultant cutting force F_r was used instead of the cutting force components. The resultant cutting force F_r were calculated from the cutting force components in Equation (1), and the experimental data are shown in Table 2.

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

Table 2. The experiment design with test run order and the measured values of surface roughness and cutting force.

Std Order	Run Order	PtType	Blocks	Input Machining Variables				Response Variables	
				FT	*NP*	*P* (MPa)	*Q* (l/min)	R_a (μm)	F_r (N)
1	24	1	1	Emulsion	MoS_2	5	100	0.143	421.58
2	13	1	1	Soybean	MoS_2	5	200	0.075	331.70
3	6	1	1	Emulsion	Al_2O_3	5	200	0.069	205.20
4	10	1	1	Soybean	Al_2O_3	5	100	0.126	311.93
5	7	1	1	Emulsion	MoS_2	7	200	0.136	398.11
6	12	1	1	Soybean	MoS_2	7	100	0.132	281.96
7	20	1	1	Emulsion	Al_2O_3	7	100	0.116	489.07
8	14	1	1	Soybean	Al_2O_3	7	200	0.115	407.32
9	8	1	1	Emulsion	MoS_2	5	100	0.135	385.12
10	23	1	1	Soybean	MoS_2	5	200	0.072	356.09
11	15	1	1	Emulsion	Al_2O_3	5	200	0.064	196.16
12	19	1	1	Soybean	Al_2O_3	5	100	0.122	312.55
13	5	1	1	Emulsion	MoS_2	7	200	0.091	361.81
14	16	1	1	Soybean	MoS_2	7	100	0.143	284.58
15	9	1	1	Emulsion	Al_2O_3	7	100	0.126	473.74
16	2	1	1	Soybean	Al_2O_3	7	200	0.106	396.10
17	21	1	1	Emulsion	MoS_2	5	100	0.126	404.88
18	18	1	1	Soybean	MoS_2	5	200	0.072	346.25
19	3	1	1	Emulsion	Al_2O_3	5	200	0.071	175.57
20	17	1	1	Soybean	Al_2O_3	5	100	0.102	304.60
21	1	1	1	Emulsion	MoS_2	7	200	0.096	358.23
22	22	1	1	Soybean	MoS_2	7	100	0.139	305.17
23	4	1	1	Emulsion	Al_2O_3	7	100	0.121	449.93
24	11	1	1	Soybean	Al_2O_3	7	200	0.103	403.74

The ANOVA analysis with 95% confidence level is carried out for surface roughness R_a and resultant cutting force F_r with R^2 equal to 88.00% and 97.69%, respectively. Tables 3 and 4 show the results of ANOVA analysis. The last columns of Tables 3 and 4 show that most of the input variables, have the p-values smaller than the significance level (0.05). It means that the fluid type, nanoparticles, air pressure and air flow rate have the significant influences on the response parameters R_a and F_r. The regression models with coefficient of determination (R^2) equal to 88.00% for R_a and 97.69% for F_r prove that the experimental data fit well with the experimental design model.

Table 3. Results of ANOVA analysis of surface roughness R_a.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value
Model	7	0.014038	0.002005	16.76	0.000
Linear	4	0.011994	0.002999	25.07	0.000
FT	1	0.000007	0.000007	0.06	0.811
NP	1	0.000590	0.000590	4.93	0.041
P	1	0.002542	0.002542	21.25	0.000
Q	1	0.008855	0.008855	74.02	0.000
2-Way Interactions	3	0.002043	0.000681	5.69	0.008
*FT*NP*	1	0.001683	0.001683	14.07	0.002
*FT*P*	1	0.000345	0.000345	2.88	0.109
*FT*Q*	1	0.000015	0.000015	0.13	0.728
Error	16	0.001914	0.000120		
Total	23	0.015952			

Table 4. Results of ANOVA analysis of the cutting force F_r.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value
Model	7	152,436	21,776.6	96.56	0.000
Linear	4	44,346	11,086.5	49.16	0.000
FT	1	3207	3206.9	14.22	0.002
NP	1	500	500.3	2.22	0.156
P	1	30,683	30,682.7	136.05	0.000
Q	1	9956	9956.3	44.15	0.000
2-Way Interactions	3	108,090	36,029.9	159.77	0.000
*FT*NP*	1	13,564	13,563.7	60.14	0.000
*FT*P*	1	16,362	16,362.0	72.55	0.000
*FT*Q*	1	78,164	78,164.0	346.60	0.000
Error	16	3608	225.5		
Total	23	156,044			

From Figures 2 and 3, it can be seen that the Normal Probability Plot compare the probability distribution of residuals shown as points with the normal distribution shown as a straight line. The results in both graphs show that the residuals are distributed very closely around the reference line. According to the normal distribution law, the frequency of residual values which are centered around the center of distribution, but the histogram graph in Figure 3 shows that the frequency of the residual values fairly evenly distributed (possibly according to the rectangular distribution).

The graphs of versus fit and versus order show the relationship of the residuals with their respective values and the order of data points of the regression model. These points are randomly distributed around the 0 line, which proves that the imported R_a and F_r data are not affected by any controlled variable with a rule and the time factor other than the input machining parameters.

Pareto charts (Figures 4 and 5) show that the limit line of the area where the inversion hypothesis is rejected has the horizontal position of 2.12. The input machining parameters exceed the right of the limit line, which indicates that they have the influences on the response factors.

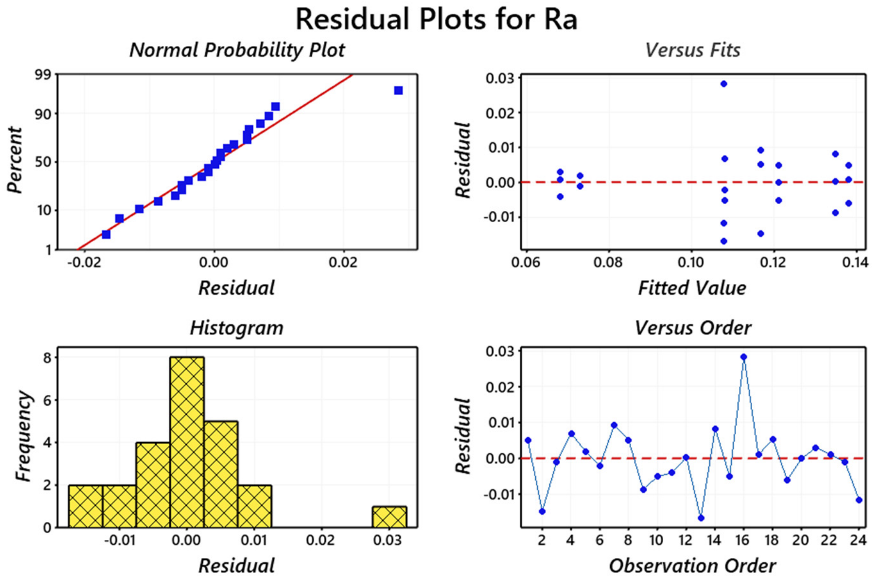

Figure 2. Residual plots of surface roughness R_a.

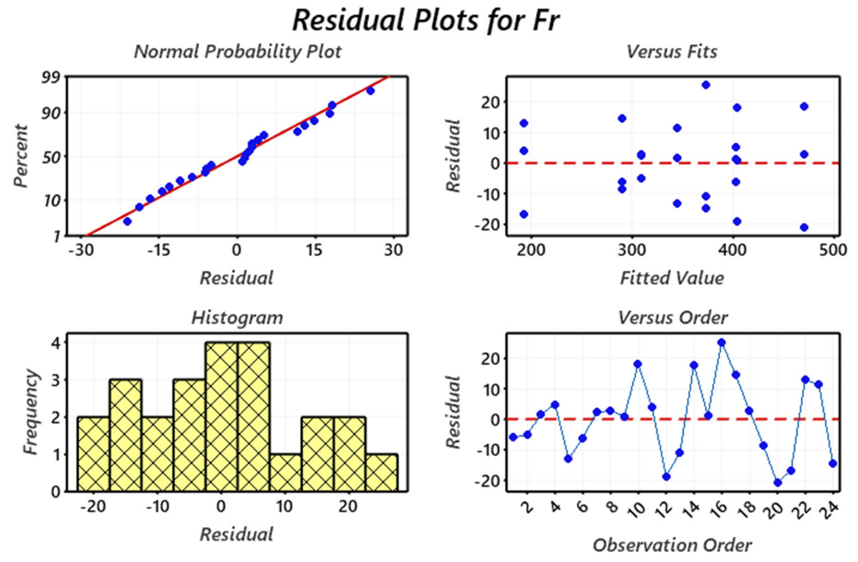

Figure 3. Residual plots of resultant cutting force F_r.

The Pareto chart of the standardized effects with α = 0.05 for the response parameter R_a is shown in Figure 4. The type of nanoparticles, air flow rate and air pressure have strong influences, in which air flow rate causes the strongest effect, followed by air pressure and nanoparticle type. The fluid type has a very little influence. With this result, it can be seen that, to improve surface roughness, the reasonable air flow rate and air pressure should be firstly selected before choosing the type of nanoparticles. The interaction effects between investigated variables have the great influence on the surface roughness value R_a, in which the interaction between fluid type and nanoparticle (AB) is the largest influence, followed by the interaction between fluid type and air pressure (AC) (Figure 4). This result has scientific and practical meanings in that, despite the little effect of fluid type on the surface roughness, its effect is significant when adding nanoparticles. Accordingly, nanoparticles suspended in the cutting oil have a significant effect on the surface roughness values.

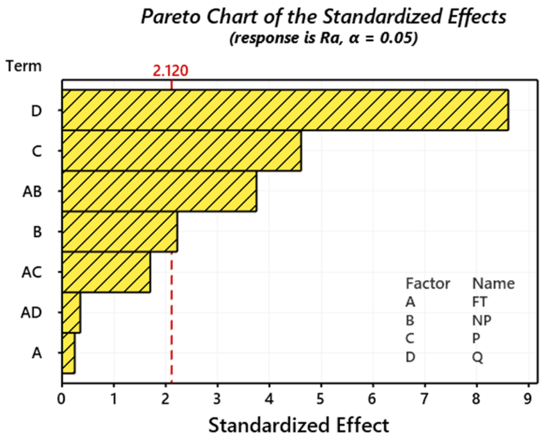

Figure 4. Pareto chart of effects of input machining factors on surface roughness R_a. (A is *FT*: Fluid type, B is *NP*: nanoparticle, C is *P*: air pressure, D is *Q*: air flow rate).

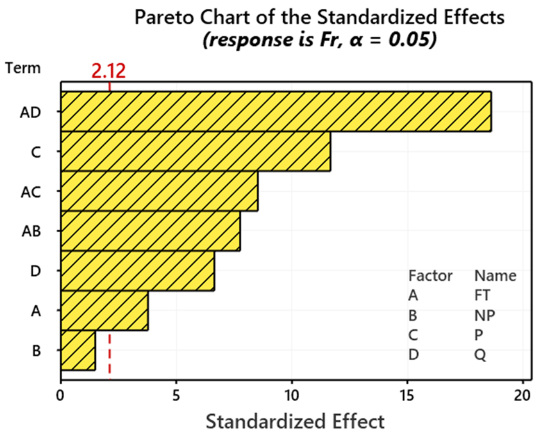

Figure 5. Pareto chart of effects of input machining factors on the resultant cutting force F_r. (A is *FT*: Fluid type, B is *NP*: nanoparticle, C is *P*: air pressure, D is *Q*: air flow rate).

The Pareto chart of the standardized effects with α = 0.05 for the resultant cutting force F_r is shown in Figure 5. The fluid type, air flow rate and air pressure have strong influences, in which air pressure causes the strongest effect, followed by air flow rate and fluid type. The nanoparticle type has a very little influence. All the interaction effects between investigated variables have the great influence on the resultant cutting force F_r, in which the interaction between fluid type and air flow rate (AD) is the largest influence, followed by the interaction between fluid type and air pressure (AC) and then the interaction between fluid type and nanoparticle type (AB) (Figure 5). This result indicates that it is very meaningful to study the appropriate selection of the fluid type, nanoparticle type, air pressure and air flow rate because the effect of air pressure P is related to the oil mist formation, droplet delivery and droplet retention in cutting zone. In addition, the air flow rate affects the amount of cutting fluid and the number of nanoparticles penetrated into contact zone.

The graphs of interaction effects between experimental variables and response variables in Figures 6 and 7 show that only the fluid type interacts with nanoparticles, air pressure P and air flow rate Q. The interaction effects of nanoparticles and air pressure with the other variables are not significant, so they are not shown in Figures 6 and 7.

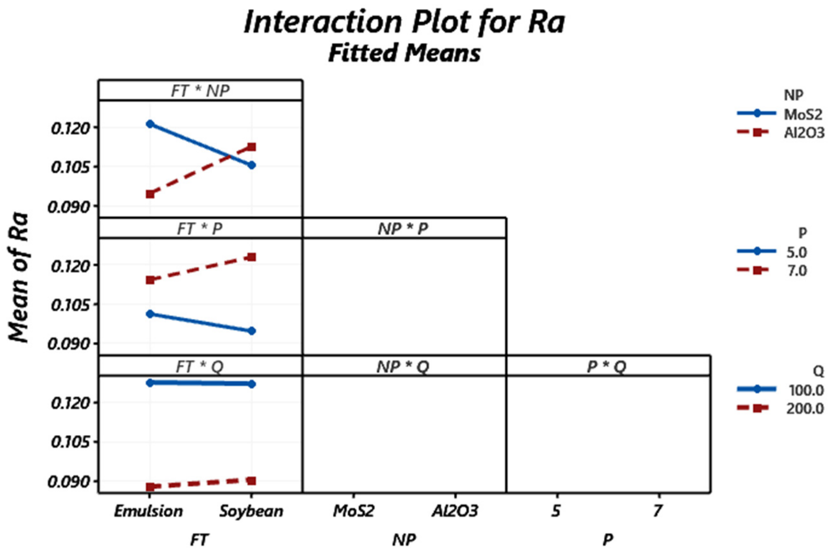

Figure 6. Interaction plot of input machining factors on surface roughness R_a.

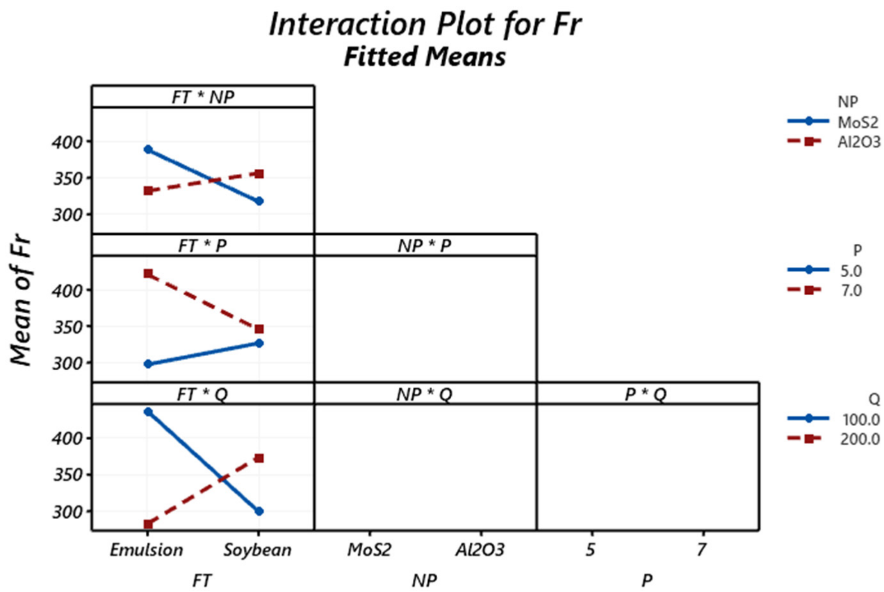

Figure 7. Interaction plot of input machining factors on the resultant cutting force F_r.

The interaction effect between fluid type and nanoparticle (*FT*NP*): when changing the type of nanoparticles from MoS_2 nanoparticle (solid line) to Al_2O_3 nanoparticle (dashed line), the slope and direction of these lines significantly change for R_a (Figure 6) and F_r (Figure 7). This proves that the presence of nanoparticles in the cutting fluids has a great influence on the cooling lubricating properties of the based fluids [2,27]. Hence, the selection of the based cutting oil and nanoparticle type to create nano cutting oil suitable for each specific machining condition will be necessary to improve machining performance.

The interaction effect between fluid type and air pressure (*FT*P*): When changing air pressure from 5 bar (solid line) to 7 bar (dashed line), the slope and direction of the lines change much and also indicate that the influence of the *FT*P* effect is significant. The effect on F_r (Figure 7) is larger than that on R_a (Figure 6), which is also shown in Figures 4 and 5. It can be explained that the formation of droplets and the introduction of the oil mist into the cutting zone depend on many factors, and among of these, the cutting oil viscosity and the air pressure are the two most influential. Hence, two types of cutting oils, including emulsion with low viscosity and soybean oil with higher viscosity, interact with air pressure obviously.

The interaction effect of fluid type with air flow rate (*FT*Q*): When changing the air flow rate from 100 l/min (solid line) to 200 l/min (dashed line), the interaction effect on surface roughness R_a (Figure 6) and the resultant cutting force F_r (Figure 7) reveals the big difference. For the response variable R_a, the solid and dashed lines are almost parallel, which proves that this interaction has a negligible effect on R_a (clearly shown on the Pareto diagram in Figure 4). The main reason here is that, in machining hard materials, the surface roughness R_a depends mainly on the scratches of cutting tool on the machined surface (kinematic cause), and the air flow rate has little influence on the cutting kinematics, so it has little effect on R_a. For the response variable F_r (Figure 7), the dashed and solid lines significantly change not only the direction and but also the slope. It indicates that the interaction *FT*Q* has a great influence on F_r (clearly shown on Pareto chart in Figure 5). The reason is that the combination of fluid type characterized by viscosity with air flow rate will affect the amount of cutting fluid delivered to the contact faces, thus affecting the frictional interaction in the cutting zone. When the viscosity of the cutting oil is high, only the moderate amount of cutting oil delivery may be required. For the cutting oil having low viscosity, the larger amount of oil is required.

(a) The Effect of Fluid Types

The two investigated cutting oils, emulsion and soybean oil, show a little different influence on the surface roughness R_a (Figure 8). For machining the materials with low hardness, usually smaller than 30 HRC, the soybean oil, a type of vegetable oil, gives better results. It can be explained that soybean oil is mainly composed of fatty acid and triglyceride -COOH in the fatty acid molecules and -COOR in triglyceride both belong to polar groups, which gives them excellent lubrication property [39,50]. On the other hand, soybean oil has higher viscosity than oil-in-water emulsion, so it contributes the better lubrication performance [9,40]. However, for difficult-to-cut materials, such as hardened steel with high hardness, oil-in-water emulsion brings out better results. The main reason is that soybean oil has low ignition temperatures (about 450°F (232.2 °C)) [38], so for hard machining, its application is limited due to the very high cutting heat generated from the contact zone, and it often burns, thereby reducing the effectiveness in lubrication and cooling. Oil-in-water emulsion has the higher ignition temperature than that of soybean oil, it is more suitable for hard machining [38].

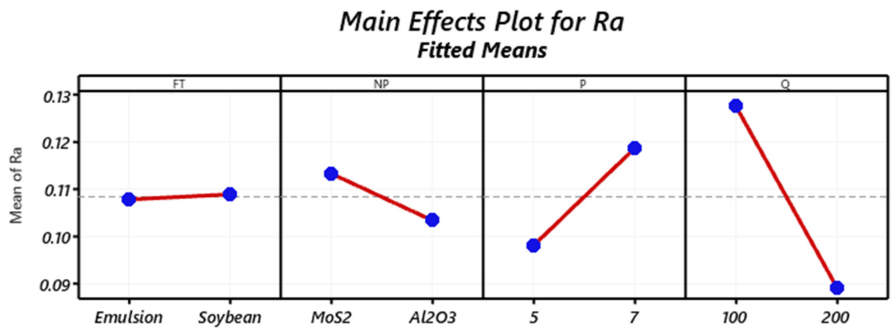

Figure 8. Main effects plot of input machining factors on surface roughness R_a.

Moreover, when machining hard materials, the formation of surface roughness is mainly due to surface scratches of the cutting tool, and the influence of other causes is not much [51,52], so the effect of fluid type exhibits a little difference. For the resultant cutting force F_r, the difference in the influence of fluid type is clearly observed in Figure 9, and soybean oil shows the better result because it has the higher viscosity, so the lubricating performance is better. In addition to that, the presence of nanoparticles in soybean oil contributes to enhance the thermal conductivity and lubricating performance of the based oil [40], which is also reflected by the strong influence of the interaction effect between fluid type and nanoparticles in Figures 4 and 5.

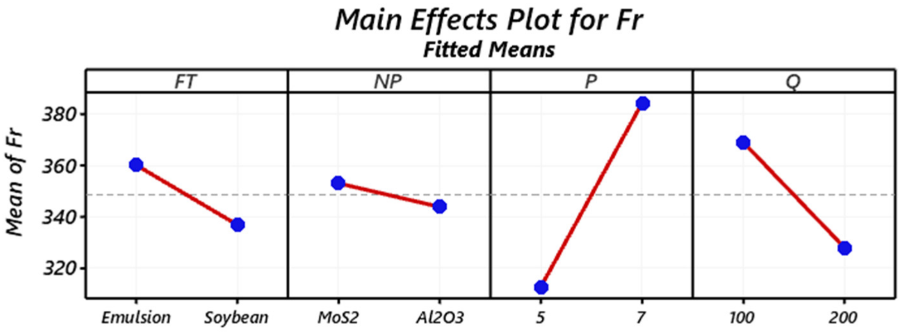

Figure 9. Main effects plot of input machining factors on the resultant cutting force F_r.

(b) The Effect of Nanoparticles

MoS_2 and Al_2O_3 nanoparticles significantly influence on R_a and F_r. Al_2O_3 nanoparticles better results in terms of R_a and F_r due to the different in nanoparticle morphology and properties. Al_2O_3 nanoparticles possess the outstanding lubricating ability due to their nearly spherical morphology, so the rolling mechanism is the main lubrication mechanism [2,38], and they also have very good thermal conductivity to enhance the cooling effect [40,53]. Meanwhile, MoS_2 nanomaterial only has good lubricating ability due to nano-sheet structure, and the main lubricating mechanism is tribo-film formation [49,52,54].

There are many factors affecting the frictional properties in cutting zone when using these two types of nanoparticles, in which nanoparticle concentration and nanoparticle size are the main influencing factors. In this study, because the concentration of Al_2O_3 nanoparticles is more suitable, the results are better [48,53]. However, for each of the different cutting conditions, the concentration used for each type of nanoparticles has the different optimal values. Therefore, the concentration also has a great influence on the usage efficiency of each nanoparticle type. The investigated nanoparticle concentration for MoS_2 used in this study has not yet promoted its maximum efficiency [52,54,55]. Therefore, it is necessary to have specific studies to investigate and optimize this parameter for different machining conditions.

(c) The Effects of Air Pressure and Air Flow Rate

Both air pressure P and air flow rate Q greatly affect the surface roughness and cutting forces. The results show that the use of lower air pressure and higher air flow rate gives better results for both surface roughness and cutting forces, which are consistent with previous results [20,56]. The reason is that air pressure and air flow rate strongly influence the ability to form, bring and keep oil mist in the cutting zone [12]. Due to face milling characterized by the open machining method, if too low air pressure is used, the ability to form and deliver oil mist into the cutting zone is limited. However, the droplet of oil mist is not pushed out of the cutting zone. On the contrary, if using too high air pressure, the ability to form and deliver oil mist into the cutting zone is better, but the oil mist is pushed out of the contact area, thus limiting the lubricating performance. In addition, increasing the air flow rate will rise the amount of lubricating oil delivered to the cutting zone, so it will improve the efficiency of the lubrication process. Air pressure and air flow rate are continuous variables, so further studies and investigations are required to determine the optimal values. This issue will be discussed in the next studies.

4. Conclusions

In this work, the influence of fluid type, nanoparticle type, air pressure and air flow rate on the resultant cutting force F_r and surface roughness value R_a in hard milling process has been evaluated. The experimental results show that the input machining variables and their interaction effects strongly influence on the objective functions, which are evaluated by p-values. The evaluation of the regression model through the coefficient of determination R^2 = 88.00% (for R_a) and R^2 = 97.69% (for F_r) indicates that the obtained data are in good agreement with the experimental data.

All four investigated variables affect the objective functions, in which the influence on the resultant cutting force F_r is larger than that on the surface roughness R_a. For F_r, air pressure P has the strongest effect, followed by air flow rate Q, fluid type and nanoparticles type, respectively. For R_a, air flow rate has the strongest effect, followed by air pressure, nanoparticle type and fluid type, respectively.

The interaction effects between variables are mainly the nanoparticle type, air pressure and air flow rate with the fluid type. From these, the interaction effect between the fluid type and the nanoparticle type (*FT*NP*) on the response parameters is significant and interesting for further investigations. Even though the effect of each variable alone may not be large, the interaction between them has a great influence on the objective functions. The assessment helps to select and combine the type of cutting fluid with the nanoparticle type to prepare nano cutting fluid suitable for specific machining conditions in order to improve cutting conditions and enhance the technical and economic efficiency of the machining processes.

From the obtained results, the use of the lower air pressure and higher air flow rate tends to be more favorable for better results. However, they are two continuous variables, so it is necessary to investigate to find the optimal value for each specific machining case. Al_2O_3 nanoparticles show the better results than MoS_2 nanosheets. The applicability of soybean oil, a type of vegetable oil, is proven to be enlarged in hard milling by suspending nanoparticles. Hence, this work suggests using Al_2O_3 soybean oil-based nanofluid rather than oil-in-water emulsion for MQL system, because it not only meets the technical requirements but also is suitable to the green and environmentally friendly machining, a step toward the sustainable production. Moreover, this work contributes the very important technical guides for technicians to apply NFMQL using vegetable oil in hard machining practice.

In further study, more investigations should be focused on the application of Al_2O_3/MoS_2 hybrid nano cutting fluid for MQL hard milling process. The optimal values of air pressure and air flow rate are necessary to find out. In addition to that, the nanoparticle concentration is a complicated function, which should be studied and optimized for each machining condition.

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