

Article

Experimental Investigation on Cutting Forces in Sustainable Hard Milling of Hardox 500 Steel Under $\text{Al}_2\text{O}_3/\text{MoS}_2$ Hybrid Nanofluid MQCL Environment

Tran The Long 

Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen 250000, Vietnam; tranthelong@tnut.edu.vn; Tel.: +84-985-288-777

Abstract: Hardox 500 is a special low-alloy, martensitic steel possessing extraordinary wear resistance, high hardness, and high ductility; thus, it has been widely used in many industrial applications. Nevertheless, this type of steel has a low machinability and is grouped among the difficult-to-machine materials. Hence, this paper's objective was to study its hard milling performance under minimum quantity cooling lubrication (MQCL) conditions using an $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil. The Box–Behnken response surface methodology was used to investigate the effects of the nanoparticle concentration (NC), cutting speed (v), and feed rate (f) on the total cutting force F and cutting force coefficient F_y/F_z . The obtained results indicate that the cutting efficiency of Hardox 500 steel was improved thanks to the enhancement in cooling lubrication from the MQCL using the $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil. The applicability of vegetable oil and coated carbide inserts is thus extended to the hard milling of difficult-to-cut materials. Moreover, the provision of the appropriate ranges and optimal set of investigated variables obtained in this paper will be useful guides for technologists and further studies. Concretely, $\text{NC} = 0.5\text{--}0.7\%$, $v = 110\text{--}115$ m/min, and $f = 0.08\text{--}0.10$ mm/tooth are the optimal set for the total cutting force F , while $\text{NC} = 0.5\%$, $v = 138\text{--}140$ m/min, and $f = 0.08\text{--}0.09$ mm/tooth are suggested for the cutting force coefficient F_y/F_z .

Keywords: Hardox 500; hard milling; hard machining; MQL; MQCL; nanofluid; hybrid nano cutting oil; total cutting force; cutting force coefficient



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1. Introduction

Recently, sustainable machining has been drawing growing attention within the metal cutting industry. The simplest way to ensure environmentally friendly characteristics is to eliminate or maximally reduce the usage of cutting oil. Another approach is the replacement of mineral cutting oils with biodegradable ones, like vegetable oil and vegetable-based oil. Many studies have been carried out in line with these directions. Among them, dry hard milling has been applied to machines, such as steels with high hardness (usually above 45 HRC) [1]. This process has brought an improvement in productivity [2] while ensuring a high machined-surface quality, as well as environmentally friendly properties [3]. However, the huge amount of cutting heat required is a major cause of early worn tools and the machined surface's deterioration [4]. In addition to that, thermal shock phenomena result in the discontinuous cutting character of hard milling, which limits the use of cutting fluid under flood conditions [3,4]. To overcome these problems, the requirements for cooling, lubrication, and cutting tool materials play crucial roles in successful hard milling. The cutting inserts used for hard machining must possess high hardness and

good heat resistance, like coated carbide [3], ceramics [5], Cubic Boron Nitride (CBN) [6], diamond [7], and so forth. Moreover, the minimum quantity cooling (MQC), minimum quantity lubrication (MQL), and nanofluid minimum quantity lubrication (NF MQL) have been studied and proven to be suitable for hard machining technology. Sartori et al. [8] used cooled gaseous nitrogen in a range of temperatures between 0° and −150 °C to assist the semi-finishing turning of a Ti6Al4V titanium alloy. The findings indicated a significant reduction in tool wear under N₂ cooled at −150 °C compared to Liquid Nitrogen (LN₂) and wet conditions. Additionally, the machined-surface integrity under the cooled N₂ conditions was improved in terms of the deformed layer and the main typologies of the surface defects. Pereira et al. [9] investigated the hybrid CO₂ + MQL's effectiveness for milling Inconel 718. The authors also made a comparison with dry, wet, CO₂ standalone, and MQL conditions. They concluded that the milling performance under the hybrid CO₂ + MQL environment showed the best results and reached values about 90% higher than those from wet machining. The superior cooling and lubricating effects were the main factors behind the obtained results. Sharma et al. [10] conducted a review of the nanofluid minimum quantity lubrication (NF MQL) in machining and compared it to dry and wet cutting as well as to MQL using conventional oils. The authors claimed that most studies have shown that better cooling and lubricating effects result from NF MQL and MQL conditions. They could be a viable alternative to a flood coolant to achieve sustainable characteristics.

In the MQL method, the lubricant, in the form of an oil mist with high pressure, is directly sprayed onto the cutting zone, so better lubrication has been reported when compared to flood coolants in terms of cutting forces, cutting temperature, tool life, and surface quality [11]. However, the application of this method in hard machining does not show the findings expected to result from the low cooling efficiency [4]. The utilization of nanofluid as the base fluid for MQL to improve the cooling and lubricating performance is an up-to-date topic, and some studies have pointed out promising results. Nanofluids are formed by suspending nanoparticles, such as Al₂O₃, graphite, graphene, MoS₂, TiO₂, SiC, and so forth, with a suitable concentration. The objective is to enhance the cooling and lubricating effects of the base oil [12]. In addition, nanoparticles also play a role in reducing the base oil viscosity [13]. Hence, many researchers have pointed out the effectiveness of nanofluid MQL for hard cutting processes. Abbas et al. [14] studied the effects of Al₂O₃ nanofluid MQL conditions on the hard turning performance of AISI 1045 steel. A better thermal conductivity was noted, and the friction coefficient was reduced, leading to an improvement in machining efficiency. Şirin and Kivak found better results when milling the Inconel X-750 superalloy, due to an enhancement in the thermal conductivity and lubricity by using nano cutting oil [15]. Uysala et al. [16] investigated the impact of MoS₂ nanofluid MQL on the milling performance of AISI 420 stainless steel. The findings indicated that a longer tool life and better machined-surface quality resulted from the superior lubricating performance of the MoS₂ nano cutting oil. Also, the nanoparticle concentration and oil flow rate exhibited significant influences and should be focused upon and optimized. Lee et al. [17] achieved a reduction in the friction coefficient of up to 23% by using diamond nanofluid, thereby improving the cutting outcomes in terms of the surface quality and cutting heat when compared to cutting oil without nanoparticles. In a study by Ali et al. [13] on the application of Al₂O₃ and TiO₂ nano solutions in engine lubricating oils, the friction coefficient and wear amount were reduced by 11% and 2.6%, respectively, due to the superior lubricating performance of Al₂O₃ and TiO₂ nanoparticles. Maruda et al. [18] studied the different copper nanoparticle sizes (22 nm, 35 nm, 65 nm, and 80 nm) and concentrations (0.25%, 0.5%, 0.75%, and 1.0%) in the base oil of the MQL system for the turning process of 316L stainless steel. The obtained findings revealed that

the better surface topography was tightly related to the usage of the smaller nanoparticle size. Among the investigated concentrations, the concentration of 0.5% is more suitable for better surface quality and lower power consumption. In addition, the agglomerations of copper nanoparticles can occur in the case of increasing the concentration from 0.5% to 0.8%, which negatively impacts the machining outputs [19].

The technological parameters of nano cutting oils include the base oil type and the characteristics of nanoparticles (grain size, morphology, and concentration). Hegab et al. [20] investigated the effectiveness of a carbon nanotube (CNT) nanofluid MQL on the turning performance of the Ti-6Al-4V alloy. The superior cooling effect of the carbon nanotube plays a key role in surface quality improvement and tool wear reduction. Also, the CNT concentration and feed rate strongly influence the machined-surface quality. In addition, a better lubricating performance resulting from the high hardness and nearly spherical morphology of Al_2O_3 nanoparticles was reported, which enhanced the tool machinability when turning the Inconel 718 alloy [21]. Eltaggaz et al. [22] compared the different cooling lubrication modes including dry, flooded, MQL, and nanofluid MQL for the hard milling of ADI steel. The obtained findings indicated an improvement in the thermal conductivity of vegetable oil containing Al_2O_3 nanoparticles. In addition, the presence of Al_2O_3 nanoparticles effectively contributed to reducing the coefficient friction in the cutting zone and improving lubrication and cooling performance, thereby decreasing the cutting forces and enhancing the machined-surface quality. The similar results were reported when Al_2O_3 nanoparticles were suspended in palm oil for MQL grinding of the nickel alloy GH4169 [23]. Luo et al. [24] found a good resistance of Al_2O_3 nanofluid to high temperature.

In order to improve the cooling effect of the MQL technique, minimum quantity cooling lubrication (MQCL) has been developed and studied. The better cooling and lubricating performance of the MQCL technique in turning the Ti6Al4V alloy was reported when compared to dry and flooded conditions [25]. Maruda et al. [26] investigated the effects of MQCL parameters on the hard turning performance of AISI 1045 steel and found out that the emulsion mist formation in contact zones effectively improves the cooling and lubricating property. The more favorable condition for chip formation and the reduction in the chip-thickening coefficient was noted in the turning process of austenitic stainless steel 316L under the MQCL condition [27]. Nevertheless, the cooling effect of the MQCL condition in these studies resulted from the good cooling property of the emulsion cutting oil (water-soluble cutting oil).

Zhang et al. [28] evaluated the tool life and cutting forces in end milling of Inconel 718 under dry and MQCL environments. Through the experimental results, MQCL with biodegradable vegetable oil improved the end milling performance with tool life extension and cutting force reduction. Hariprasad and his co-authors [29] studied the impacts of the cutting edge radius on chip formation and surface quality in the MQCL end milling of Ti6Al4V. In this work, the sub-zero air from the vortex tube mechanism is supplied to an MQL nozzle to form an MQCL condition. The larger edge radius of the tools led to the better penetration of MQCL aerosol into the cutting zone, which contributed to decrease the cutting force, cutting temperature, tool wear, and surface roughness values. Anand et al. [30] conducted an experimental investigation on the MQCL technique using soluble oil in turning Ti-6Al-4V. The obtained results indicated the better machining efficiency based on cutting forces, tool wear, and contact faces when compared to wet cutting. Nevertheless, the use of a true MQCL device to a spray-cooled minimal quantity oil based on the principle of the Ranque–Hilsch vortex tube is still limited [31,32]. Hence, in this paper, the Frigid-X Sub-Zero Vortex Tool Cooling Mist System made by Nex Flow™, Richmond Hill, ON, Canada [33], was used to create the MQCL environment for the hard milling process of Hardox 500 steel.

Hardox 500 steel, produced by the SSAB company in Sweden [34], is not intended for further heat treatment and possesses a fairly high hardness (470–530 HBW). In addition, this type of steel has high strength and superior wear resistance as well as high ductility. Hence, it is widely used in heavy industries such as stone mining, coal mining, oil exploitation, cement production, electricity production, and mechanical processing industries, making vehicle bodies, crushers, bucket trucks, bulldozers, and so forth. Nevertheless, possessing many good mechanical properties at the same time, Hardox 500 steel has low machinability and is grouped among the difficult-to-cut materials [35]. The additives of hybrid nanoparticles in the base oil for the MQCL system will result in supplementary cooling and lubricating effects that improve the cutting performance. Therefore, the application of $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid MQCL in the hard milling of Hardox 500 steel will create economic, technical, and environmental significance. This is a novel research topic, but little information has been reported [35,36]. This article aims to study the influence of the investigated parameters (nanoparticle concentration, cutting speed, and feed rate) on the total cutting force F (N) and cutting force coefficient F_y/F_z in the hard milling process of Hardox 500 steel under an MQCL environment using $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil.

2. Materials and Methods

The set-up diagram of the experiments and measurements is shown in Figure 1. A Mazak vertical center smart 530C (Yamazaki Mazak Corporation, 1–131 Takeda, Oguchi-cho, Niwa-gun, Aichi-Pref, Japan) was used for the experiments. The APMT 1604 PDTR LT30 PVD TiAlN-coated carbide inserts (flank angle (11°), nose radius (0.66 mm)) were mounted on the SHIJIE BAP 400R-50-22-4T face mill head. The diameter of the face mill head was 50 mm, and a single cutting edge was used. After each cutting trial, the cutting insert was replaced by a new one. For the MQCL system, the Frigid-X Sub-Zero Vortex Tool Cooling Mist System (Nex Flow™, Richmond Hill, ON, Canada) was used, alongside $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid with soybean oil as the base oil, the air pressure regulator, and PT-0136 compressed air. Al_2O_3 nanoparticles and MoS_2 nanosheets with an average grain size of 30 nm were produced by Soochow Hengqiu Graphene Technology Co., Ltd. (Suzhou, China) and Luoyang Tongrun Info Technology Co., Ltd. (Luoyang, China), respectively. The mixing ratio of $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid in the soybean oil is 80:20 by the suggestion of some works in the literature [36,37]. The Ultrasons-HD ultrasonicator (JP SELECTA, Abrera, Spain) generated 600W ultrasonic pulses at 40 kHz for one hour to uniformly suspend the nanoparticles in the soybean oil to prepare the $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil, which was directly used for the MQCL system. The schematic shown in Figure 2 illustrates how the $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid MQCL environment assisted to hard milling process. The $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid is siphoned into the MQCL device and cooled by means of a small vortex tube. The sub-zero hybrid nanofluid was directly introduced to the flank face of the cutting tool. The cutting force component values were measured by a Kistler quartz three-component dynamometer (9257BA). The designation of cutting force direction in single-insert face milling is shown in Figure 3. In this study, the dimension of Hardox 500 steel workpieces is $150 \times 100 \times 15$ mm. Tables 1 and 2 show the elemental composition and mechanical properties of Hardox 500 steel. The resultant cutting force F and its values are calculated by Equations (1) and (2).

$$\vec{F} = \vec{F}_x + \vec{F}_y + \vec{F}_z \quad (1)$$

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

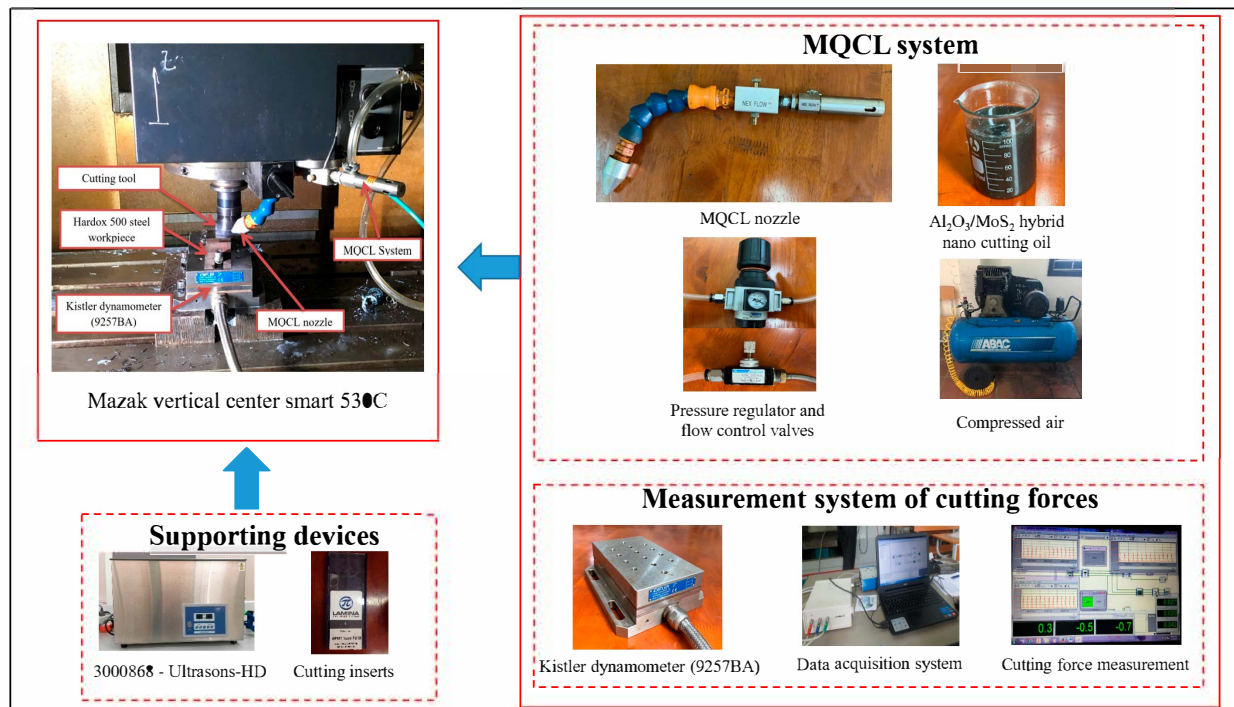


Figure 1. The diagram of experiments and measurements.

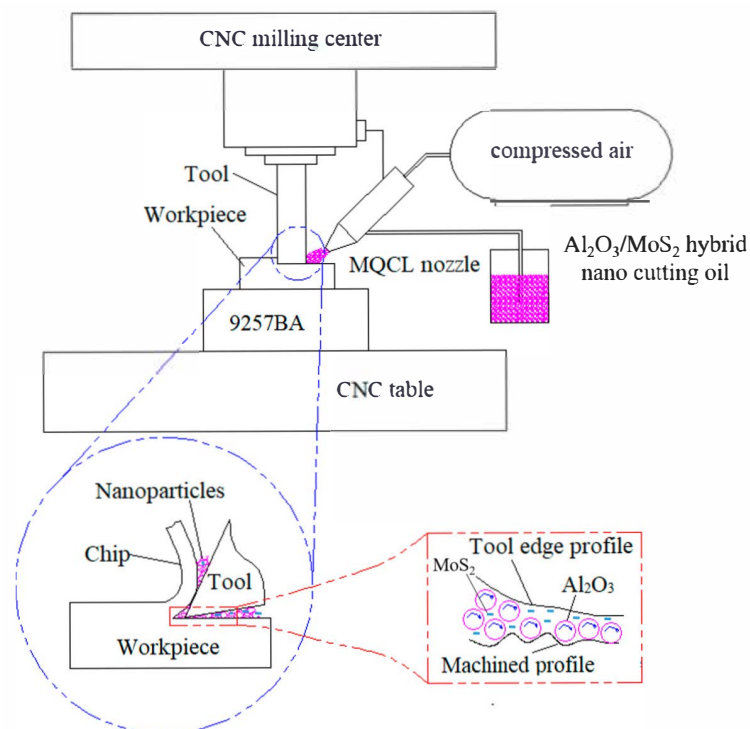


Figure 2. A schematic of hard milling experiments under $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid MQCL environment.

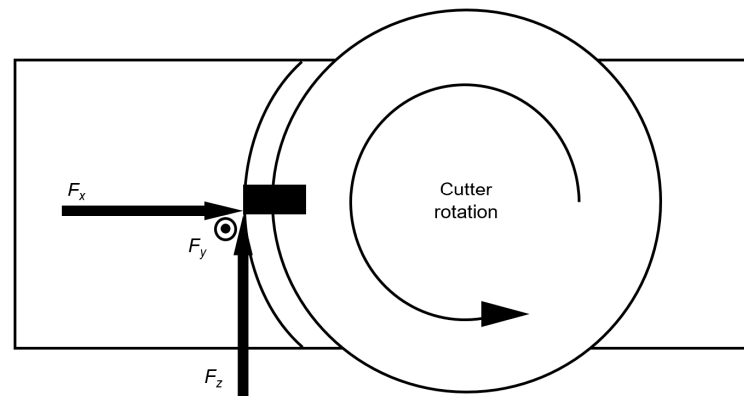


Figure 3. Forces on tool in single insert face milling with the tangential force F_z , feed force F_x , and axial force F_y (directed out of the page).

Table 1. Elemental composition of Hardox 500 steel.

Elemental Composition (Max %)								
C	Si	Mn	P	S	Cr	Ni	Mo	B
0.3	0.7	1.6	0.25	0.01	1.5	1.5	0.6	0.005

Table 2. Mechanical properties of Hardox 500 steel.

Yield Strength, MPa	Tensile Strength, MPa	Elongation, %	Hardness Range, HBW	Hardness Range, HRC
1250	1400	10	470–530	49–50

3. Results and Discussion

The experimental design was built by using the Box–Behnken response surface methodology. The influences of the investigated parameters (nanoparticle concentration (NC), cutting speed (v), and feed rate (f)) on the total cutting force F (N) and cutting force coefficient F_y/F_z were evaluated as shown in Table 3. The selection of input variables and their values was based on previous works [36,38].

Table 3. Input parameters and responses.

Input Variables	Symbol	Low Level	High Level	Responses
Nanoparticle concentration (%)	NC	0.5	1.5	Total cutting force F (N), cutting force coefficient F_y/F_z
Cutting speed (m/min)	v	80	140	
Feed rate (mm/tooth)	f	0.08	0.16	

The experiments were carried out by following the RunOrder. Each of the cutting trials was repeated three times under the same cutting condition and the average values of the cutting forces were reported. The measured output variables of the experimental design are summarized in Table 4.

Table 4. Summary of the design of experiment and the measured cutting force values.

Std Order	Run Order	PtType	Blocks	Input Parameters			Output Parameters	
				NC (%)	v (m/min)	f (mm/tooth)	F (N)	F_y/F_z
1	10	2	1	0.5	80	0.12	321	0.579
2	2	2	1	1.5	80	0.12	381	0.679
3	1	2	1	0.5	140	0.12	307	0.557
4	18	2	1	1.5	140	0.12	307	0.659
5	16	2	1	0.5	110	0.08	180	0.670
6	22	2	1	1.5	110	0.08	259	0.701
7	4	2	1	0.5	110	0.16	221	0.681
8	24	2	1	1.5	110	0.16	405	0.723
9	30	2	1	1	80	0.08	221	0.618
10	12	2	1	1	140	0.08	213	0.603
11	29	2	1	1	80	0.16	350	0.719
12	27	2	1	1	140	0.16	386	0.896
13	15	0	1	1	110	0.12	226	0.746
14	6	0	1	1	110	0.12	227	0.737
15	11	0	1	1	110	0.12	225	0.720
16	14	2	1	0.5	80	0.12	323	0.564
17	5	2	1	1.5	80	0.12	381	0.638
18	28	2	1	0.5	140	0.12	207	0.665
19	9	2	1	1.5	140	0.12	308	0.687
20	13	2	1	0.5	110	0.08	184	0.712
21	23	2	1	1.5	110	0.08	273	0.713
22	3	2	1	0.5	110	0.16	160	0.768
23	21	2	1	1.5	110	0.16	400	0.760
24	19	2	1	1	80	0.08	214	0.664
25	8	2	1	1	140	0.08	224	0.614
26	7	2	1	1	80	0.16	344	0.724
27	25	2	1	1	140	0.16	390	0.890
28	20	0	1	1	110	0.12	227	0.718
29	26	0	1	1	110	0.12	225	0.735
30	17	0	1	1	110	0.12	180	0.851

Minitab 19 software was used to study the experimental data with a significance level $\alpha = 0.05$ and obtain the results. Equation (3) is the regression model for the influences of the investigated parameters on the total cutting force F . The coefficient of determination $R^2 = 81.51\%$ proves that the proposed model is consistent with the experimental data. The Pareto charts evaluate the influences of the input parameters on the total cutting force F and cutting force coefficient F_y/F_z given in Figures 4 and 5.

$$F \text{ (N)} = 1373 - 339*NC - 17.29*v - 2441*f + 132*NC*NC + 0.0728*v*v + 5466*f*f - 0.144*NC*v + 1599*NC*f + 8.3*v*f \quad (3)$$

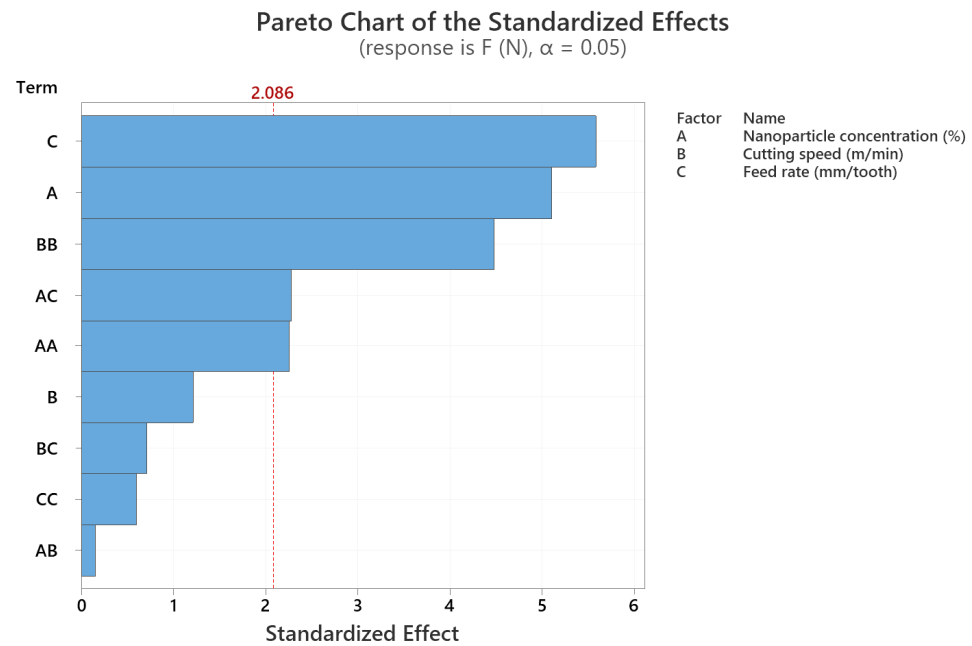


Figure 4. Pareto chart of influences of the input variables on total cutting force F .

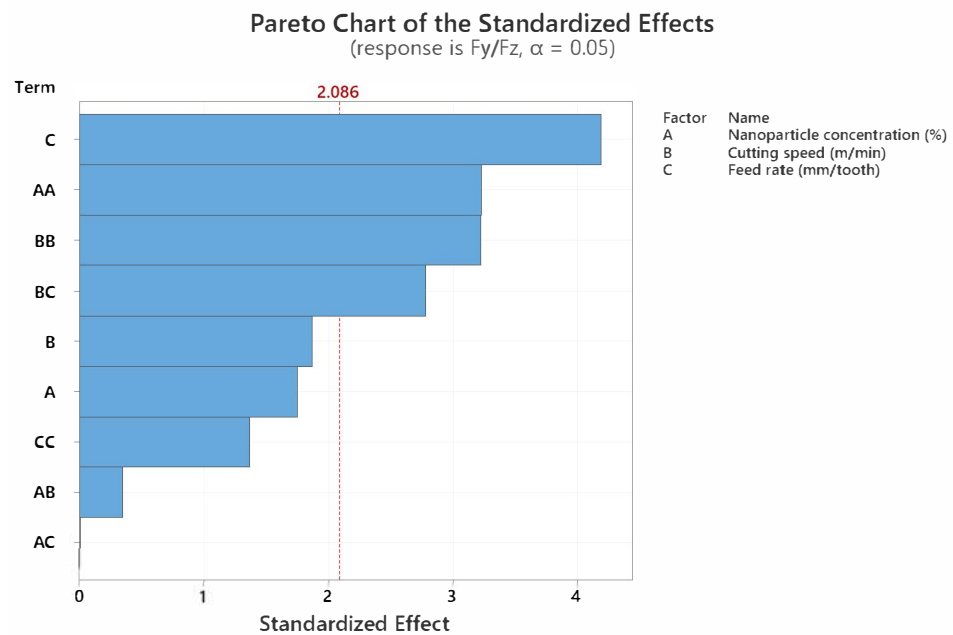


Figure 5. Pareto chart of influences of the input variables on cutting force coefficient F_y/F_z .

In Figure 4, the factors that exceed the reference line with the value of 2.086 are statistically significant and cause a strong influence on the total cutting force. Among the investigated variables, the feed rate f has the largest influence on the total cutting force, followed by the nanoparticle concentration and the second-order interaction effect of cutting speed. In addition, it was noticeable that the interaction effect between nanoparticle concentration and feed rate and the second-order interaction effect of nanoparticle concentration ($NC*NC$) also had significant influences. For the cutting force coefficient F_y/F_z in Figure 5, the feed rate is still the factor with the strongest impact, while the nanoparticle concentration and cutting speed ($NC*v$) have little influence. However, the second-order interaction effect of the nanoparticle concentration ($NC*NC$) and cutting speed ($v*v$), as well as the interaction effect between the cutting speed and feed rate ($v*f$), strongly affects the cutting force coefficient F_y/F_z .

From Figure 6, it can be seen that the total cutting force value increases sharply with the growth in feed rate. The main reason is the increased area of the cutting layer combined with the high strength and toughness of Hardox 500 steel. When NC increased from 0.5% to about 0.6%, the total cutting force decreased slightly and reached the smallest value in the survey range. This is a reasonable value range for the nanoparticles to penetrate into the cutting zone and exert their cooling lubrication characteristics, thereby decreasing the friction coefficient and cutting heat [24]. The total cutting force F value increased rapidly with the increase in the nanoparticle concentration to 1.5%, reflecting that the large number of nanoparticles entering the cutting zone caused compression and impedance phenomena [4]. Hence, it interrupts the lubrication process and hinders the cutting process [10]. Meanwhile, when the cutting speed went up from 80 m/min to 110 m/min, the total cutting force decreased but increased with the growth in the cutting speed from 110 m/min to 130 m/min. It can be explained that the unique combination of high temperatures on the contact faces between the cutting tool and workpiece combined with low feed rate in hard milling generates self-induced heat, leading to decreased cutting forces [1].

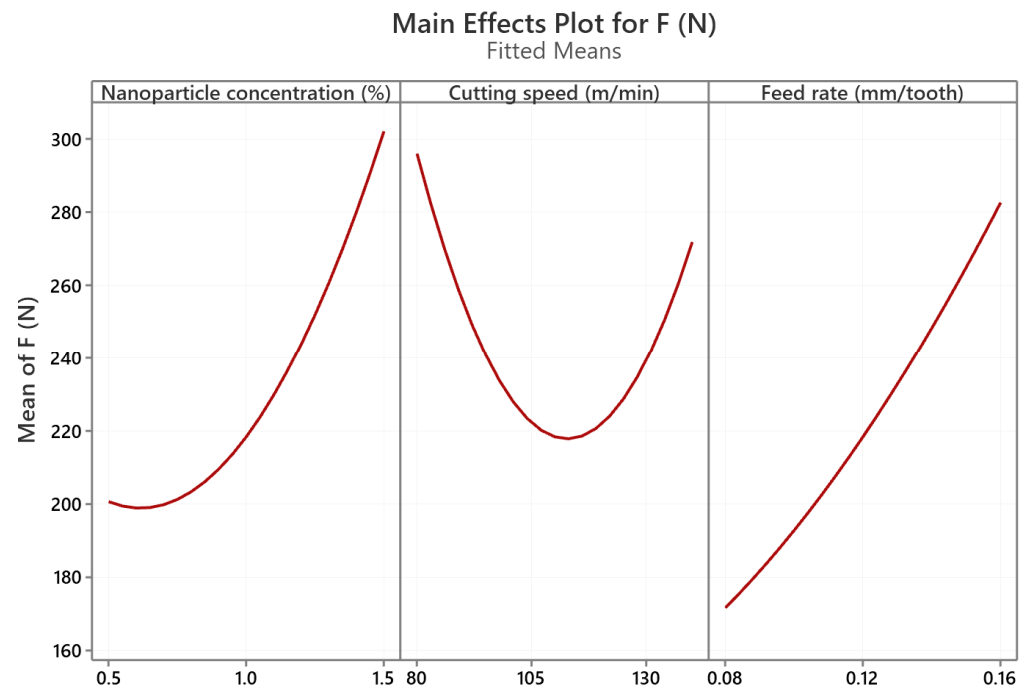


Figure 6. Main effects of the investigated variables on the total cutting force F .

For the cutting force coefficient F_y/F_z in Figure 7, the impacts of NC and v are similar. In the case of the rise in NC from 0.5% to 1.1% and v from 80 m/min to 115 m/min, the cutting force coefficient increased and reached a peak. This coefficient decreased when NC further increased to 1.5% and v reached 140 m/min. At the same time, the cutting force coefficient F_y/F_z rapidly increased with the growing feed rate. This indicates that the increasing rate of the axial thrust component F_y is faster than that of the tangential force F_z . This phenomenon reflects the impact of the high strength and high toughness of Hardox 500 steel which has a significant influence on the cutting force variation. Also, it causes elastic deformation affecting F_y . The smaller the cutting force coefficient F_y/F_z , the more favorable the chip formation process is. However, if this coefficient is large, the process of chip formation is difficult, causing vibration and dimensional errors [39]. Therefore, the study of the cutting force coefficient F_y/F_z is significant in the efficiency evaluation of the cutting process as well as choosing reasonable technological conditions.

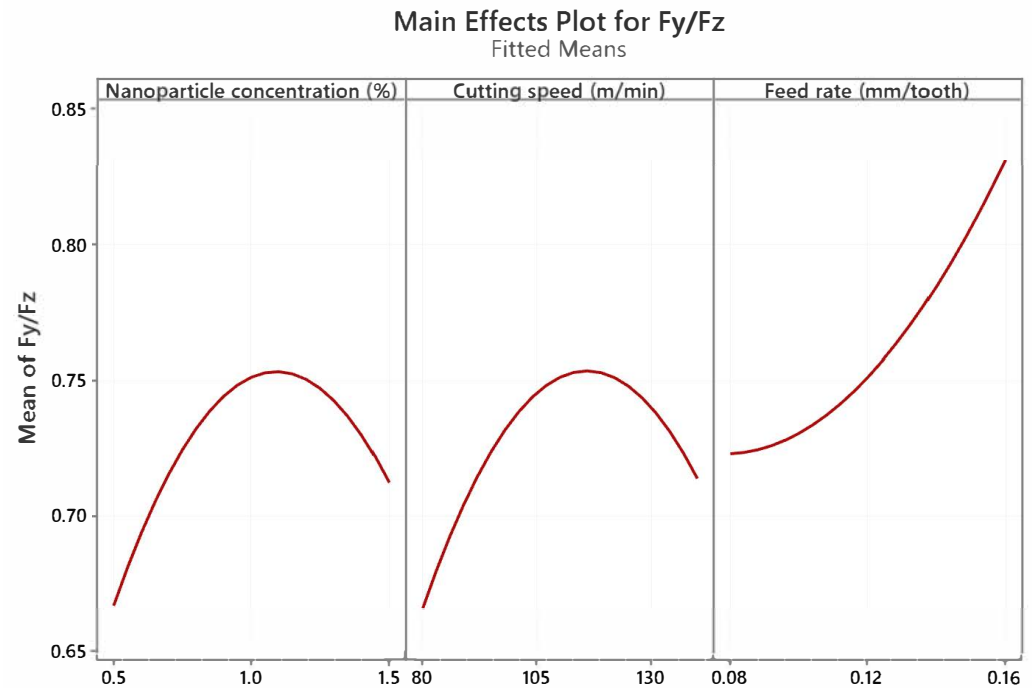


Figure 7. Main effects of the investigated variables on the cutting force coefficient F_y/F_z .

The effects of the surveyed factors on the total cutting force values are shown in Figures 8–10. In Figure 8, for $f = 0.12$ mm/tooth, it can be observed that a low concentration of nanoparticles combined with a medium cutting speed will result in the smallest total cutting force (Figure 8a). Specifically, $NC = 0.55$ – 0.70% and $v = 109$ – 115 m/min should be used to achieve a total cutting force $F < 200$ N (Figure 8b). For $v = 110$ m/min, a feed rate of $f = 0.08$ – 0.12 mm/tooth and $NC = 0.5$ – 1.3% are recommended to achieve the total cutting force $F < 200$ N (Figure 9). For $NC = 1.0\%$, a feed rate of $f = 0.08$ – 0.10 mm/tooth and $v = 95$ – 135 m/min are suggested to achieve a total cutting force $F < 200$ N (Figure 10).

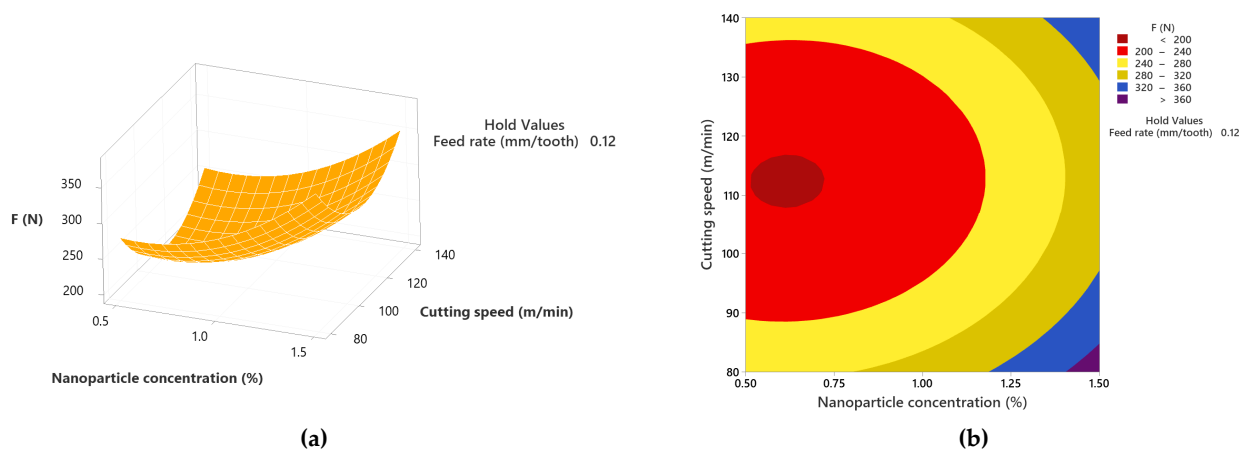


Figure 8. Interaction influences of nanoparticle concentration and cutting speed on the total cutting force F : (a) surface plot; (b) contour plot.

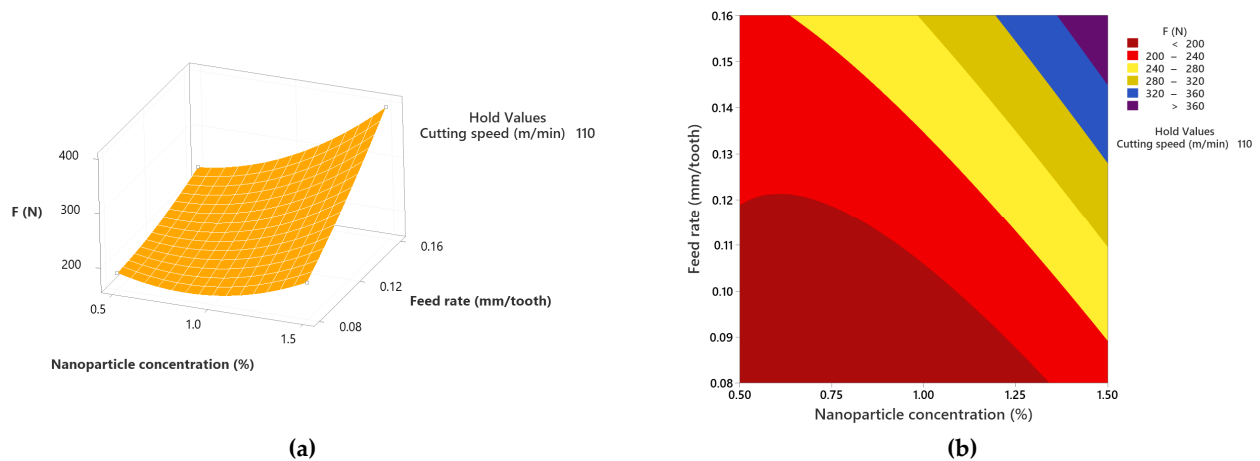


Figure 9. Interaction influences of nanoparticle concentration and feed rate on the total cutting force F : (a) surface plot; (b) contour plot.

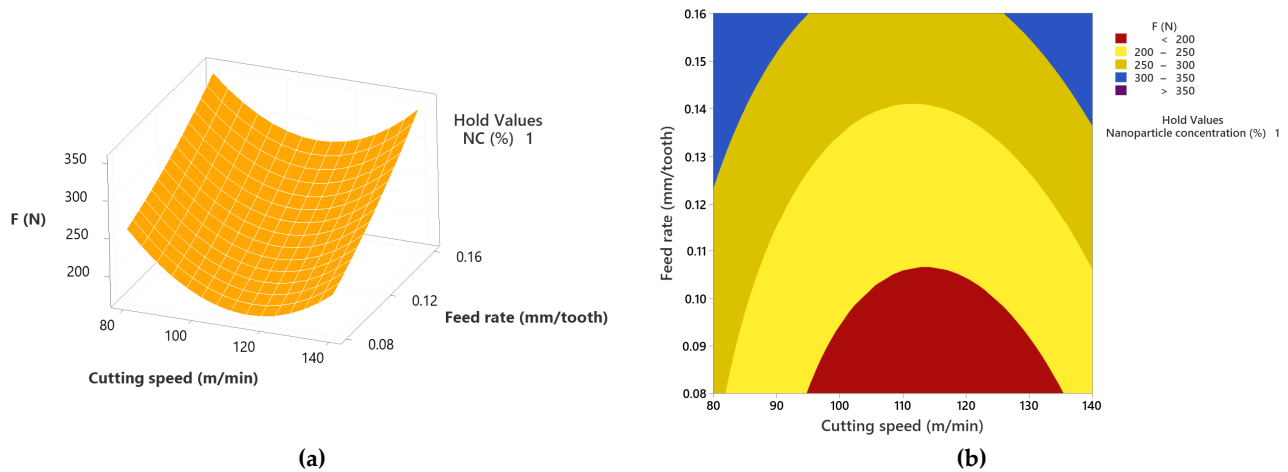


Figure 10. Interaction influences of cutting speed and feed rate on the total cutting force F : (a) surface plot; (b) contour plot.

Thus, for the requirement of smaller cutting forces, the reasonable ranges of $NC = 0.5\text{--}0.7\%$, $v = 110\text{--}115$ m/min, and $f = 0.08\text{--}0.10$ mm/tooth can be selected for $F < 200$ N.

The impacts of the surveyed factors on the cutting force coefficient F_y/F_z are shown in Figures 11–13. In Figure 11, for $f = 0.12$ mm/tooth, the plot indicates that a low concentration of nanoparticles combined with a low cutting speed will give the smallest cutting force coefficient (Figure 11a). Specifically, $NC = 0.5\%$ and $v = 80\text{--}85$ m/min are selected to achieve $F_y/F_z < 0.6$ (Figure 11b). In the case of $v = 110$ m/min, the feed rate $f = 0.08\text{--}0.10$ mm/tooth and $NC = 0.5\%$ are used for the cutting force coefficient $F_y/F_z < 0.65$ (Figure 12). If NC is kept fixed at 1.0% , a feed rate of $f = 0.08\text{--}0.09$ mm/tooth and $v = 138\text{--}140$ m/min are chosen to reach a smaller F_y/F_z ($F_y/F_z < 0.65$) (Figure 13).

Accordingly, $NC = 0.5\%$, $v = 138\text{--}140$ m/min, and $f = 0.08\text{--}0.09$ mm/tooth are the reasonable ranges and are selected to achieve a smaller cutting force coefficient F_y/F_z .

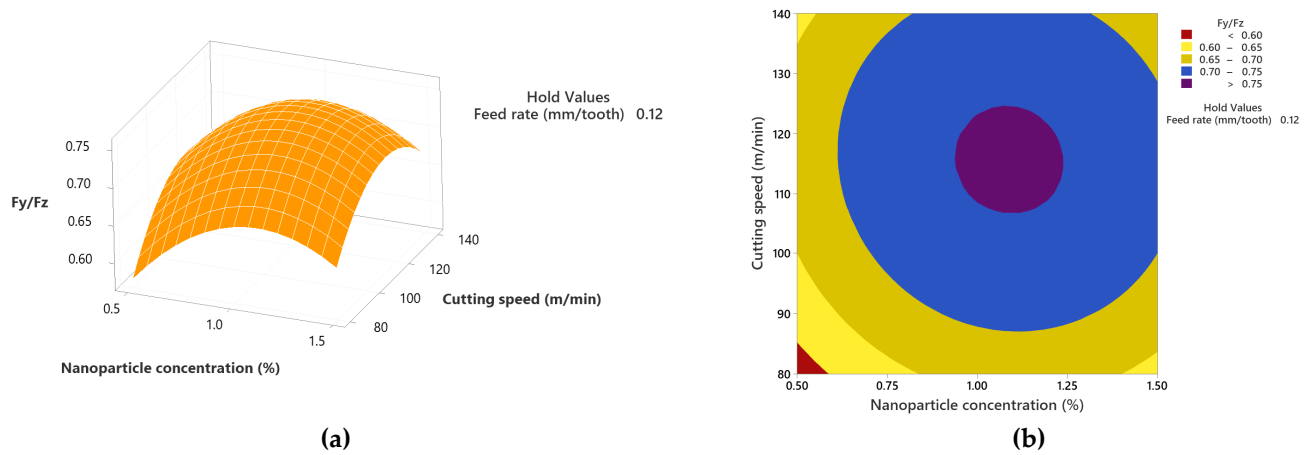


Figure 11. Interaction influences of the nanoparticle concentration and cutting speed on the cutting force coefficient F_y/F_z : (a) surface plot; (b) contour plot.

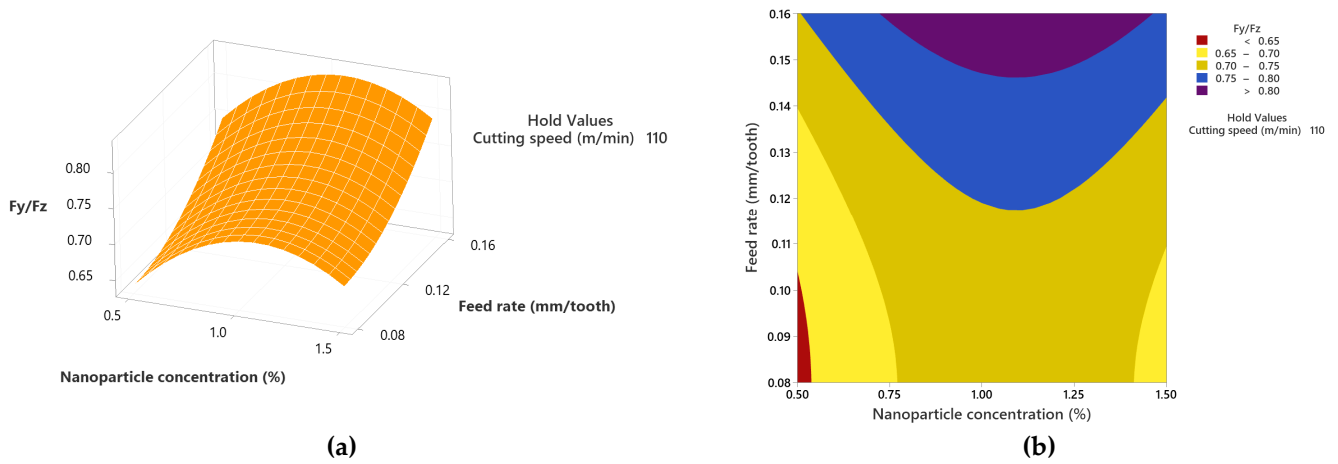


Figure 12. Interaction influences of the nanoparticle concentration and feed rate on the cutting force coefficient F_y/F_z : (a) surface plot; (b) contour plot.

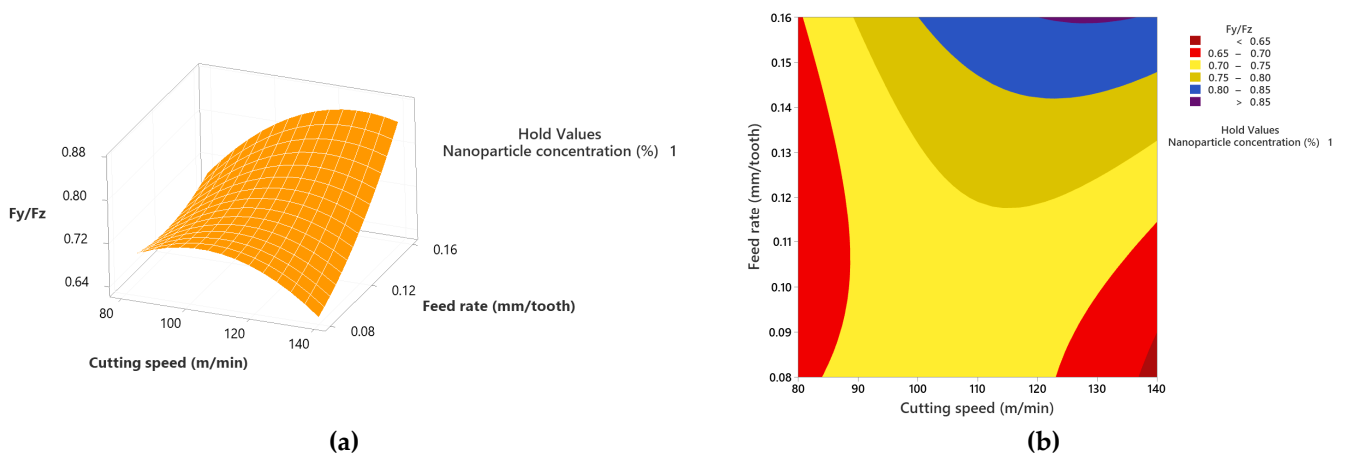


Figure 13. Interaction influences of the cutting speed and feed rate on the cutting force coefficient F_y/F_z : (a) surface plot; (b) contour plot.

Through the obtained results shown in the surface and contour graphs, the selection process for the technological parameters will be quickly performed to achieve the desired output values. However, to obtain the exact values, optimization is needed. The optimization results for each output variable including the total cutting force F and the cutting

force coefficient F_y/F_z are given in Figures 14 and 15. In Figure 14, the optimal value set $NC = 0.8636\%$, $v = 115.0620$ m/min, and $f = 0.08$ mm/tooth is determined to achieve the smallest total cutting force value $F = 167.2690$ N. For convenience in practical application, $NC = 0.9\%$, $v = 115$ m/min, and $f = 0.08$ mm/tooth are used. In Figure 15, the optimal value set $NC = 0.5\%$, $v = 140$ m/min, and $f = 0.08$ mm/tooth is determined to achieve the smallest cutting force coefficient value $F_y/F_z = 0.5572$.

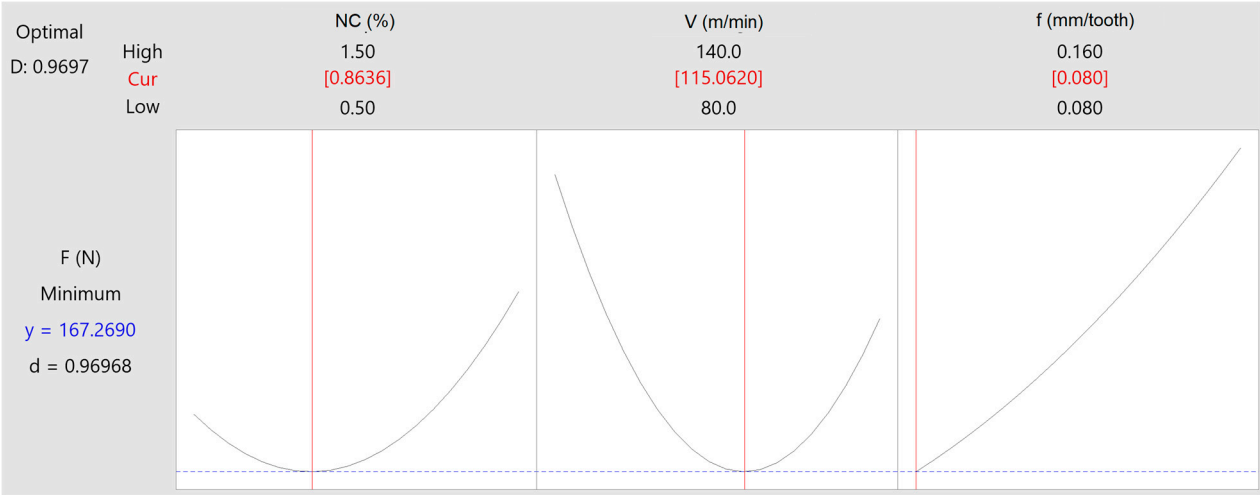


Figure 14. Optimization result for the total cutting force F .

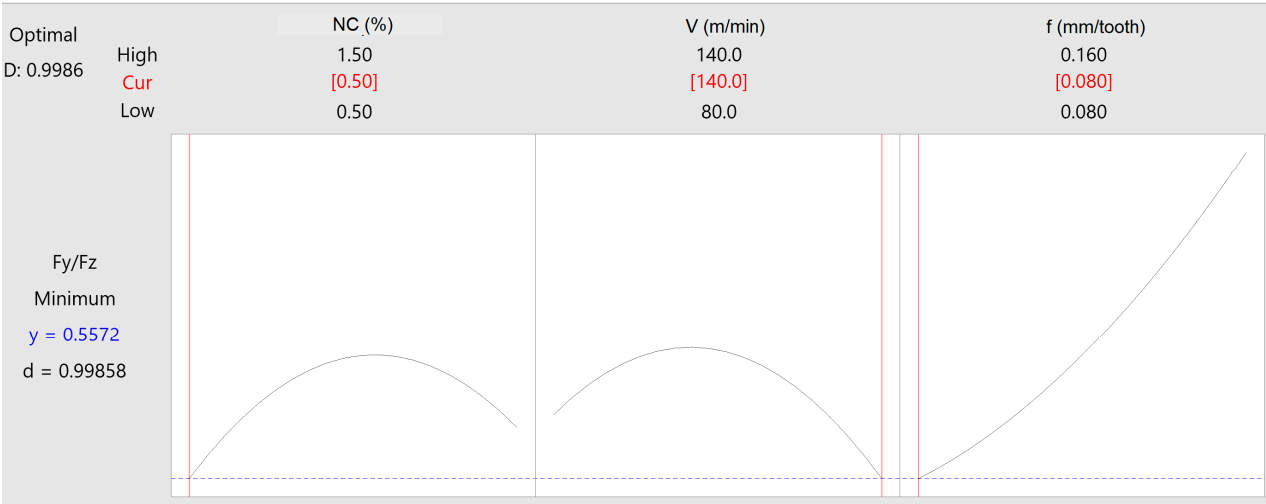


Figure 15. Optimization result for the cutting force coefficient F_y/F_z .

Figure 16 illustrates the result of multi-objective optimization for the responses including the total cutting force and cutting force coefficient. In order to simultaneously achieve the smallest total cutting force ($F = 203.9055$ N) and cutting force coefficient ($F_y/F_z = 0.5950$), $NC = 0.5\%$, $v = 130.9091$ m/min, and $f = 0.08$ mm/tooth are determined to be the optimal set. For practical application, $NC = 0.5\%$, $v = 131$ m/min, and $f = 0.08$ mm/tooth are chosen.

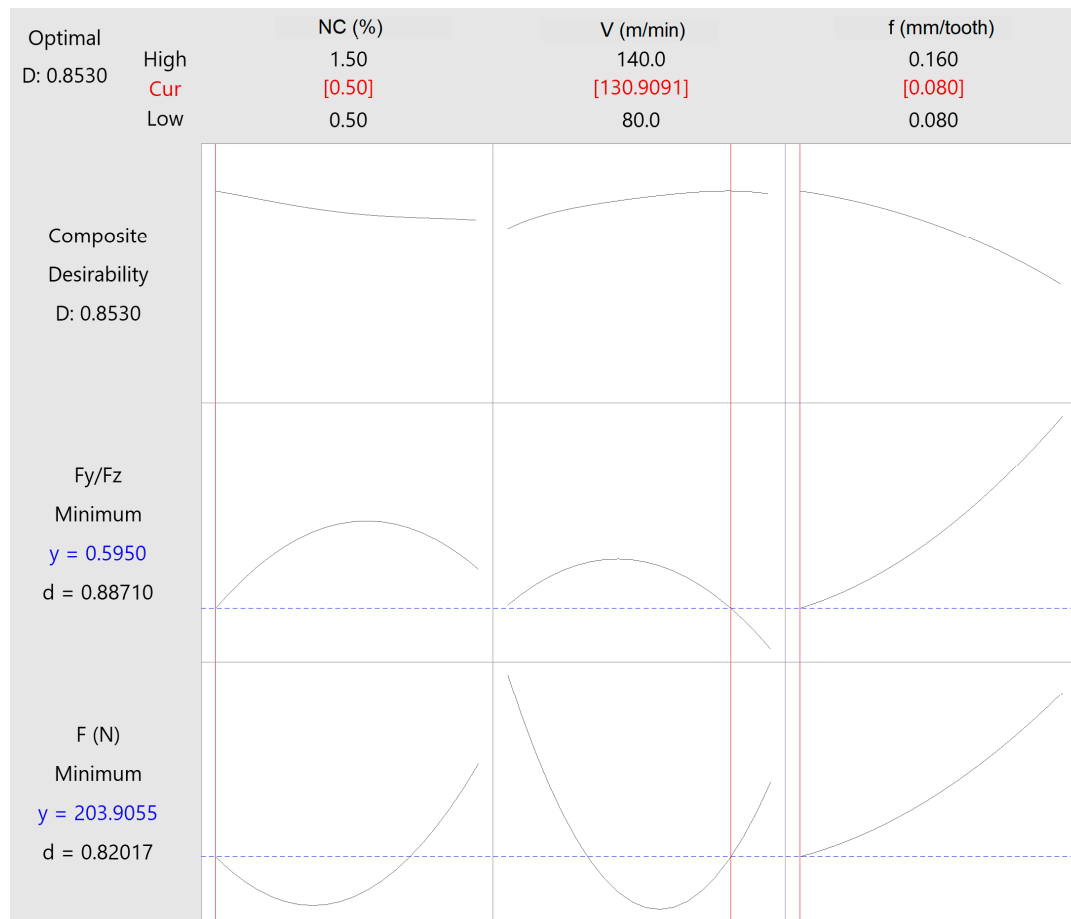


Figure 16. Multi-objective optimization results for the total cutting force F and cutting force coefficient F_y/F_z .

4. Conclusions

In the presented work, the influences of $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil on the hard milling performance of Hardox 500 steel were investigated. The effects of the input parameters (nanoparticle concentration, cutting speed, and feed rate) on the total cutting force F and cutting force coefficient F_y/F_z were studied and evaluated. The main contributions of the study are summarized as follows:

$\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nano cutting oil promoted the lubricating and cooling advantages of the nanoparticle component, hence contributing to improvement of the cooling lubrication capacity of the base cutting oil as well as the machinability of coated carbide inserts. Specifically, the cutting speed was increased from 50–55 m/min as recommended by the manufacturer to 130–140 m/min in the hard milling of Hardox 500 steel (49–50 HRC). Furthermore, the applicability of vegetable oil is extended to the hard milling, which contributes to ensuring sustainability.

Among the investigated parameters, the feed rate has the greatest influence on the total cutting force and cutting force coefficient. Additionally, it was noticeable that the nanoparticle concentration significantly influences the total cutting force F , while for the cutting force coefficient F_y/F_z , the second-order interaction of nanoparticle concentration shows a significant effect. The force component F_z is the tangential force and is the active force, while the force component F_y is the passive force, caused by the elasticity of the workpiece and the technological system. This coefficient has a great influence on tool wear and machined-surface quality and causes dimensional errors. In particular, in grinding or machining hard materials and difficult-to-cut materials, this coefficient not only reflects

the magnitude ratio of these two force components but can also be used as a criterion to indirectly evaluate the machinability, flank wear, and tool life [39,40].

The reasonable technological guidelines for achieving the smaller total cutting force F and cutting force coefficient F_y/F_z are provided. Specifically, $NC = 0.5\text{--}0.7\%$, $v = 110\text{--}115$ m/min, and $f = 0.08\text{--}0.10$ mm/tooth are suitable and are chosen for the smaller total cutting force F . Meanwhile, $NC = 0.5\%$, $v = 138\text{--}140$ m/min, and $f = 0.08\text{--}0.09$ mm/tooth should be suggested to achieve the smaller cutting force coefficient F_y/F_z . In addition, the cutting force coefficient F_y/F_z has practical significance in evaluating the machinability and monitoring the wear condition of cutting tools because cutting forces can be directly measured and monitored continuously during the cutting process while wear measurements can only be performed by stopping the cutting process and removing the cutting inserts.

Single-objective and multi-objective optimization was performed to determine the optimal set of values for the investigated parameters. These optimal sets provide the valued guidelines for further studies and practical applications.

In future studies, further investigations should focus on the feed force F_x and the ratios of F_x/F_z and F_x/F_y . Also, tool wear, tool life, and wear mechanisms under MQCL using nano hybrid cutting oil require further study.

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