Vol. 45, No. 2 (2023) 272-284, DOI: 10.24874/ti.1453.02.23.05

Tribology in Industry

www.tribology.rs

RESEARCH

Influence of Technology Parameters on the Total Cutting Force in the Hard Turning Process with NF MQL and NF MQCL Method Using Nanofluids

Minh Tuan Ngo[a,*]

[a]*Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam.*

Keywords:

MQL
MQCL
Hard turning
Nanofluids
Cutting force
Lubricant

* Corresponding author:

Minh Tuan Ngo
E-mail: minhtuanngo@tnut.edu.vn

Received: 26 February 2023
Revised: 11 March 2023
Accepted: 3 May 2023

A B S T R A C T

Hard turning technology has received much attention and is becoming an alternative to the grinding process due to its high productivity, suitability for complex profiles, reduced use of cutting oil, and good surface quality. However, very severe cutting zone conditions such as very high friction, cutting forces and temperature in the cutting zone require special cutting tool materials and limited cutting modes. MQL and MQCL methods with nano-cutting oils are used to support hard-turning processes that improve cutting efficiency while ensuring environmentally friendly properties. Currently, the selection of suitable lubrication methods, base oil, and nanoparticle type is an issue that needs to be researched. Moreover, the trend of researching suitable lubricating technology so that conventional cutting tools (carbide inserts) can be used in hard machining is also an interesting research trend. This paper focuses on analyzing and evaluating the machining efficiency when turning 90CrSi (60 - 62 HRC) steel using MQL and MQCL by adding Al_2O_3 *and* MoS_2 *nanoparticles to the base liquid (soybean oil and emulsion). Analysis of variance (ANOVA) was used to evaluate the influence of the MQL and MQCL parameters on the total cutting force. At the same time, the trend and influence of the parameters MQL and MQCL on the total cutting force are also analyzed. The obtained results showed that the uses of MQL with nanofluid made from* MoS_2 *and emulsion or MQCL with nanofluid made from* Al_2O_3 *and soybean can significantly reduce the total cutting force. The obtained results showed that the machinability of carbide inserts was improved and the highest machinable hardness was increased from 35 HRC to 60 ÷ 62 HRC (rising by approximately 75%) by using the nanofluid MQL and MQCL methods. Furthermore, MQCL gives better performance than MQL, and the* MoS_2 *nanofluid exhibits a better result in terms of the total cutting force values than the* Al_2O_3 *nanofluid. From these results, technical guidance will be provided for further studies using* Al_2O_3*,* MoS_2 *or hybrid* Al_2O_3/MoS_2 *nanofluids for MQL and MQCL methods, as well as their application in machining practice.*

1. INTRODUCTION

In recent years, the hard turning process is being widely used to replace the grinding process in industrial production. However, the hard turning process still has many problems such as high cutting force and cutting heat, causing part deformation and reducing tool life [1,2].

High cutting force and high temperature at the cutting interface can affect the surface hardness [3], the distribution of residual stresses [4], workpiece material properties and microstructure, workpiece dimensions [5], and tool wear [6]. Therefore, the cooling/lubricating capabilities of the cutting fluids are essential for the productive chip removal operation in the hard machining process. However, this occupation of cutting fluids by customary flood cooling can cause thermal shock, and damage the tool and workpieces. Moreover, this method has also adversely altered environmental integrity, human health, and economy [7]. Therefore, in recent years, many new lubrication and cooling technologies have been researched and applied in hard machining processes such as minimum quantity lubrication (MQL), minimum quantity cooling lubrication (MQCL), Nanofluid minimum quantity lubrication (NFMQL).

MQL technology is a new cooling lubrication technology used in hard machining to overcome the disadvantages of dry machining and flood cooling technology. In the MQL method, a small amount of lubricating fluid is introduced into the cutting zone in the form of oil droplets to improve frictional conditions. Research on the application of MQL technology in hard turning process has been studied by many authors. The studies mainly focus on and investigate the influence of the parameters of the MQL technology on the efficiency of the cutting process [8]. The results of the studies show that when using MQL technology, it is possible to improve the surface quality and increase tool life compared to dry machining and flood cooling technologies. Rajaguru and et al. have investigated the machining of super duplex stainless steel under different coolant environments to improve its machinability [9]. Turning experiments were performed under dry, flood, and MQL conditions to enhance the machinability in respect of Fc and Ra. Findings have indicated that the MQL method outperformed other conditions. Li and et al. studied and applied the MQL approach in micro-grinding process [10]. The results indicated that this approach provided an improvement in Ra and a reduction in Fc. Similarly, an enhancement by 15% in the matter of Ra and Fc was reported by the research of Singh et al. [11] in hard turning process under the MQL technique. Bedi et al. studied the impact of cutting speed on Ra and Fc when turning AISI 304 under dry and MQL conditions and they found that MQL provided better Ra and lower Fc than the dry turning process [12]. Also, Uysal investigated the milling process under MQL at flow rates of 20 ml/h and 40 ml/h from the perspective of cutting temperature and flank wear [13-14]. The results showed that MQL at a flow rate of 40 ml/h delivered acceptable results in comparison to MQL at a flow rate of 20 ml/h. The application of MQL approach in machining operations exhibited various benefits such as limited harmful effects on the environment caused by the abundant use of the conventional cutting fluid, less production cost, and increased worker safety [15]. Nevertheless, it has also its own restriction related to the mediocre cooling function because of incapability of the lesser oil flow rate to fully limit heat generation at both primary and secondary machining regions in the cutting of hard-to-machine materials [16]. Therefore, there appears to be a need to improve the cutting performance of MQL process. In this way, the applications of nanofluids assisted MQL [17,18] and hybrid nanofluids assisted MQL [19] have recently become important research trends in order to enhance the MQL efficiency.

In recent years, the MQCL method has been studied and applied to the hard machining process by many authors. The MQCL method also delivers a small amount of lubricant into the cutting area in the form of a mist. However, in the MQCL method, that amount of lubricant is cooled so that in addition to the lubricating capacity it is possible to reduce the temperature of the cutting zone [20]. The results of the study by Pervaiz et al. on turning Ti6Al4V alloy using MQCL have shown the ability to lubricate and cool more effectively than the dry machining and flood method [21].

Maruda et al. analyzed the efficiency of AISI 1045 steel turning hardening process using MQCL with different technological parameters [22]. The research results of Maruda et al (2018) analyzed the formation of emulsion oil droplets in the form of mist during hard machining using MQCL. Research results have shown that the MQCL method improves cooling and lubrication efficiency, and reduces friction and tool wear. The influence of the MQCL method on chip deformation in the cutting zone is analyzed by Krolczyk [23].

Moreover, the surface quality and surface layer structure are better under MQCL than those in dry condition. The reason is that low-temperature oil droplets are formed, providing superior cooling effect, thereby reducing surface deformation. The diameter and number of oil droplets are strongly influenced by the nozzle distance, air flow rate and air pressure [24], and they can be controlled by air flow rate and the nozzle distance. Marudal studied effects of extreme pressure and anti-wear additives on surface topography and tool wear during MQCL turning of AISI 1045 steel [25]. The results shown that The application of the MQCL method with the extreme pressure and anti-wear additives led to a decrease in particular surface topography parameters in comparison with the effects of dry cutting and the effects of machining under MQCL conditions. Krishnan and et al proposed a low cost multijet minimum quantity cooling lubrication (MJMQCL) system with three jets for milling Ti-6Al-4V [26]. In this study, the cutting force is found to be lowest for the jet positions – jet 1–20° and jet 3–160° - as there is lubricant coverage of the cutting zone during the entire 180° of cutter contact for this position.

However, most of the new research focuses on using cutting oils for the purpose of reducing friction and temperature in the cutting zone. Studies have shown that the characteristics of the oil change with temperature, so it is necessary to study to determine the appropriate cutting parameters and lubrication conditions when using the MQCL method.

However, MQL and MQCL have limitations concerning the moderate cooling function owing to the insufficient oil flow rate to entirely restrict heat generation at chip removal zones in cutting hard-to-machine materials. Thus, there is a requirement to enhance the cooling capability of the MQL and MQCL techniques. Therefore, the applications of nanofluid-assisted MQL (N-MQL) [27] and N-MQCL [28] have recently become the main study to increase MQL and MQCL performance.

Nanofluids are being studied for applications in machining because of their many advantages in terms of thermal properties and lubricating properties. The application of nano-cutting oil to lubricate and cool the cutting area has been studied by many authors [29-30]. Sharma et al. have analyzed and evaluated the effectiveness of the application of MQL with nano-cutting oil in the cutting process [31]. The research results have shown that the minimum quantity lubrication (NFMQL) method with nanofluids shows promising results compared with the MQL using normal oil in terms of cutting zone temperature and surface roughness. Shen et al studied the effect of nanofluids mixed with nanodiamonds, and nanoparticles Al_2O_3 and water on the grinding process of cast iron [32]. Research has shown higher grinding efficiency, lower tangential cutting force, better surface structure, and lower grinding temperature when using nanofluids for grinding. Ramanuj Kumar studied Application of Al_2O_3 and MoS_2 nanofluid through spray impingement technique in hard turning process. This research focuses on the analysis of flank wear (VBc), cutting temperature (T), average surface roughness (Ra), and chip morphology in the hard turning process using nanofluids. Abrasion is the dominant wear mechanism identified for both types of Al2O3 and MoS_2 nano cutting fluids [33]. Setti et al studied the effect of flow rate and concentration of Al_2O_3 nanofluid in the grinding process of Ti-6Al-4 V alloy. Research results show that using Al_2O_3 nanofluid reduces the cutting temperature in the grinding area, reducing friction and improving grinding ability [34]. Vasu and Reddy studied the performance of Al_2O_3 nanofluids in the machining process of Inconel 600 alloy [35]. Research results have shown that nanoparticle-enhanced MQCL can lead to significant reductions in cutting force, surface roughness, temperature, and tool wear. Xiufang Bai and et al. studied the effects of concentrations of Al2O3 nanoparticles on the cutting force and the surface quality during minimum quantity lubrication (MQL) milling 45 steel using cottonseed oil [36]. The result indicated that the specific energy is at the minimum (114 J/mm3), and the roughness value is the lowest (1.63 µm) when the concentration is 0.5 wt%. Oleksandr Gutnichenko and et al. study Influence of graphite nanoadditives to vegetable-based oil on machining performance when MQCL assisted hard turning process [37]. Nitesh Anand and et al. investigated the role of minimum quantity cooling-lubrication (MQCL) with soluble oil, aqueous alumina and hBN nanofluids in turning of Ti-6Al-4V [38]. This research indicated that Aqueous alumina and hBN nanofluids have failed to provide acceptable performance as compared to soluble oil, all applied in MQCL mode. . Z. Dongkun et al. (2014) analyzed the effect on surface roughness and cutting force when applying three types of nanoparticles (MoS_2, ZrO_2, and Carbon nanotubes (CNTs)) [39]. The analysis results show that the cutting forces significantly reduced and surface roughness was better, in which MoS_2 NFMQL was more effective than the other investigated ones. Moreover, the investigation of MQL hard turning process of ADI, a difficult-to-cut material, using Al_2O_3 nanoparticles suspended with vegetable oil compared to dry, flood, and MQL with pure oil was reported in [40]. The MQL machining performance using 4.0% Al_2O_3 vegetable oil-based nano cutting oil showed the better results because the improvement of thermal conductivity and lubricating property of the based oil. Hence, the significant reduction of friction coefficient leads to decrease the cutting forces and extend the tool life [41,42].

Recently, MoS_2 nanoparticles are applied to mix with the cutting oil to form MoS_2 nanofluid used in MQL for improving the cooling lubrication in machining [43], which has gained the great interest of many researchers. MoS_2 NFMQL helped to reduce the specific energy and surface roughness in grinding process [44]. Parash Kalita studied and applied MoS_2 NFMQL to grinding process of cast iron [45]. The results also indicated the reduction of specific energy and improvement of surface quality compared to wet grinding. Yanbin Zhang et al. analyzed the lubricating efficiency of MoS2/CNT hybrid nanofluid in grinding of Ti alloy [46]. The results show that hybrid nanofluid is more effective than using a single type of nanoparticle in the based oil. In 2015, the authors also studied the application of MoS2 NFMQL in grinding. MoS2 nano cutting fluid contributes to increase the lubricating efficiency, thereby reducing cutting temperature and grinding force [47].

A review of previous publications shows that the use of nanofluids in hard machining using MQL and MQCL brings positive effects on cutting force, surface roughness, tool wear, and tool life. The main reason is that the nanoparticles have improved the physical properties of conventional cutting oils, thereby improving the efficiency of the MQL and MQCL methods. However, each MQL and MQCL method gives different results when using different nanofluids and cutting parameters. Furthermore, the improvement of the efficiency of conventional cutting tools in hard machining by using new cooling lubricating technology is also of interest. For these reasons, the authors focused on conducting a study on the application of MQL and MQCL on hard turning 90CrSi steel (60–62 HRC) using nanofluids (Al_2O_3 and MoS_2) with the different based oils. The results of this study will not only provide important techniques to guide the use of Al_2O_3 and MoS_2 nanoparticles in hard machining using NF-MQL and NF-MQCL, but also a premise to carry out further studies. Thesse research results also are the basis of hybrid nanofluids applications and development for sustainable production.

2. EXPERIMENTAL DETAIL

The experimental set up is shown in Figure 1. The experimental process was carried out on a lathe CS-460x1000 (Pin Shin Machinery Co., LTD, Taichung city, Taiwan) having a maximum spindle speed of 2000 (rev/min) at the experimental center of the Thai Nguyen University of Technology. All experiments were performed with the carbide inserts CNMG120404-TM T9125 mounted on the tool holder of KYOCERA (PCLNR 2020 K-16). In the study, the workpieces are 40mm diameter 90CrSi steel with hardness HRC=60-62. The chemical composition of the workpiece are shown in Table 1.

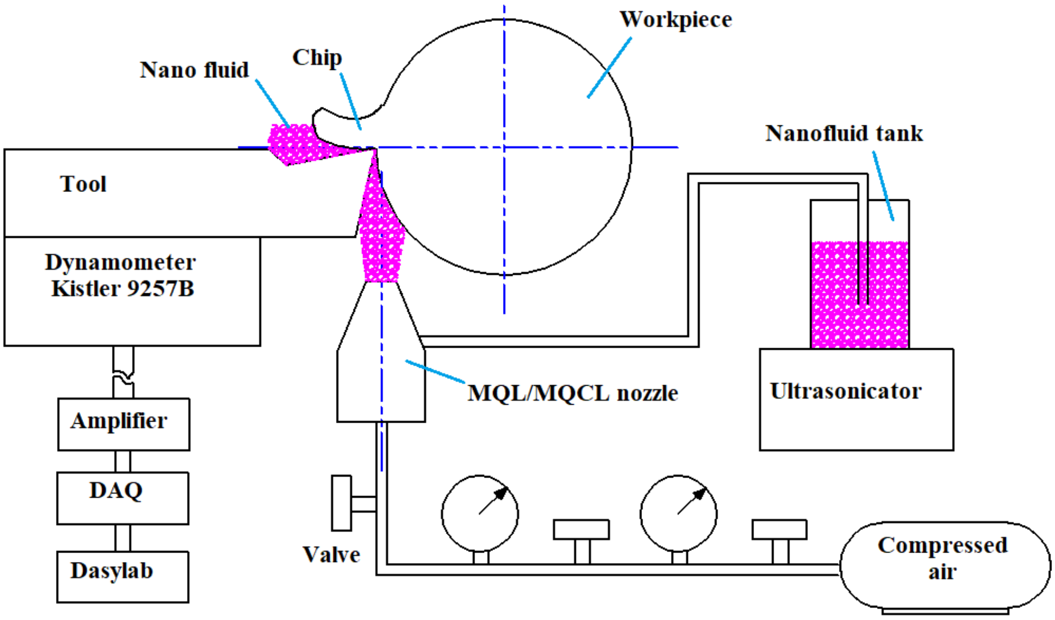


Fig. 1. Experiment set up.

Table 1. The chemical composition of 90CrSi.

Elements	C	Si	Mn	Ni	S	P	Cr	Mo	W	V	Ti	Cu
Wt (%)	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

MQL and MQCL units are used to transmit the cutting fluids to the cutting area. NOGA MQL nozzle and some accompanying equipment including an air compressor, pressure stabilizer, emulsion oil, soybean oil, Al_2O_3, and MoS_2 nanoparticles. The MQL system uses NOGA's MQL injector (Noga minicool MC1700); The MQCL system uses Frigid-X Sub-Zero Vortex injectors (58LUBECOOL-1) from Nex Flow™ (Canada). Three component cutting force of all trials were measured by A Kistler 9257BA dynamometer (Kistler Instruments (Pte) Ltd, Midview, Singapore) with data acquisition system A/D DQA N16210 (made by National instruments, USA), and DASYlab 10.0 software. Alumina nanoparticles with the average size of 30 nm were made by Soochow Hengqiu Graphene Technology Co., Ltd., Suzhou, China (Figure 2). MoS_2 nanoparticles with the size of 30 nm (average) were made by Luoyang Tongrun Info Technology Co., Ltd., Luoyang, China (Figure 3).

The nanoparticle concentration was calculated by the following weight percent concentration (wt %). The Al_2O_3 and MoS_2 nanoparticles do not dissolve in soybean oil and emulsion and will sink to the bottom after a short time. The non-uniform distribution of the nanoparticles will bring out very little effectiveness on MQL hard machining compared to the base fluids. Another important point is that the nanoparticles in the bottom also cause waste. To ensure uniform distribution of Al_2O_3 and MoS_2 nanoparticles in fluids, the prepared nanofluids are kept in an Ultrasons-HD ultrasonicator; generating 600 W ultrasonic pulses at 40 kHz, and the time for different concentrations of 1.0% and 3.0 wt % is at least 40 min., 90 min. to ensure the uniform distribution of the nanoparticles respectively. In order to use the obtained nanofluids effectively and avoid the precipitation of agglomerated nanoparticles during a long time of machining, the nanofluids were placed in the 3000868-Ultrasons-HD and directly used for MQL/MQCL system.

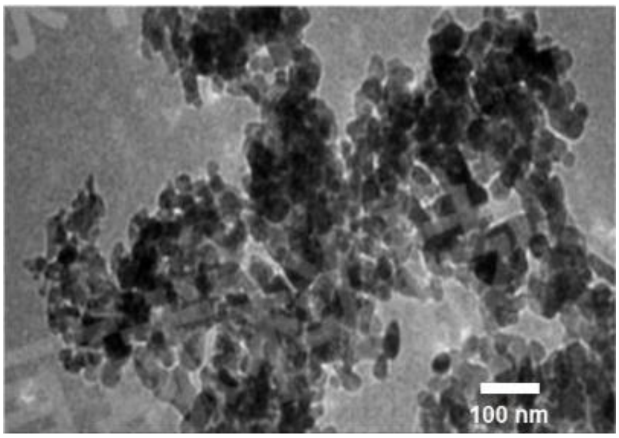


Fig. 2. The image of Al_2O_3 nanoparticles.

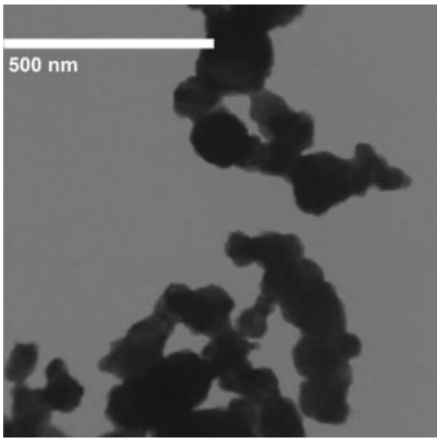


Fig. 3. The image of MoS_2 nanoparticles.

Within the scope of the study, The experimental method 2k-p was used with 06 survey variables to build an experimental planning diagram of the effect of fluid type (FT), lubricating method (LM), nanoparticle type (NP), nanoparticle concentration (NC); cutting speed (V) and feed rate (f) to total cutting force Fr. Each input factor is examined at two levels of value as shown in Table 2.

Table 2. Input parameter and their values.

No.	Experimental variables	Symbol	Levels	
			Low	high
1	Fluid type (FT)	A	Emulsion (Em)	Soybean oil (So)
2	Lubricating method (LM)	B	MQL	MQCL
3	Nanoparticle (NP)	C	Al_2O_3	MoS_2
4	Nanoparticle concentration (NC-wt%)	D	1%	3%
5	Cutting speed (V-m/min)	E	80	160
6	Feed rate (f-mm/rev)	F	0.1	0.2

Design expert 11 software was used for experimental design, the experimental matrix was built with 30 experiments. All experiments were performed in random order (run order), The total cutting force value is calculated from the value of 3 components and is shown in Table 3.

Table 3. The experimental matrix and results.

Std	Run	A:FT	B:LM	C:NP	D:NC (%)	E:V (m/min)	F:f (mm/rev)	Fr (N)
13	1	Em	MQCL	MoS_2	1	80	0,1	286.6
12	2	So	MQL	MoS_2	1	80	0,2	291.2
8	3	So	MQCL	Al_2O_3	1	80	0,2	202.6
23	4	So	MQCL	Al_2O_3	3	80	0,1	305.9
28	5	So	MQL	MoS_2	3	80	0,1	296.2
21	6	Em	MQCL	Al_2O_3	3	160	0,1	150.5
22	7	Em	MQCL	Al_2O_3	3	160	0,1	142.4
18	8	Em	MQL	Al_2O_3	3	80	0,2	180.5
3	9	So	MQL	Al_2O_3	1	160	0,1	388.4
16	10	So	MQCL	MoS_2	1	160	0,1	225.5
14	11	Em	MQCL	MoS_2	1	80	0,1	281.5
9	12	Em	MQL	MoS_2	1	160	0,2	302.0
17	13	Em	MQL	Al_2O_3	3	80	0,2	184.1
24	14	So	MQCL	Al_2O_3	3	80	0,1	290.6
32	15	So	MQCL	MoS_2	3	160	0,2	265.4
27	16	So	MQL	MoS_2	3	80	0,1	351.8
20	17	So	MQL	Al_2O_3	3	160	0,2	369.0
5	18	Em	MQCL	Al_2O_3	1	160	0,2	311.1
31	19	So	MQCL	MoS_2	3	160	0,2	266.8
26	20	Em	MQL	MoS_2	3	160	0,1	223.8
7	21	So	MQCL	Al_2O_3	1	80	0,2	199.9
1	22	Em	MQL	Al_2O_3	1	80	0,1	438.1
30	23	Em	MQCL	MoS_2	3	80	0,2	222.9
6	24	Em	MQCL	Al_2O_3	1	160	0,2	311.1
29	25	Em	MQCL	MoS_2	3	80	0,2	219.1
4	26	So	MQL	Al_2O_3	1	160	0,1	399.0
2	27	Em	MQL	Al_2O_3	1	80	0,1	441.5

Std	Run	A:FT	B:LM	C:NP	D:NC (%)	E:V (m/min)	F:f (mm/rev)	Fr (N)
15	28	So	MQCL	MoS_2	1	160	0,1	236.0
10	29	Em	MQL	MoS_2	1	160	0,2	297.3
11	30	So	MQL	MoS_2	1	80	0,2	286.0
25	31	Em	MQL	MoS_2	3	160	0,1	223.9
19	32	So	MQL	Al_2O_3	3	160	0,2	384.7

3. RESULTS AND DISCUSSION

ANOVA analysis for the total cutting force with significance level α = 0.05 was performed on Design expert software 11. The results of ANOVA analysis are shown in Table 4.

The analysis results show that the Fisher coefficient value for the model is quite large 19.39 and the P value is very small compared to 0.05, which proves that the predictive model is suitable and less affected by noise. In which the survey factors A, B, C, D, F and interactions AB, AD, AE, BD, BF mainly affect the objective function Fr. In addition, the coefficient R2 (93%) and the coefficient adj R2 (88.5%) are large, also demonstrating the appropriateness of the survey model.

The influence of the survey variables and their interactions on the total cutting force Fr is also shown on the Pareto chart, figure 4. The Bonferronium limit line has a value of 4.122 (red) and the T limit line has a value of 3.01 (black). All the variables and their interactions that are above the Bonferroni limit line inevitably affect the objective function value Fr. While the factors above the limit line T have a high probability of affecting the objective function value Fr.

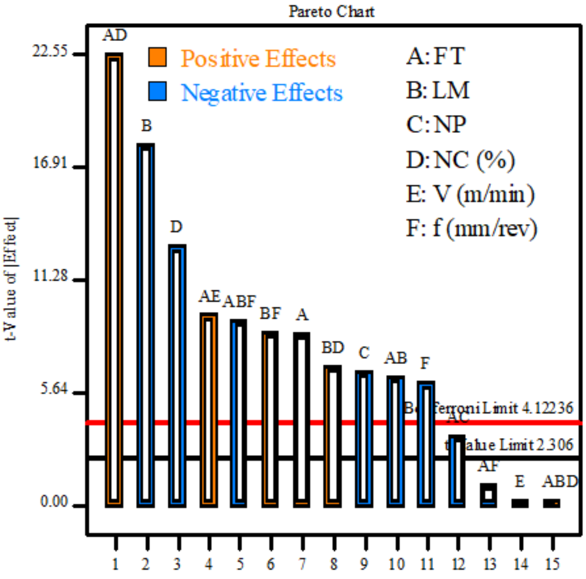


Fig 4. Pareto chart for Fr.

The independent influence of the survey factors on the total cutting force is shown in Figure 5. The interaction effect between the investigated factors on the total cutting force Fr is shown in Figure 6. The results shown in Figure 3a show that when machining the hardened steel 90CrSi using nanofluids with Emulsion oil has a smaller cutting force than using nanofluids with soybean oil.

Table 4. The results ANOVA analysis for F_r.

Source	Sum of	df	Mean	F-value	p-value
Model	178060.8	13	13696.98	19.39	5.91E-08
A-FT	9205.893	1	9205.893	13.04	0.002
B-LM	40582.32	1	40582.32	57.46	5.23E-07
C-NP	5599.635	1	5599.635	7.93	0.011442
D-NC (%)	21024.16	1	21024.16	29.77	3.5E-05
E-V (m/min)	10.48815	1	10.48815	0.014	0.904357
F-f(mm/ rev)	4705.019	1	4705.019	6.66	0.018832
AB	5192.014	1	5192.014	7.35	0.014301
AC	1500.983	1	1500.983	2.13	0.162109
AD	63336.5	1	63336.5	89.68	2.05E-08
AE	11361.56	1	11361.56	16.09	0.00082
AF	143.3587	1	143.3587	0.20	0.657698
BD	6020.322	1	6020.322	8.52	0.009148
BF	9378.541	1	9378.541	13.28	0.001856
Residual	12712.28	18	706.2377		
Lack of Fit	10719.63	2	5359.814	43.04	3.64E-07
Pure Error	1992.65	16	124.5407		

The reason is that when the cutting temperature is high, soybean oil is more flammable (due to its lower combustion temperature), reduces the lubricating capacity, and makes the cutting force higher [48]. Especially when cutting with high cutting speed (160m/min), the cutting heat increases, which is the main reason why the cutting force when using nano oil with emulsion is much smaller than when using soybean oil (figure 6d). The addition of nanoparticles increases the viscosity and thermal conductivity, thereby improving the lubricating and cooling capacity of the base oil, and reducing the cutting force of the machining process.

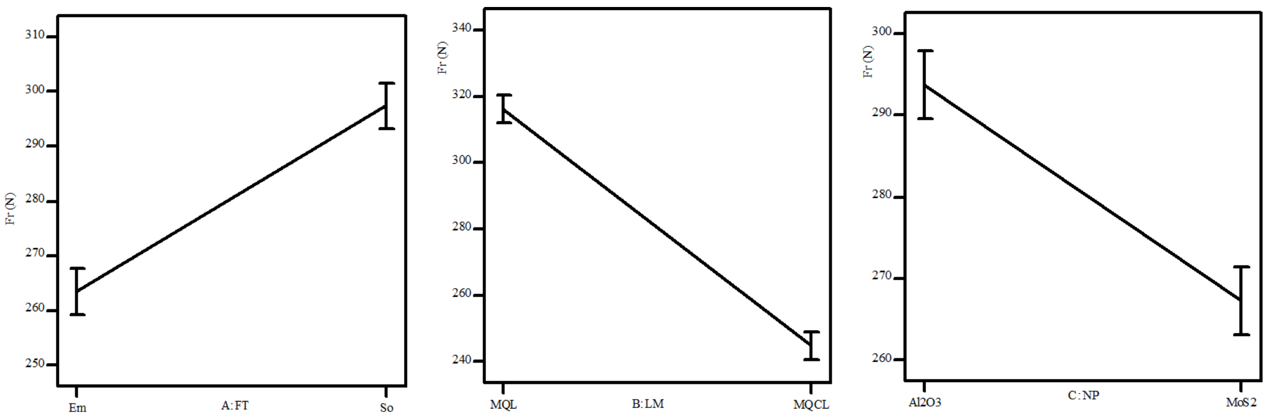
Figure 5b shows that the MQCL method gives a smaller total cutting force than the MQL method. However, when using MQL, Emulsion oil gives a much smaller cutting force than soybean oil. And when using MQCL, the total cutting force Fr is less affected by the type of oil, Figure 5a.

In addition, Figure 6e depicts the interaction between the nanoparticle concentration and the cooling lubrication method. When the nanoparticle concentration is small, the MQCL method gives a much smaller cutting force than the MQL method because the nanoparticle solution quickly enters the cutting area, having both a lubricating and cooling effect. However, the MQCL method cools the air using the Ranque-Hilsch effect [49], thereby reducing the pressure and flow rate of the refrigerant air stream compared to the inlet stream. The nanofluids' viscosity increases with a large concentration of nanoparticles, so when using MQCL, the nanoparticle droplets penetrate the cutting region less. Therefore, despite the addition of cooling capacity with MQCL, the cutting force is not reduced much compared to the MQL method.

The analysis results also show that using MoS_2 particles, the cutting force is smaller than using Al_2O_3 particles (Figure 5c). This results are also clearly shown in the figure 6b. From the obtained results, to achieve the small total cutting force, the emulsion and MoS_2 nanoparticles should be used. The reason is that Nanoparticles MoS_2 has a sheet shape and a large Van der Waals force, so it is easy to form adhesion layers on the surface and reduce friction in the shear zone [50].

The nanoparticle concentration also affects the total cutting force, when increasing nanoparticle concentration, While the total cutting force Fr also decreased with (Figure 5d). This was more evident when using emulsion oil, the total cutting force decreased from 350 N to 200 N with increasing particle concentration from 1% to 3% (figure 6c). While using soybean oil, the cutting force increased slightly with increasing seed concentration. The reason is that soybean oil has a higher viscosity, so when using a large concentration of nanoparticles, it can cause clustering and cause compression to increase the cutting force [51].

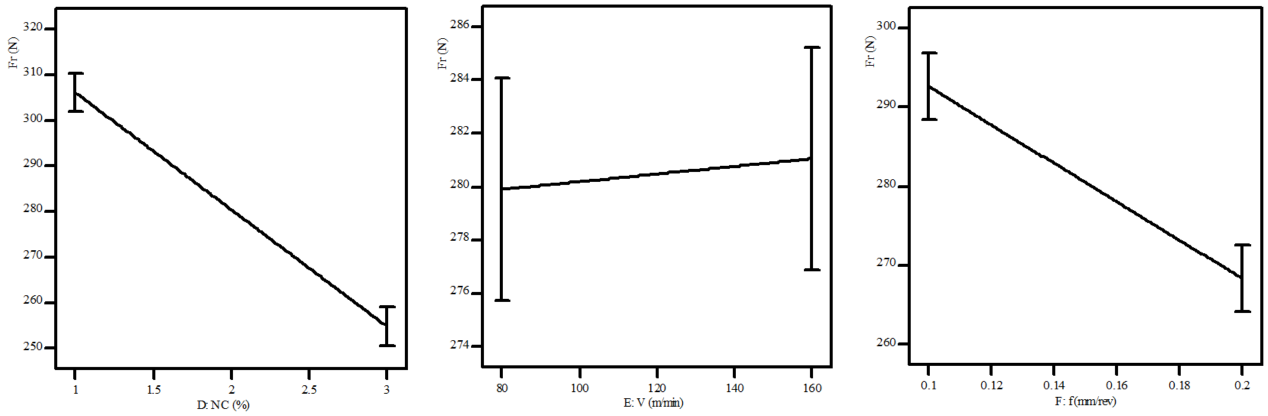
The results in Figure 5e show that in the survey range, the mean cutting force is less affected by the cutting speed. However, With each type of base oil, the cutting speed affects the cutting force value differently. When using emulsion oil, the cutting force decreases with increasing cutting speed, while with soybean oil the cutting force increases with increasing cutting speed. However, the cutting force decreases with increasing feed rate from 0.1 to 0.2 mm/rev (figure 5f), especially with the MQL method (figure 6f). The reason may be that, when increasing the feed rate, it is favorable for the nanofluid to penetrate into the cutting area and reduce the cutting force Fr.



(a) Fluid type (A-FT)

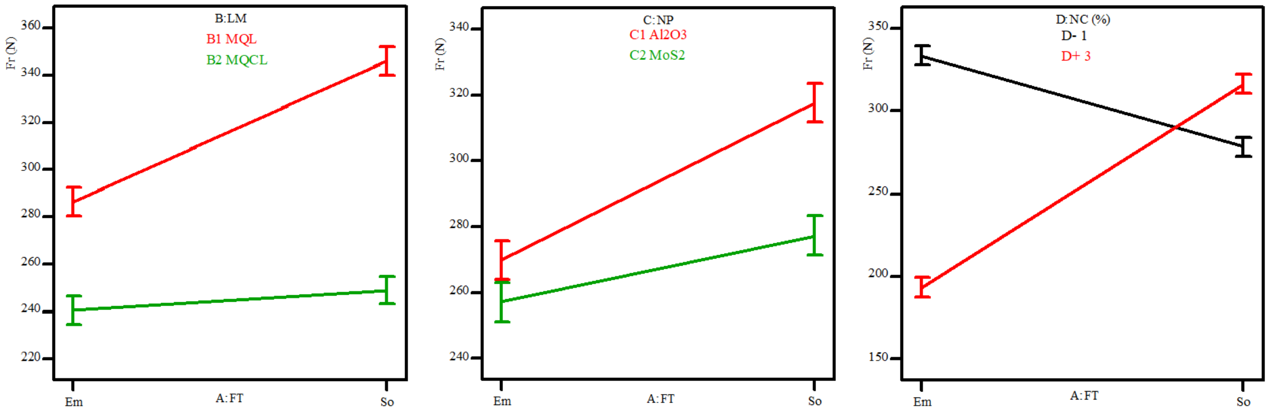
(b) Lubricant method (B:LM)

(c) Nanoparticle (C-NP)

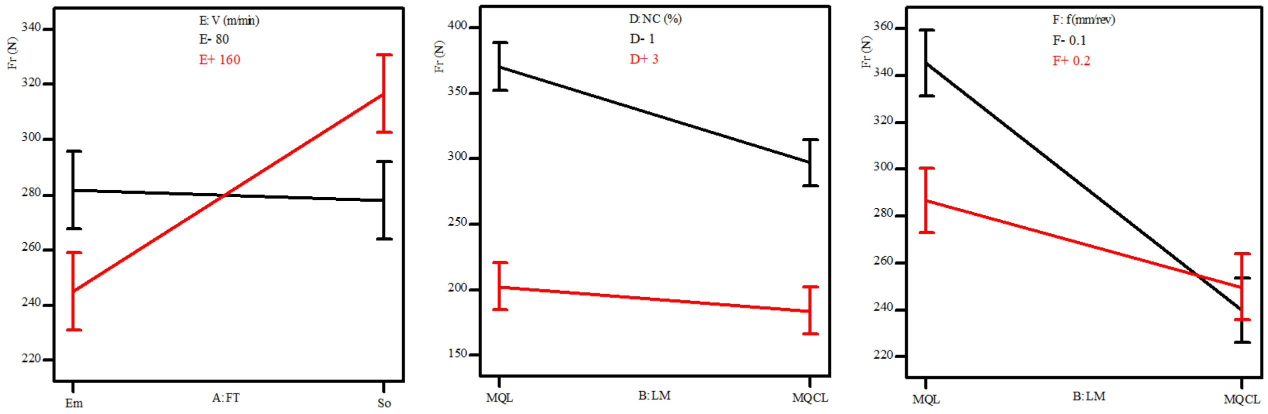


(d) Nanoparticle concentration(D-NC) (e) Cutting speed (E-V) (f) Feed rate (F-f)

Fig. 5. The influence of the survey variables on the total cutting force Fr.



(a) FT* LM (A*B) (b) FT*NP (D-NC) (c) FT*NC (A*D)



(d) FT*V (A*E) (e) LM*NC (B*D) (f) LM*F (B*F)

Fig. 6. Interaction effect between the investigated variable on the total cutting force Fr.

4. CONCLUSION

In this study, the influences of fluid type, lubrication method, nanoparticle type, nanoparticle concentration, cutting speed and feed rate on surface roughness are investigated by ANOVA analysis with the help of Design Expert 11 software. The 2FI model is suitable for analyzing the level and trend of the influence of the investigated factors on the total cutting force. The effects of input variables and their interaction on the objective function are also studied. To enhance the cooling and lubricating performance for the hard turning process, the MQL and MQCL techniques using Al_2O_3 and MoS_2 nano cutting fluids were utilized. The main contributions of this study can be summarized as follows.

The machinability of carbide inserts has been greatly improved and extended for hard turning by using the MQL and MQCL methods combined with the use of nanofluids. Research results show that this insert is recommended by the manufacturer for machining before heat treatment with a hardness of 35HRC, but can be effectively used for hard machining with a hardness of 60-62 HRC under the same conditions recommended by the manufacturer. This will lead to alternatives and economic benefits.

The MQCL method shows a higher cooling efficiency, which enhances heat dissipation in the cutting zone compared to the MQL technique, thereby reducing the total cutting force Fr. When using MoS_2 Nanofluid, the total cutting force is lower than that of Al_2O_3 nanofluid. However, using the appropriate nanoparticle concentration for each nanofluid is a very important factor and has a great influence on the total cutting force Fr. Therefore, further studies are needed to investigate and optimize this parameter. Also, the Interaction of fluid type and lubrication method (FT*LM); liquid type and nanoparticle type (FT*NP); liquid type and nanoparticle concentration (FT*NC); and the lubrication method and feed rate (LM*f) have a significant influence on the total cutting force, thereby suggesting research directions for further studies.

Acknowledgements

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

REFERENCES

[1] J.P. Davim, V.P. Astakhov, *Machining of Hard Metals*, Springer, 2011, doi: 10.1007/978-1-84996-450-0

[2] A. Ebrahimi, M.M. Moshksar, *Evaluation of machinability in turning of microalloyed and quenched-tempered steels : Tool wear, statistical analysis, chip morphology*, Journal of Materials Processing Technology, vol. 9, iss. 2, pp. 910–921, 2009, doi: 10.1016/j.jmatprotec.2008.02.067

[3] E.G. Martínez, A.Martínez. Martínez, M.C.M. Tendero, V.M. Eguía, *Proposal of a combined experimental-simulation methodology for the evaluation of machining temperature in turning processes*, Measurement, vol. 189, 2022, doi: 10.1016/j.measurement.2021.110632

[4] N.T. Mathew, V. Laxmanan, *Temperature rise in workpiece and cutting tool during drilling of titanium aluminide under sustainable environment*, Materials and Manufacturing Processes, vol. 33, iss. 16, pp. 1765-1774, 2018, doi: 10.1080/10426914.2018.1476770

[5] Z.B. Hou, R. Komanduri, *General solutions for stationary/moving plane heat source problems in manufacturing and tribology*, International Journal of Heat and Mass Transfer, vol. 43, pp. 1679-1698, 2000, doi: 10.1016/S0017-9310(99)00271-9

[6] N.A. Abukhshim, P.T. Mativenga, M.A. Sheikh, *Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining*, International Journal of Machine Tools and Manufacture, vol. 46, iss. 7-8, pp. 782-800, 2006, doi: 10.1016/j.ijmachtools.2005.07.024

[7] R. Mallick, R. Kumar, A. Panda, A.K. Sahoo, *Current Status of Hard Turning in Manufacturing: Aspects of Cooling Strategy and Sustainability*, Lubricants, vol. 11, iss. 3, 2023, doi: 10.3390/lubricants11030108

[8] N. Sultana, N.R. Dhar, *A critical review on the progress of MQL in machining hardened steels*, Advances in Materials and Processing Technologies, vol. 8, iss. 4, 2022, doi: 10.1080/2374068X.2022.2036041

[9] J. Rajaguru, N, Arunachalam, *A comprehensive investigation on the effect of flood and MQL coolant on the machinability and stress corrosion cracking of super duplex stainless steel*, Journal of Materials Processing Technology, vol. 276, 2020, doi: 10.1016/j.jmatprotec.2019.116417

[10] K.-M. Li, C.-P. Lin, *Study on minimum quantity lubrication in micro-grinding*, The International Journal of Advanced Manufacturing Technology, vol, 62, pp. 99–105, 2012, doi: 10.1007/s00170-011-3789-1

[11] G. Singh, C.I. Pruncu, M.K. Gupta, M. Mia, A.M. Khan, M. Jamil, D.Y. Pimenov, B. Sen, V.S. Sharma, *Investigations of machining characteristics in the upgraded MQL-assisted turning of pure titanium alloys using evolutionary algorithms*, Materials, vol. 12, iss. 6, 2019, doi: 10.3390/ma12060999

[12] S.S. Bedi, G.C. Behera, S. Datta, *Effects of cutting speed on MQL machining performance of AISI 304 stainless steel using uncoated carbide insert: application potential of coconut oil and rice bran oil as cutting fluids*, Arabian Journal for Science and Engineering, vol. 45, pp. 8877-8893, 2020, doi: 10.1007/s13369-020-04554-y

[13] A. Uysal, *Investigation of flank wear in MQL milling of ferritic stainless steel by using nano graphene reinforced vegetable cutting fluid*, Industrial

Lubrication and Tribology, vol. 68, iss. 4, pp. 446-451, 2015, doi: 10.1108/ILT-10-2015-0141

[14] A. Uysal, *An experimental study on cutting temperature and burr in milling of ferritic stainless steel under MQL using nano graphene reinforced cutting fluid*, Advanced Materials Proceedings, vol 2, iss. 9, pp. 560-563, 2017, doi: 10.5185/amp.2017/038

[15] G.M. Krolczyk, R.W. Maruda, J.B. Krolczyk, S. Wojciechowski, M. Mia, P. Nieslony, G. Budzik, *Ecological trends in machining as a key factor in sustainable production - A review*, Journal of Cleaner Production, vol. 218, pp. 601-615, 2019, doi: 10.1016/j.jclepro.2019.02.017

[16] M.K. Gupta, M. Jamil, X. Wang, Q. Song, Z. Liu, M. Mia, H. Hegab, A.M. Khan, A.G. Collado, C.I. Pruncu, G.M. Shah Imran, *Performance evaluation of vegetable oil-based nano-cutting fluids in environmentally friendly machining of Inconel-800 Alloy,* Materials, vol. 12, iss. 17, 2019, doi: 10.3390/ma12172792

[17] A.K. Sharma, A.K. Tiwari, A.R. Dixit, *Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A review*, Journal of Cleaner Production, vol. 127, pp. 1-18, 2016, doi: 10.1016/j.jclepro.2016.03.146

[18] A.K. Sharma, R.K. Singh, A.R. Dixit, A.K. Tiwari, *Characterization and experimental investigation of Al2O3 nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL)*, Materials Today proceedings, vol. 3, iss. 6, pp. 1899-1906, 2016, doi: 10.1016/j.matpr.2016.04.090

[19] M. Jamil, A.M. Khan, H. Hegab, L. Gong, M. Mia, M.K. Gupta, N. He, *Effects of hybrid Al2O3- CNT nanofluids and cryogenic cooling on machining of Ti-6Al-4V*, International Journal of Advanced Manufacturing Technology, vol. 102, pp. 3895-3909, 2019, doi: 10.1007/s00170-019-03485-9

[20] N. Anand, A.S. Kumar, S. Paul, *Effect of cutting fluids applied in MQCL mode on machinability of Ti-6Al-4V*, Journal of Manufacturing Processes, vol. 43, pp. 154–163, 2019, doi: 10.1016/j.jmapro.2019.05.029

[21] S. Pervaiz, I. Deiab, A. Rashid, M. Nicolescu, *Minimal quantity cooling lubrication in turning of Ti6Al4V: Influence on surface roughness, cutting force and tool wear,* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 231, iss. 9, pp. 1542–1558, 2017, doi: 10.1177/0954405415599946

[22] R.W. Maruda, G.M. Krolczyk, E. Feldshtein, P. Nieslony, B. Tyliszczak, F. Pusavec, *Tool wear characterizations in finish turning of AISI 1045 carbon steel for MQCL conditions*, Wear, vol. 372–373, pp. 54–67, 2017, doi: 10.1016/j.wear.2016.12.006

[23] R.W. Maruda, G.M. Krolczyk, P. Niesłony, J.B. Krolczyk, S. Legutko, *Chip formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition*, Procedia Engineering, vol. 149, pp. 297–304, 2016, doi: 10.1016/j.proeng.2016.06.670

[24] G.M. Krolczyk, R.W. Maruda, J.B. Krolczyk, P. Nieslony, S. Wojciechowski, S. Legutko, *Parametric and nonparametric description of the surface topography in the dry and MQCL cutting conditions*, Measurement, vol. 121, pp. 225–239, 2018, doi: 10.1016/j.measurement.2018.02.052

[25] R.W. Maruda, G.M. Krolczyk, S. Wojciechowski, K. Zak, W. Habrat, P. Nieslony, *Effects of extreme pressure and anti-wear additives on surface topography and tool wear during MQCL turning of AISI 1045 steel*, Journal of Mechanical Science and Technology, vol 32, pp. 1585-1591, 2018, doi: 10.1007/s12206-018-0313-7

[26] P.G. Krishnan, P. Saravanan, D.S. Raj, S. Hussain, V.R. Shankar, N. Raj, *Optimization of jet position and investigation of the effects of multijet MQCL during end milling of Ti-6Al-4V*, Journal of Manufacturing Processes, vol. 64, pp. 392-408, 2021, doi: 10.1016/j.jmapro.2021.01.038

[27] A.K. Sharma, A.K. Tiwari, A.R. Dixit, *Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review*, Journal of Cleaner Production, vol. 127, pp. 1–18, 2016, doi: 10.1016/j.jclepro.2016.03.146

[28] S. Chinchanikar, S.S. Kore, P. Hujare, *A review on nanofluids in minimum quantity lubrication machining*, Journal of Manufacturing Processes, vol. 68, pp. 56–70, 2021, doi: 10.1016/j.jmapro.2021.05.028

[29] M.K. Gupta, M. Jamil, X. Wang, Q. Song, Z. Liu, M. Mia, H. Hegab, A.M. Khan, A.G. Collado, C.I. Pruncu, G.M. Shah Imran, *Performance evaluation of vegetable oil-based nanocutting fluids in environmentally friendly machining of Inconel-800 Alloy*, Materials, vol. 12, iss. 17, 2019, doi: 10.3390/ma12172792

[30] X. Wang, Y. Song, C. Li, Y. Zhang, H.M. Ali, S. Sharma, R. Li, M. Yang, T. Gao, M. Liu, X. Cui, Z. Said, Z. Zhou, *Nanofluids application in machining: a comprehensive review*, The International Journal of Advanced Manufacturing Technology, 2023, doi: 10.1007/s00170-022-10767-2

[31] J. Sharma, B.S. Sidhu, *Investigation of effects of dry and near dry machining on AISI D2 steel using vegetable oil*, Journal of Cleaner Production, vol. 66, pp. 619–623, 2014, doi: 10.1016/j.jclepro.2013.11.042

[32] B. Shen, A.J. Shih, S.C. Tung, *Application of nanofluids in minimum quantity lubrication grinding*, Tribology Transactions, vol. 51, iss. 6, pp. 730–737, 2008, doi: 10.1080/10402000802071277

[33] R. Kumar, A.K. Sahoo, P.C. Mishra, R.K. Das, *Influence of Al2O3 and TiO2 nanofluid on hard turning performance*, The International Journal of Advanced Manufacturing Technology, vol. 106, pp. 2265-2280, 2019, doi: 10.1007/s00170-019-04754-3

[34] D. Setti, M.K. Sinha, S. Ghosh, P. Venkateswara Rao, *Performance evaluation of Ti-6Al-4V grinding using chip formation and coefficient of friction under the influence of nanofluids*, International Journal of Machine Tools and Manufacture, vol. 88, pp. 237–248, 2015, doi: 10.1016/j.ijmachtools.2014.10.005

[35] V. Vasu, G.P.K. Reddy, *Effect of minimum quantity lubrication with Al_2O_3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy*, Proceedings of the Institution of Mechanical Engineers Part N Journal of Nanoengineering and Nanosystems, vol. 225, iss. 1, pp. 3–15, 2012, doi: 10.1177/1740349911427520

[36] X. Bai, J. Jiang, C. Li, L. Dong, H. Muhammad Ali, S. Sharma, *Tribological Performance of Different Concentrations of Al2O3 Nanofluids on Minimum Quantity Lubrication Milling*, Chinese Journal of Mechanical Engineering, vol. 36, iss. 1, 2023, doi: 10.1186/s10033-022-00830-0

[37] O. Gutnichenko, V. Bushlya, S. Bihagen, J.E. Ståhl, *Influence of graphite nanoadditives to vegetable-based oil on machining performance when MQCL assisted hard turning*, Procedia CIRP, vol. 77, pp. 437–440, 2018, doi: 10.1016/j.procir.2018.08.281

[38] N. Anand, A.S. Kumar , S. Paul, *Effect of cutting fluids applied in MQCL mode on machinability of Ti-6Al-4V*, Journal of Manufacturing Processes, vol. 43, pp. 154–163, 2019, doi: 10.1016/j.jmapro.2019.05.029

[39] D. Zhang, C.Li, D. Jia, Y. Zhang, X Zhang, *Specific grinding energy and surface roughness of nanoparticle jet minimum quantity lubrication in grinding*, Chinese Journal of Aeronautics, vol. 28, iss. 2, pp. 570–581, 2018, doi: 10.1016/j.cja.2014.12.035

[40] A. Eltaggaz, P. Zawada, H.A. Hegab, I. Deiab, H.A. Kishawy, *Coolant strategy influence on tool life and surface roughness when machining ADI*, The International Journal of Advanced Manufacturing Technology, vol. 94, pp. 3875–3887, 2018, doi: 10.1007/s00170-017-1088-1

[41] H. Hegab, H.A. Kishawy, U. Umer, A. Mohany, *A model for machining with nano-additives based minimum quantity lubrication*, International Journal of Advanced Manufacturing Technology, vol. 102, pp. 2013–2028, 2019, doi: 10.1007/s00170-019-03294-0

[42] H. Hegab, H.A. Kishawy, *Towards Sustainable Machining of Inconel 718 Using Nano-Fluid Minimum Quantity Lubrication*, Journal of Manufacturing and Materials Processing, vol. 2, iss. 3, 2018, doi: 10.3390/jmmp2030050

[43] R.S. Vajjha, D.K. Das, *A review and analysis on influence of temperature and concentration of nanofluids on thermophysical properties, heat transfer and pumping power*, International Journal of Heat and Mass Transfer, vol. 55, pp. 4063–4078, 2012, doi: 10.1016/j.ijheatmasstransfer.2012.03.048

[44] P. Kalita, A.P. Malshe, K.P. Rajurkar, *Study of tribo-chemical lubricant film formation during application of nanolubricants in minimum quantity lubrication (MQL) grinding*, CIRP Annals, vol. 61, iss. 15-16, pp. 327–330, 2012, doi: 10.1016/j.cirp.2012.03.031

[45] P. Kalita, A.P. Malshe, S. Arun Kumar, V.G. Yoganath, T. Gurumurthy, *Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants*, Journal of Manufacturing Processes, vol. 14, iss. 2, pp. 160–166, 2012, doi: 10.1016/j.jmapro.2012.01.001

[46] Y. Wang, C. Li, Y. Zhang, M. Yang, B. Li, D. Jia, Y. Hou, C.Mao, *Experimental evaluation of the lubrication properties of the wheel/workpiece interface in minimum quantity lubrication (MQL) grinding using different types of vegetable oils*, Journal of Cleaner Production, vol. 127, pp. 487–499, 2016, doi: 10.1016/j.jclepro.2016.03.121

[47] Y. Zhang, C. Li, D. Jia, D. Zhang, X. Zhang, *Experimental evaluation of MoS_2 nanoparticles in jet MQL grinding with different types of vegetable oil as base oil*, Journal of Cleaner Production, vol. 87, pp. 930–940, 2016, doi: 10.1016/j.jclepro.2014.10.027

[48] S. Debnath, M.M. Reddy, Q.S. Yi, *Environmental friendly cutting fluids and cooling techniques in machining: A review*, Journal of Cleaner Production, vol. 83, pp. 33–47, 2016, doi: 10.1016/j.jclepro.2014.07.071

[49] G.J. Ranque, *Experiments on expansion in a vortex with simultaneous exhaust of hot air and cold air,* Le Journal De Physique et le Radium**,** vol. 4, pp. 112-114, 1933.

[50] T.M. Duc, T.T. Long, P.Q. Dong, *Effect of the alumina nanofluid concentration on minimum quantity lubrication hard machining for sustainable production*, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, vol. 233, iss. 17, pp. 5977–5988, 2019, doi: 10.1177/0954406219861992

[51] F. Günan, T. Kıvak, Ç.V. Yıldırım, M. Sarıkaya, *Performance evaluation of MQL with Al_2O_3 mixed nanofluids prepared at different concentrations in milling of Hastelloy C276 alloy*, Journal of Materials Research and Technology, vol. 9, iss. 5, pp. 10386–10400, 2020 http://doi.org/10.1016/j.jmrt.2020.07.018