Quest Journals
Journal of Research in Mechanical Engineering
Volume 7 ~ Issue 9 (2021) pp: 08-17
ISSN(Online) : 2321-8185
www.questjournals.org

Research Paper

Analysis and Prediction of Surface Roughness in Hard Milling of Hardox 500 Steel Using MQCL Condition with Al_2O_3/MoS_2Hybrid Nanofluid

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ABSTRACT
The work presents the application of MQCL using Al_2O_3/MoS_2 hybrid nano cutting oil for hard milling of Hardox 500 steel using coated carbide tools. Box-Benken experimental designand ANOVA analysis were used to study the effects of nanoparticle concentration, cutting speed, and feed rate on surface roughness R_z. The results indicated themachinability of carbide tools and hard machining performance were improved due tothe better cooling and lubricating effect created from MQCL technique and Al_2O_3/MoS_2 hybrid nano cutting oil. Furthermore, soybean oil, a type of vegetable oil, can be effectively used for hard milling process of a difficult-to-cut material like Hardox 500 steel, which plays an important role in encounter the climate change and will be a step towards to sustainable production.

KEYWORDS: *hard milling; hard machining; MQCL; Al_2O_3/MoS_2 hybrid nano cutting oil; nanoparticles; difficult-to-cut material.*

Received 13September, 2021; Revised: 26 September, 2021; Accepted 28 September, 2021

I. INTRODUCTION

Hardox 500 alloy steel is widely used in manufacturing industry when the parts are required with high hardness, toughness and good wear resistance. Due to the special properties, there are many difficulties in cutting Hardox 500 steel by conventional processes, such as, poor surface quality, high cutting forces and very high cutting temperature, making the wear rate faster and shortening the tool life. Hence, the cutting condition and productivity are limited in dry and wet condition [1]. Therefore, many researchers have proposed the alternative solution for overcome these problems in order to improve machining efficiency. Furthermore, due to the increasing concerns for the environment and human health, new cooling and lubricating methods and lubricants have been studied for machining processes. Among them, minimum quantity cooling lubrication (MQCL) is considered an environmental friendliness and gained growing interest in metal cutting field. This method delivers a very small amount of cutting oil into the cutting zone combined with cool air stream, thereby improving machining efficiency and significantly reducing coolant usage[2]. NiteshAnand et al. [3] studied the application of MQCL in machining titaniumalloy. This research showed that MQCL method gave the better results than flood condition. Grzegorze et al.[4] analyzed and compared tool wear in turning AISI 1045 steel under MQCL environment with dry cutting. The results indicated that the MQCL method can effectively reduce tool wear and prolong the tool life compared to dry condition.

Recently, the application of nano cutting oil in cutting processes has also attracted the attention of the researchers all over the world. Nano cutting oils are formed by suspending nanoparticles, such asAl_2O_3, MoS_2, SiO_2, CNTs, and so on, in the based oil to improve the lubricating and cooling properties. Al_2O_3 nanoparticles have the spherical morphology, high hardness, high thermal conductivity, and chemical stability, so they are used quite commonly to reduce the friction and cutting heat generated from contact zone [5].

Vasu and Reddy studied the performance of Al_2O_3nanofluids in MQL turning of Inconel 600 alloy using [6].The experimental results revealed that the reduction of cutting force, surface roughness values and tool wear was observed in case of MQL usingAl_2O_3nano cutting oilwhen compared with using traditional cutting oils. Ali et al.[7] studied the performance of Al_2O_3 and TiO_2 nanoparticles with different concentrations. The authors found out that the coefficient of friction,kinematic viscosity, and wear decreased. Also, Al_2O_3 nanoparticles makes the wear surface smoother because the act as “ball roller” in the contact faces

Pashmfouroush et al. [8] studied the influence of nanofluids on the grinding process of Inconel 738 superalloy. Experimental results showedthe surface roughness improvement compared with conventional cutting oils. Wang et al. [9] conducted experiments to evaluate the lubricating ability of different nanofluids for MQL grinding.Among the investigated nano cutting fluids, the authors found that Al_2O_3nanofluid has good lubricating properties due to its high hardness and almost spherical morphology. In addition, MoS_2 nanoparticles have a thin layer structure, which can easily adhere to surfaces, and the MoS_2nanoparticles themselves have good lubricating ability, which can reduce friction in the shear zone[10]. ParashKalita and his co-authors [11] has studied and applied the MQL method with MoS_2nano cutting oil to grinding process of cast iron.The obtained findings indicated that MQL method using MoS_2 nanoparticles has the ability to reduce the specific energy and improve the surface quality compared to flood coolant. Z.Dongkun et al. [12] analyzed the effects on surface roughness and cutting forces when applying nanocutting oil with three different types of nanoparticles (MoS_2, ZrO_2 and Carbon nanotubes). The analysis results revealed that the cutting forces decreased and surface roughness of the machined surface improved. Moreover, MoS_2nanocutting oil is significantly more effective than the two other types.

In recent years, in order to further improve the cooling and lubricating characteristics of nano cutting fluids as well as take advantage of the most outstanding properties of each type of nanoparticles, the combination of two different types of nanoparticles in cutting oil to form hybrid nano cutting oil has been considered a very promising solution and there is a very little information on this research direction[13].Therefore, the authors are motivated to make a study on the influence of Al_2O_3/MoS_2 hybrid nanofluidinMQCL hard milling of Hardox 500 steel.

II. METHOD AND MATERIAL

Experiments to study the influence of technological factors on surface roughness were built as shown in the experimental diagram in Figure 1. Hardox 500 steel has size 150x100x15mm with high hardness 500HB was used. Milling The experiments were performed on Mazak 530C CNC milling machine using Lamina's TiAlN coated carbide inserts. The MQCL system includes MQCL nozzle, air pressure regulator, and air flow rate control valve. Hybrid nano cutting fluid was formed by mixing Al_2O_3 and MoS_2nanoparticles with the ratio of 8:2 into soybean oil and was ultrasonically vibrated for 45 minutes using an Ultrasons-HD ultrasonicator (JP SELECTA, Spain) with a power of 600W and a frequency of 40 KHz. Surface roughness is measured three times after each trial using Mitutoyo SJ210 and taken by the average values.

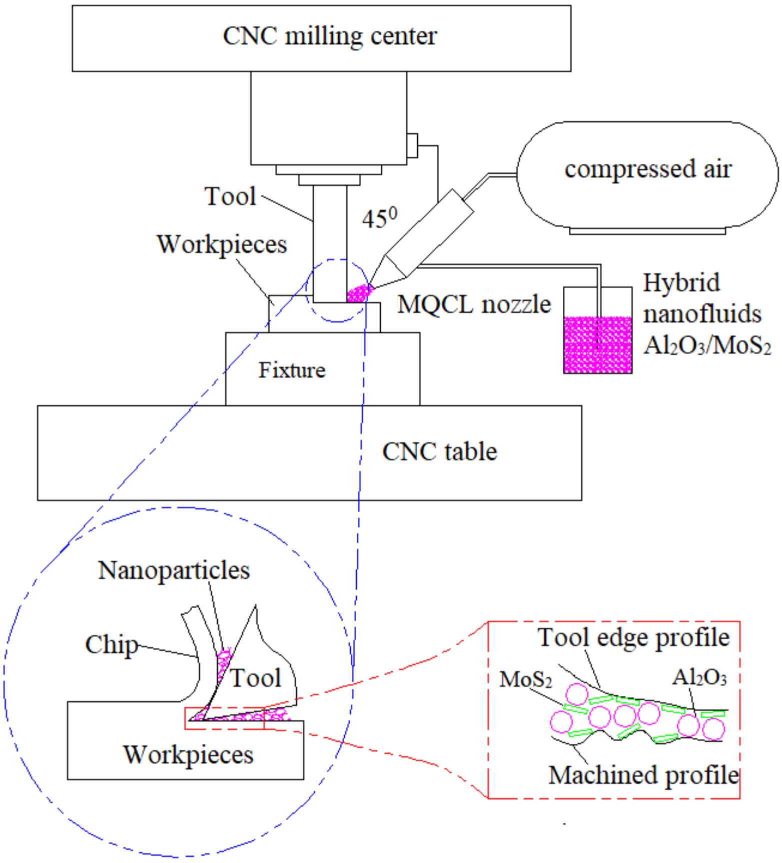


Figure 1. Experimental set up diagram

Three input parameters including nanoparticle concentration, cutting speed and feed rate and their levels are selected based on the previous study [14] as shown in Table 1. Some parameters are fixed during the experiments consisting of air flow rate of 200 ml/h, air pressure of 6 bar and depth of cut 0.12 mm). The experimental matrix of 30 experiments was established using the Box-Benken experimental design in Design expert software 11. The measured values of the surface roughness corresponding to the experiment design are shown in Table 2.

Table 1. Input machining parameters and their levels.

Input Machining Parameters	**Unit**	**Symbol**	**Level**		
			Low	Medium	high
Nanoparticle concentration	wt%	NC	0.5	1	1.5
Cutting speed	m/min	NP	110	140	170
Feed rate	mm/tooth	f	0.12	0.16	0.20

Table 2. Experimental matrix and measured result

Std Order	**Run Order**	**Input machining variables**			**Response**
		NC (wt%)	**V** (m/min)	**f** (mm/tooth)	R_z (μm)
17	1	1.5	110	0.16	0.963
19	2	1.5	170	0.16	0.948
10	3	1	170	0.12	1.001
12	4	1	170	0.2	0.863
3	5	0.5	170	0.16	0.764
16	6	0.5	110	0.16	1.447
29	7	1	140	0.16	0.931

Std Order	Run Order	Input machining variables			Response
		NC (wt%)	**V** (m/min)	**f** (mm/tooth)	**R_z** (μm)
14	8	1	140	0.16	0.933
4	9	1.5	170	0.16	0.979
22	10	0.5	140	0.2	1.183
30	11	1	140	0.16	0.938
18	12	0.5	170	0.16	0.746
24	13	1	110	0.12	1.214
2	14	1.5	110	0.16	0.937
5	15	0.5	140	0.12	0.738
13	16	1	140	0.16	0.901
26	17	1	110	0.2	1.184
8	18	1.5	140	0.2	0.886
15	19	1	140	0.16	1.191
28	20	1	140	0.16	0.911
23	21	1.5	140	0.2	0.886
21	22	1.5	140	0.12	0.742
9	23	1	110	0.12	1.369
7	24	0.5	140	0.2	1.173
25	25	1	170	0.12	0.991
6	26	1.5	140	0.12	0.747
1	27	0.5	110	0.16	1.322
20	28	0.5	140	0.12	0.723
11	29	1	110	0.2	0.919
27	30	1	170	0.2	0.915

III. RESULTS AND DISCUSSION

ANOVA analysis for surface roughness R_z was performed on Design expert 11 software with 95% confidence level and the results of ANOVA is shown in Table 3. The significance level of the research models is evaluated through Fisher's coefficient and the probability P value for the model. With the set of experimental parameters, the software proposes to use a quadratic model to investigate and predict the influence of input parameters on surface roughness R_z. The results show that the coefficient F for the survey model has a large value of F=4.9. At the same time, the probability p value for the model is less than the significance level $\alpha = 0.05$, which proves the selection model is appropriate and meaningful. The ANOVA results also show the influence of the investigated factors on R_z in which the cutting speed, interaction effect ofNC*V and the quadratic interaction of cutting speed (V^2) strongly affect the surface roughness value R_z, while other factors and their interactions have less influences.

Table 3. ANOVA result forsurface roughnessR_z

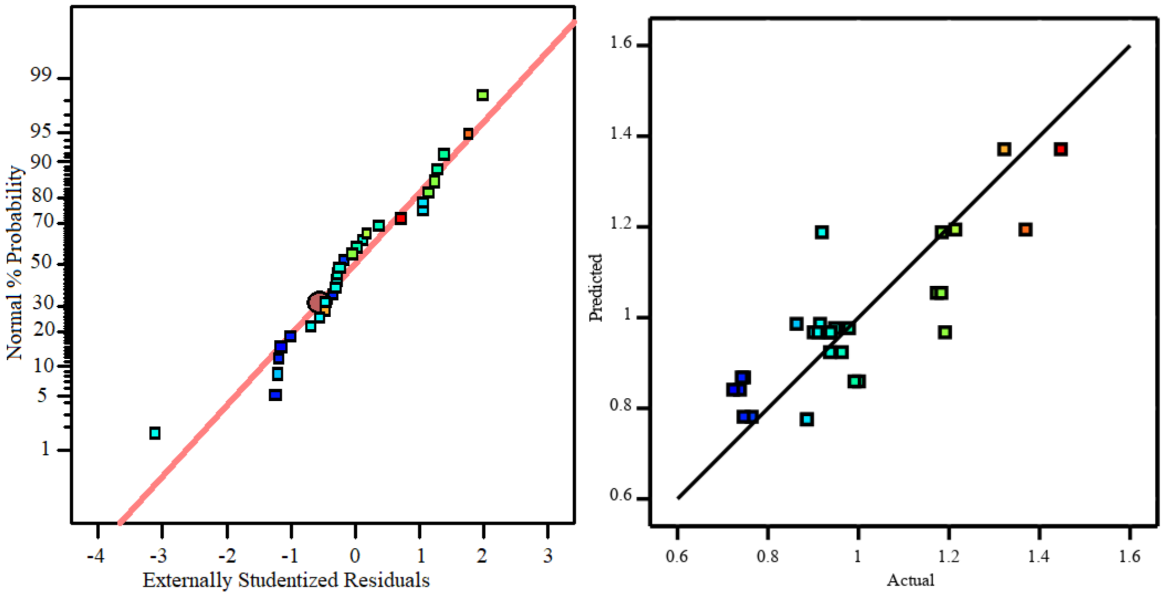
Source	Sum of	DF	Mean	F-value	p-value
Model	0.758628	9	0.084292	4.89507	0.001506
A-NC	0.063504	1	0.063504	3.687853	0.069185
B-V	0.288369	1	0.288369	16.74639	0.000567
C-f	0.014641	1	0.014641	0.850243	0.367474
AB	0.206725	1	0.206725	12.00506	0.002446
AC	0.046818	1	0.046818	2.718851	0.114789

Source	Sum of	DF	Mean	F-value	p-value
BC	0.008845	1	0.008845	0.513625	0.48186
A^2	0.029543	1	0.029543	1.715621	0.205104
B^2	0.087737	1	0.087737	5.095108	0.035335
C^2	0.002808	1	0.002808	0.163068	0.690632
Residual	0.344396	20	0.01722		
Lack of Fit	0.225941	3	0.075314	10.80864	0.000328
Pure Error	0.118455	17	0.006968		
Cor Total	1.103024	29			

A regression model to predict surface roughness has been built and given by Equation 1, which is evaluated through the coefficient of determination R^2 of 68.78% proving that the survey model and the experiment are appropriate.

$$R_z = 4.9168 - 0.5083*NC - 0.0535*V + 4.6021*f + 0.0107*NC*V - 3.825*NC*f + 0.0277*V*f - 0.253*NC^2 + 0.00012*V^2 - 12.1875*f^2 \quad (1)$$

The results of the model fit assessment are shown in the graphs of Figure 2. Figure 2a depicts a normal plot, showing that the residuals follow a normal distribution. Figure 2b shows that the predicted surface roughness values are quite close to the actual roughness values when using the predicted regression model. The residual versus prediction graph (Figure 2c) and the residual plot at the experimental points (Figure 2d) show that the calculated values are all within the bounds, that is, the selected model is suitable and no need to perform model conversion. Thus, using a quadratic model with interaction between two factors to evaluate the influence of input parameters on the surface roughness value is appropriate and statistically significant.



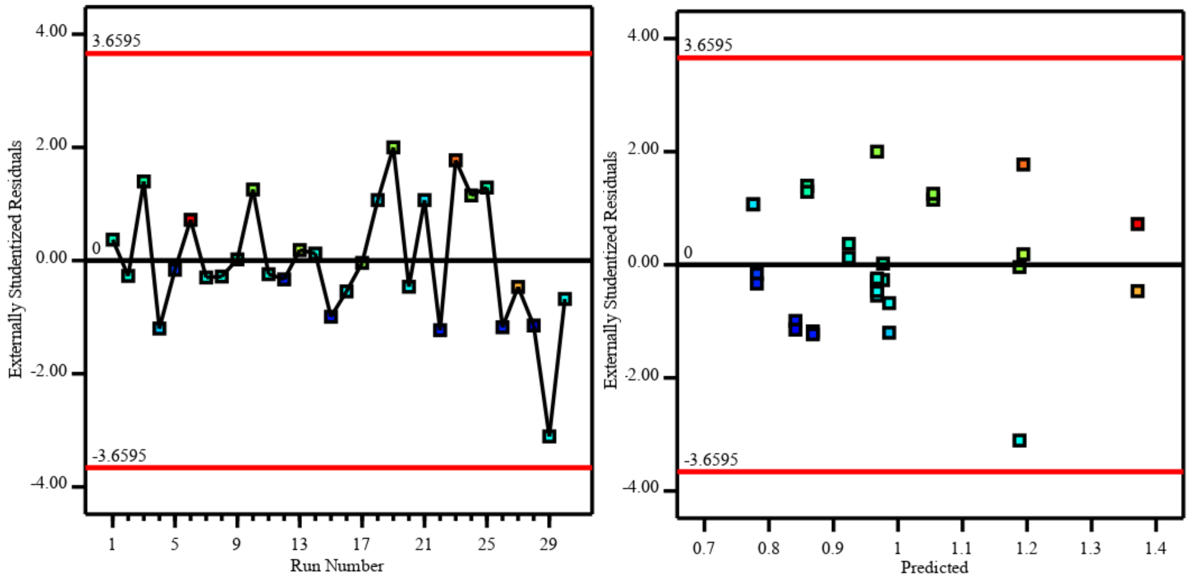
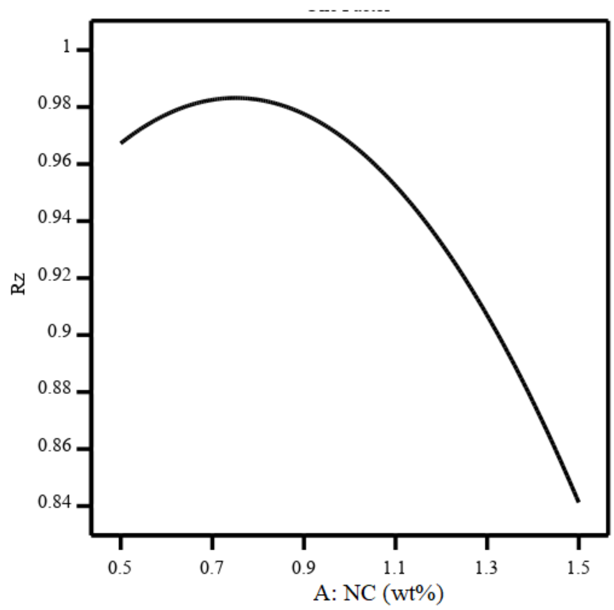
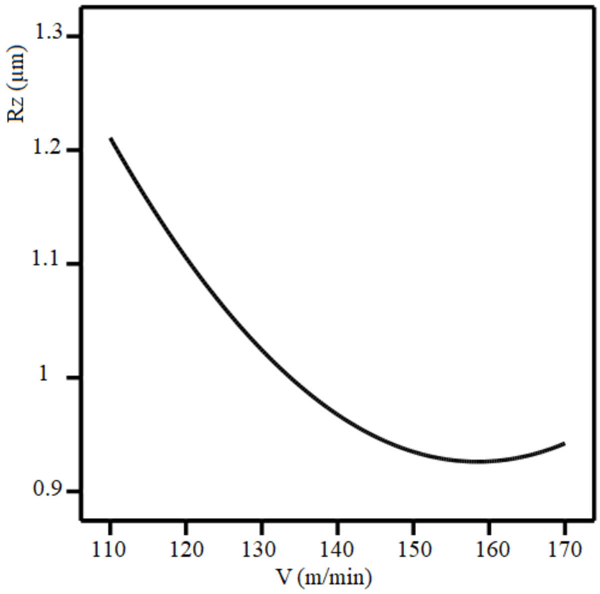


Figure 2. Residual plots ofsurface roughness R_z

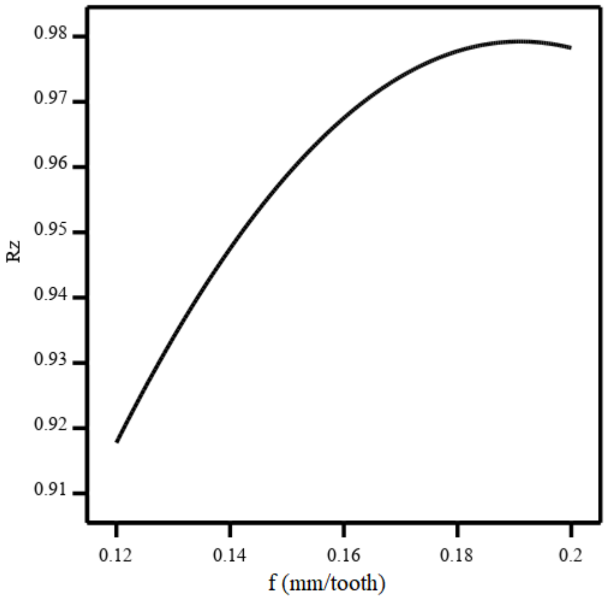
The maineffects of the input factors on the average values of surface roughness is shown in Figure 3. The results shown in Figure 3a show that the surface roughness value decreases with increasing nanoparticle concentration. The reason is that Hardox500 steel has high hardness and toughness, so MQCL method using Al_2O_3/MoS_2 hybrid nano cutting oil deliversthe oil mist into the cutting area, in which Al_2O_3 nanoparticles with high thermal conductivity create the "ball roller" effect as well as MoS_2nanosheets form tribo film to bring out the superior lubricating and coolingperformance, leading to a reduction surface roughness value. Figure 3b shows the effect of cutting speed and the surface roughness decreased when increasing the cutting speed to 150 m/min, and it goes up slightly as the cutting speed rises to 170 m/min. Figure 3c shows that the surface roughness rapidly increases with the growth of feed rate. However, the variation range of the surface roughness is relatively small, so it can be observed that in addition to being influenced by geometric factors (feed rate), the surface roughness is also greatly influenced by the concentration of nanoparticles and cutting speed.



(a) Nanoparticle concentration (NC)



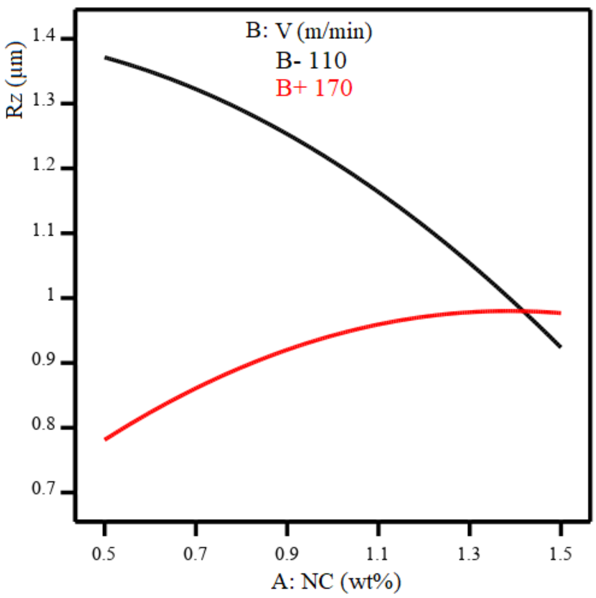
(b) cutting speed (V)



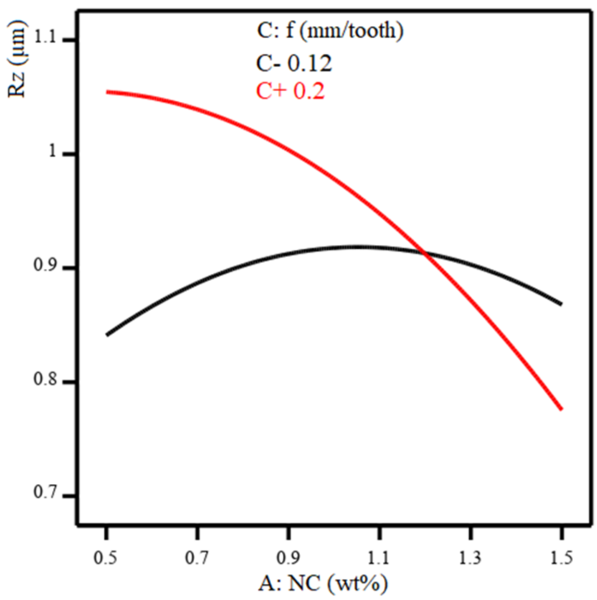
(c) feed rate (f)

Figure 3. The influence of input factors on surface roughness R_z: (a) Nanoparticle concentration (NC), (b) cutting speed (V), (c) feed rate (f)

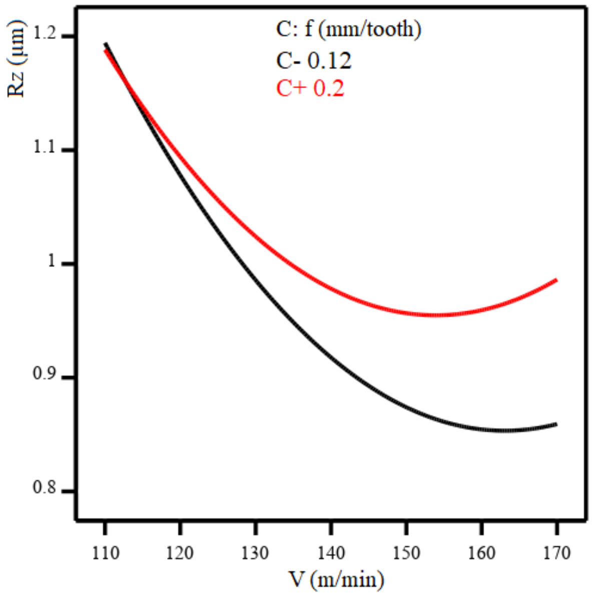
The influence of the interaction between the investigated factors on R_z is shown in Figure 4. The results show that the interaction ofNC*Vhas the strongest influence on the surface roughness. For low cutting speed (110 m/min), surface roughness decreases rapidly with increasing nanoparticle concentration. However, for high cutting speed of 170 m/min, the surface roughness grew slightly with increasing nanoparticle concentration. The reason is that, for the increasing of cutting speed, the nanoparticles tend to be ejected and more difficult to penetrate into the cutting area. While the interaction between feedrate and nanoparticle concentration also significantly affects the surface roughness value(Figure 4b). For large feed rate, surface roughness decreases sharply with risingnanoparticle concentration. However, for the case of small feed rate, the surface roughness improves slightly with increasing NC. In addition, the interaction between cutting speed and feed rate has little effect on surface roughness.



(a)The interaction effect of NC*V



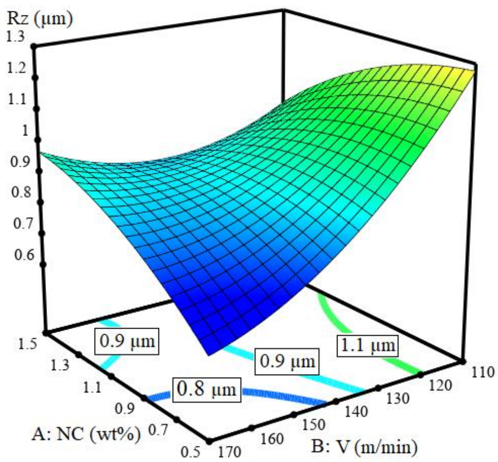
(b)The interaction effect of NC*f



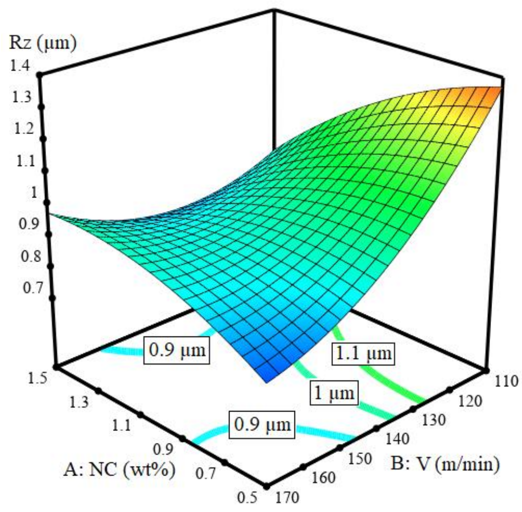
(c)The interaction effect of V*f

Figure 4. Interaction effects of input factors on surface roughness R_z: (a) NC*V; (b) NC*f; (c) V*f

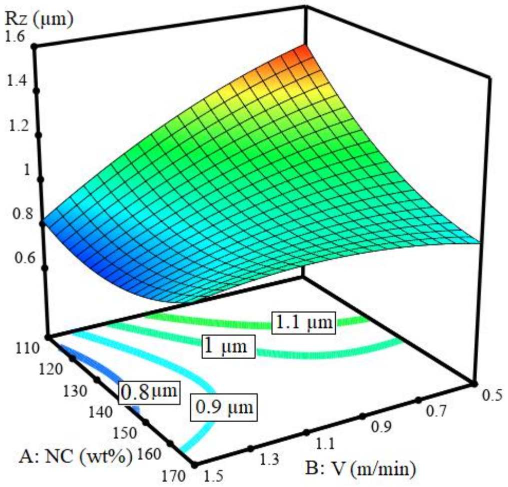
The surface plotsshowing the effects of cutting speed and nanoparticle concentration on the surface roughness corresponding to different feedrate values are shown in Figure 5. The surface plot shows the trend of surface roughness when cutting with high cutting speed and the concentration changes in the survey area. The contour plot shows the range of values achieved by the objective function when varying the cutting speed and the nanoparticle concentration corresponding to different values of the feed. For finishing (f=0.12 mm/tooth) or semi-finishing (f=0.16 mm/tooth), the surface roughness is small with high cutting speed and small nanoparticle concentration (Figure 5a,b). Forhigh level of feed rate f=0.2 mm/tooth, $R_z$is less than 0.9 µm with nanoparticle concentration greater than 1.3 wt% and cutting speed less than 160 m/min. Thus, a suitable set of parameters was provided to achieve the desired value of the surface roughness.



(a) f=0.12 mm/tooth



(b)f=0.16 mm/tooth



(c)f=0.2 mm/tooth

Figure 5. Effect of cutting speed and nanoparticle concentration on surface roughness with different feedrate values: (a) f=0.12 mm/tooth; (b) f=0.16 mm/tooth; (c) f=0.2 mm/tooth

IV. CONCLUSION

The work successfully applied MQCL using Al_2O_3/MoS_2 hybrid nano cutting oilfor hard milling of Hardox 500 steel in order to improve the machinability of the normal coated carbide inserts and cutting performance. Based on the obtained results, the higher machinability and better machining performance were reported.

The effects of nanoparticle concentration, cutting speed, and feed rate on surface roughness $R_z$under MQCL using hybrid nano cutting fluid were investigated. The effects of input variables and their interactions on R_z were studied. The technical guides were provided for further environmental friendly investigation and application. Moreover, the application of soybean oil was enlarged for hard milling by suspending Al_2O_3 and MoS_2 nanoparticles. The better cooling and lubricating of the based oil help to improve the machined surface quality.

In further study, more investigation should be focused on surface microstructure to deeply understand the cooling and lubricating mechanism of Al_2O_3/MoS_2 hybrid nano cutting fluid.

Funding: The research was funded by Thai Nguyen University of Technology, Thai Nguyen University, Viet Nam with project number of T2020-B58
Acknowledgments: The work presented in this paper is supported by Thai Nguyen University of Technology, Thai Nguyen University, Vietnam
Conflicts of Interest: The authors declare no conflict of interest

REFERENCE

[1]. Minh, D.T.; The, L.T.; Bao, N.T. Performance of Al_2O_3nanofluids in minimum quantity lubrication in hard milling of 60Si2Mn steel using cemented carbide tools. Adv. Mech. Eng. 2017, 9, 1–9, doi:10.1177/1687814017710618.
[2]. J. P. Davim and V. P. Astakhov, *Machining of Hard Metals*. 2011.
[3]. N. Anand, A. S. Kumar, and S. Paul, “Effect of cutting fluids applied in MQCL mode on machinability of Ti-6Al-4V,” *J. Manuf. Process.*, vol. 43, no. May, pp. 154–163, 2019, doi: 10.1016/j.jmapro.2019.05.029.
[4]. R. W. Maruda, G. M. Krolczyk, E. Feldshtein, P. Nieslony, B. Tyliszczak, and 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.
[5]. B. Shen, A. J. Shih, and S. C. Tung, “Peer-reviewed: Application of nanofluids in minimum quantity lubrication grinding,” *Tribol. Lubr. Technol.*, vol. 65, no. 3, pp. 73–80, 2009.
[6]. V. Vasu and 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,” *Proc. Inst. Mech. Eng. Part N J. Nanoeng. Nanosyst.*, vol. 225, no. 1, pp. 3–15, 2012, doi: 10.1177/1740349911427520.
[7]. M. K. A. Ali, H. Xianjun, L. Mai, C. Qingping, R. F. Turkson, and C. Bicheng, “Improving the tribological characteristics of piston ring assembly in automotive engines using Al2O3 and TiO2 nanomaterials as nano-lubricant additives,” *Tribol. Int.*, vol. 103, pp. 540–554, 2016, doi: 10.1016/j.triboint.2016.08.011.
[8]. F. Pashmforoush and R. Delir Bagherinia, “Influence of water-based copper nanofluid on wheel loading and surface roughness during grinding of Inconel 738 superalloy,” *J. Clean. Prod.*, vol. 178, no. January, pp. 363–372, 2018, doi: 10.1016/j.jclepro.2018.01.003.
[9]. Wang, Y., Li, C., Zhang, Y., Yang, M., Li, B., Jia, D., Hou, Y., Mao, C. (2016). 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, 127, 487–499. doi:10.1016/j.jclepro.2016.03.121
[10]. X. Li and H. Zhu, “Two-dimensional MoS_2: Properties, preparation, and applications,” *J. Mater.*, vol. 1, no. 1, pp. 33–44, 2015, doi: 10.1016/j.jmat.2015.03.003.

[11]. P. Kalita, A. P. Malshe, S. Arun Kumar, V. G. Yoganath, and T. Gurumurthy, "Study of specific energy and friction coefficient in minimum quantity lubrication grinding using oil-based nanolubricants," *J. Manuf. Process.*, vol. 14, no. 2, pp. 160–166, 2012, doi: 10.1016/j.jmapro.2012.01.001.

[12]. D. Zhang, C. Li, D. Jia, Y. Zhang, and X. Zhang, "Specific grinding energy and surface roughness of nanoparticle jet minimum quantity lubrication in grinding," *Chinese J. Aeronaut.*, vol. 28, no. 2, pp. 570–581, 2015, doi: 10.1016/j.cja.2014.12.035.

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

[14]. Duc, T.M.; Long, T.T.; Tuan, N.M. Novel Uses of Al_2O_3/MoS_2 Hybrid Nanofluid in MQCL Hard Milling of Hardox 500 Steel. Lubricants 2021, 9, 45, doi.org/10.3390/lubricants9040045