



An experimental study on hard milling of Hardox 500 steel under Minimum Quantity Cooling Lubrication using hybrid nano cutting oil

Tran Minh Duc ¹, Tran Ngoc Diep ², Tran The Long ^{3*}

^{1,3} Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam

² Hanoi Vocational College of High Technology, Tay Mo Ward, Nam Tu Liem District, Hanoi, 10000, Vietnam

* Corresponding Author: **Tran The Long**

Article Info

ISSN (online): 2582-7138

Volume: 06

Issue: 02

March-April 2025

Received: 21-01-2025

Accepted: 13-02-2025

Page No: 347-351

Abstract

The main objective of this article is to investigate the effects of nanoparticle concentration, cutting speed, and feed rate on surface roughness R_a in hard milling of Hardox 500 steel under Minimum Quantity Cooling Lubrication (MQCL) condition using Al_2O_3/MoS_2 hybrid nano cutting oil. The factorial experimental planning design with the help of Minitab 21 software was applied to evaluate the main effects and interaction effects of input machining parameters. The obtained results reveal that feed rate has the largest influence on the objective function R_a . The technical guides for nanoparticle concentration, cutting speed, and feed rate were provided for smaller R_a values during hard milling of Hardox 500 steel. Moreover, $NC=1.0-1.5\%$, $V=106-110$ m/min, and $f=0.08-0.09$ mm/tooth should be suggested for achieving the better machined surface quality.

Keywords: Hard milling; hybrid nano cutting oil; nanoparticle concentration; cutting speed; feed rate; surface roughness.

1. Introduction

Hard milling is a manufacturing process used in precision machining where the geometrically defined cutting tools are used to directly cut hard materials with the hardness usually above 45 HRC (Hardness Rockwell C), such as tool steels, stainless steels, or hardened alloys ^[1]. Hard milling is often used for creating highly accurate and intricate parts, such as molds, dies, or complex components in industries like aerospace, automotive, and medical devices ^[2]. One of the major advantages of hard milling is that it can sometimes supplement or replace traditional grinding processes. This reduces the number of steps in the manufacturing process and helps save time and costs. Grinding is typically used in the final stages of hard material machining, but hard milling can eliminate or reduce this need ^[3]. The cutting tools used in hard milling typically include high-performance carbide or coated end mills. The process often requires cutting tools that can withstand high temperatures and have high hardness and exceptional wear resistance ^[4]. Hard milling process is carried out on the advanced CNC (Computer Numerical Control) machines with high rigidity. Compared to grinding process, hard milling can be faster, with shorter lead times and reduced labor costs, making it a more efficient option for producing high-precision components. Hard milling can produce excellent surface finishes, but it often requires careful management of cutting parameters (like cutting speed, feed rate, and tool material) to ensure good results without tool wear or workpiece damage.

High cutting heat is a significant issue in hard milling processes and can negatively affect the machined surface quality, tool life, and the overall efficiency. When excessive heat is generated, it can cause thermal softening of the cutting tool material. This reduces its hardness, causing faster wear and ultimately shortening the tool life ^[3]. The high cutting heat can alter the microstructure of the material being machined, causing changes such as surface hardening or the formation of undesirable heat-affected zones (HAZ). This could result in poor surface finish and reduced fatigue strength of the workpiece ^[1]. The thermal stresses generated in the cutting zone may lead to cracking, distortion, or even thermal expansion issues in the workpiece, affecting its dimensional accuracy. In addition, high temperatures can lead to material adhesion on the cutting tool's edge, forming a built-up edge (BUE) resulted in poor surface finish and dimensional errors.

There have been some solutions to overcome the problem including Minimum Quantity Lubrication (MQL), Cryogenic Cooling,

Minimum Quantity Cooling Lubrication (MQCL), Nanofluid Minimum Quantity Lubrication (NF MQL), Nanofluid Minimum Quantity Cooling Lubrication (NF MQCL), and so on^[5, 6]. Among them, Nanofluid Minimum Quantity Cooling Lubrication (NF MQCL) refers to the method that uses a very small amount of cutting oil containing nanoparticles in low temperature, often in the form of a fine mist or spray, which is directly introduced into cutting zone^[7]. This results in high cooling and lubricating performance while minimizing the environmental and economic impact of excessive coolant use. However, the studies on this approach are still limited^[8], so the authors made a study on hard milling process of Hardox 500 steel under Nanofluid Minimum Quantity Cooling Lubrication (NF MQCL) environment. The effects of investigated parameters consisting of nanoparticle concentration, cutting speed, and feed rate on surface roughness R_a were studied.

2. Material and Methods

The hard-milling experimental set up was shown in Figure 1. Surface roughness R_a values were measured by MITUTOYO SJ-210 Portable Surface Roughness Tester (Japan). The mixing ratio of Al_2O_3/MoS_2 hybrid nanofluid in the based oil is 80:20. Ultrasons-HD ultrasonicator generating 600W ultrasonic pulses at 40 kHz was used for one hour to uniformly suspend the nanoparticles in the rice oil to prepare Al_2O_3/MoS_2 hybrid nano cutting oil. It was directly used for MQCL system

The chemical composition and mechanical properties of Hardox 500 steel are given by Tables 1, 2. The factorial experimental design of three factors and their levels is given by Table 3. The selection of values for surveyed variables was developed from the previous work^[7].

Table 1: Chemical composition in wt% of Hardox 500 steel

Chemical 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

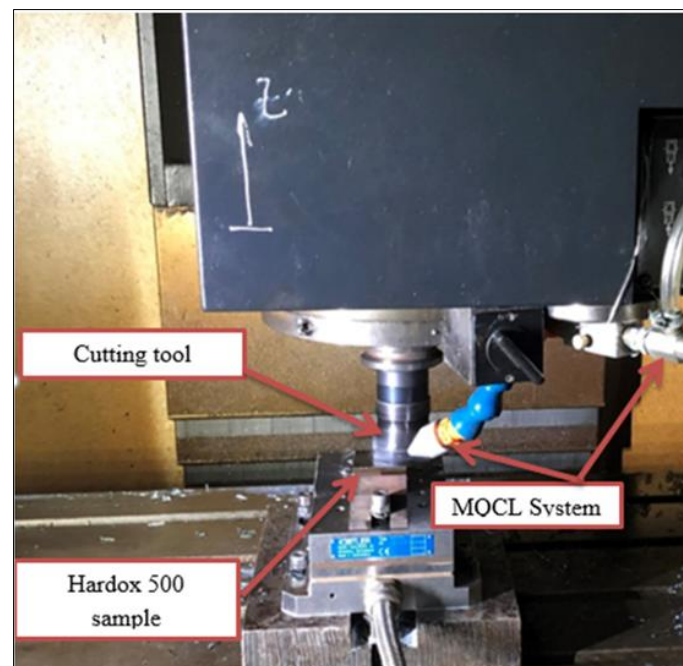


Fig 1: The experimental set up

The experimental trials were carried out by following the factorial experimental design, and the values of surface roughness R_a were measured three times right after each trial.

The measured surface roughness values were taken by the average values.

Table 3: Factorial design of three factors and their levels

Input machining parameters	Low level	High level
Nanoparticle concentration, NC (%)	0.5	1.5
Cutting speed, V (m/min)	80	110
Feed rate, f (mm/tooth)	0.08	0.12

3. Results and Discussion

The hard-turning experiments were conducted by following the full factorial experimental design, and R_a values were

reported and processed. The main effects of the investigated parameters on the surface roughness R_a are shown in figures 2, 3.

From Figure 2, the feed rate causes the strongest influence on surface roughness R_a . When the feed rate increased, the values of surface roughness R_a were reported to rapidly go up due to the increase in the area of the cross-section of the cutting layer ^[1]. At the same time, surface roughness R_a

suffers less influence by nanoparticle concentration and cutting speed, and R_a values tend to go down when NC and V increase due to the improvement of lubricating performance resulted in the presence of hybrid nano cutting oil ^[7] and the reduction of cutting forces and cutting heat ^[1].

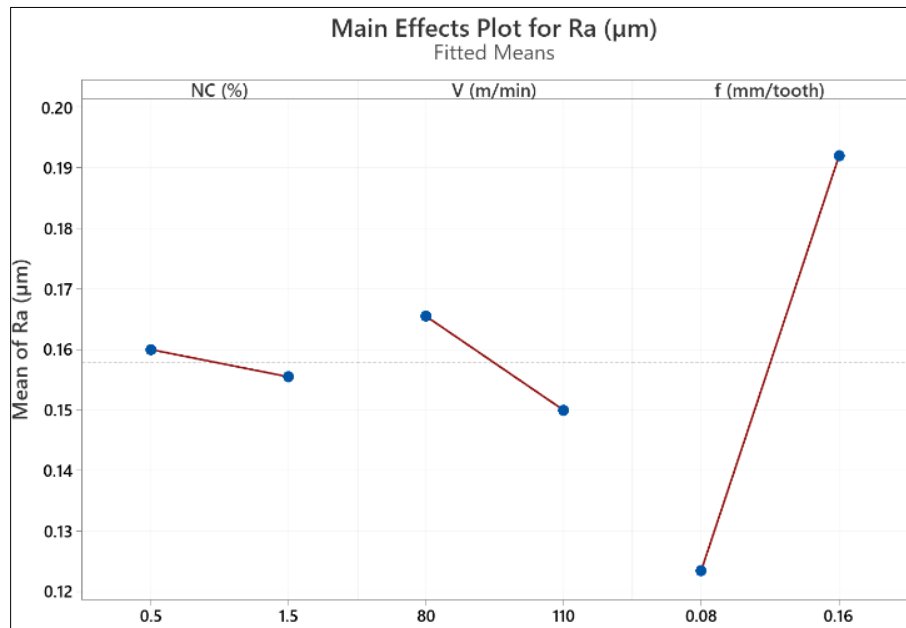


Fig 2: Main effects of input variables on surface roughness R_a

The contour plots in Figures 3-5 represent the interaction effects of surveyed variables on the surface roughness R_a . For feed rate f is fixed at 0.12 mm/tooth in Figure 3, the high levels of cutting speed and nanoparticle concentration should be selected for smaller R_a . In detail, in order to achieve $R_a < 0.15 \mu\text{m}$, $V = 106\text{--}110 \text{ m/min}$ and $\text{NC} = 1.0\text{--}1.5\%$ should be suggested.

For $V = 95 \text{ m/min}$ in Figure 4, $f = 0.08\text{--}0.09 \text{ mm/tooth}$ and $\text{NC} = 0.5\text{--}1.5\%$ should be suggested to achieve $R_a < 0.13 \mu\text{m}$. For $\text{NC} = 1.0\%$ in Figure 5, $V = 103\text{--}110 \text{ m/min}$ and $f = 0.08\text{--}0.085 \text{ mm/tooth}$ should be selected in order to achieve smaller R_a values ($R_a < 0.12 \mu\text{m}$). Hence, the proper ranges $\text{NC} = 1.0\text{--}1.5\%$, $V = 106\text{--}110 \text{ m/min}$, and $f = 0.08\text{--}0.09 \text{ mm/tooth}$ should be selected for achieving smaller R_a values.

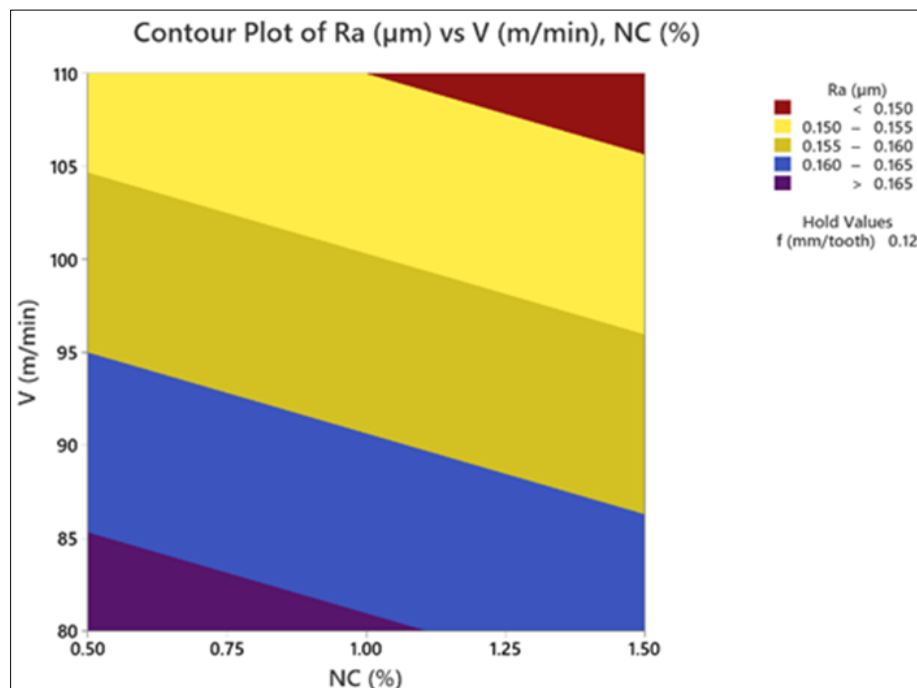


Fig 3: Contour plot of effects of cutting speed and nanoparticle concentration on surface roughness R_a (feed rate $f = 0.12 \text{ mm/tooth}$)

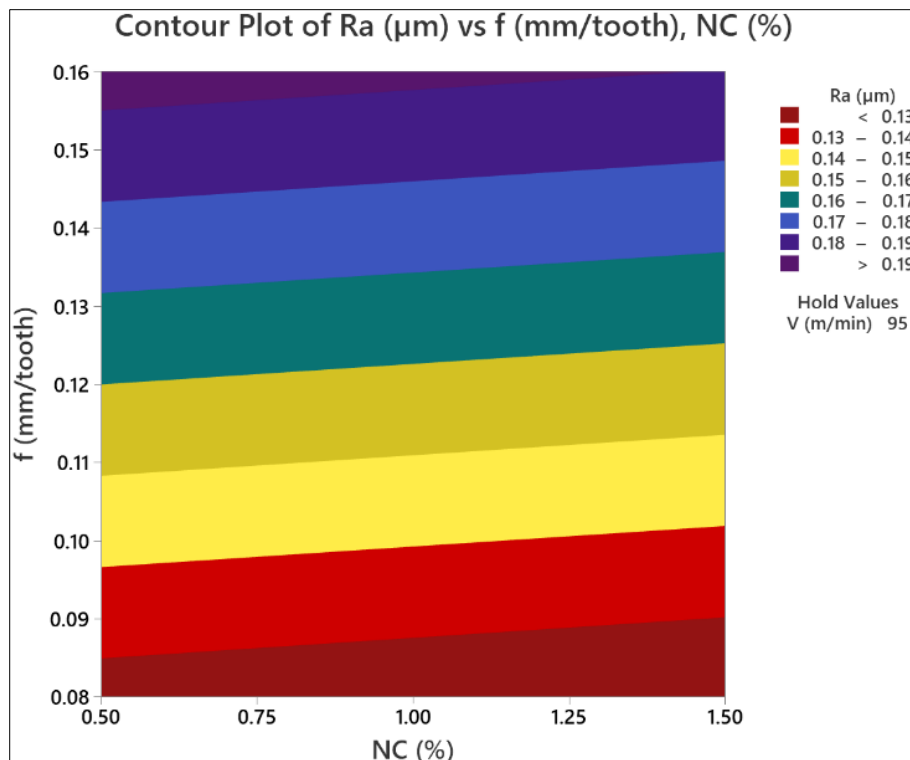


Fig 4: Contour plot of effects of feed rate and nanoparticle concentration on surface roughness R_a (cutting speed $V=95$ m/min)

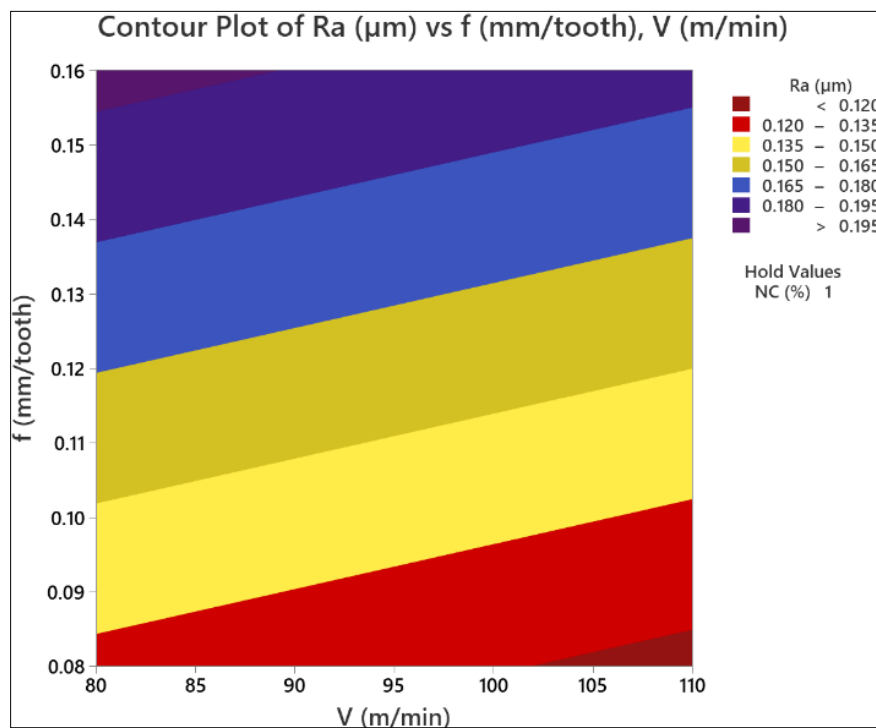


Fig 5: Contour plot of effects of feed rate and cutting speed on surface roughness R_a (nanoparticle concentration $NC=1.0\%$)

4. Conclusion

In this work, an experimental study on the effects of nanoparticle concentration, cutting speed, and feed rate on surface roughness R_a in hard milling of Hardox 500 steel was made. The factorial experimental planning design with the help of Minitab 21 software was applied to study the main effects and interaction effects of input machining parameters on R_a . Feed rate causes the strongest influence on the objective function R_a than nanoparticle concentration and cutting speed. In addition, the technical guides were provided for the suitable value ranges of the investigated parameters for specific requirements. The proper ranges $NC=1.0-1.5\%$,

$V=106-110$ m/min, and $f=0.08-0.09$ mm/tooth should be selected for achieving smaller R_a values should be recommended for the smaller surface roughness R_a values, which will play an important role for future studies in hard milling process. In future work, more investigations should be focused on the lubricating and cooling mechanism of hybrid nanoparticles.

Acknowledgments

The work presented in this paper is supported by Thai Nguyen University of Technology, Thai Nguyen University, Vietnam.

5. References

1. Davim JP. Machining of hard materials. Springer-Verlag London Limited; 2011.
2. C- aliskan H, Kurbanoglu C, Panjan P, Cekada M, Kramar D. Wear behavior and cutting performance of nanostructured hard coatings on cemented carbide cutting tools in hard milling. *Tribology International*. 2013;62:215–22. DOI: 10.1016/j.triboint.2013.02.035.
3. Tran Minh D, Tran The L, Tran Bao N. Performance of Al_2O_3 nanofluids in minimum quantity lubrication in hard milling of 60Si2Mn steel using cemented carbide tools. *Advances in Mechanical Engineering*. 2017;9:1–9. DOI: 10.1177/1687814017710618.
4. Uysal A, Demiren F, Altan E. Applying minimum quantity lubrication (MQL) method on milling of martensitic stainless steel by using nano MoS_2 reinforced vegetable cutting fluid. *Procedia - Social and Behavioral Sciences*. 2015;195:2742–7. DOI: 10.1016/j.sbspro.2015.06.384.
5. Sharma AK, Tiwari AK, Dixit AR. Effects of minimum quantity lubrication (MQL) in machining processes using conventional and nanofluid-based cutting fluids: A review. *Journal of Cleaner Production*. 2016;127:1–18. DOI: 10.1016/j.jclepro.2016.03.146.
6. Sidik NAC, Samion S, Ghaderian J, Yazid MN. Recent progress on the application of nanofluids in minimum quantity lubrication machining: A review. *International Journal of Heat and Mass Transfer*. 2017;108:79–89. DOI: 10.1016/j.ijheatmasstransfer.2016.11.105.
7. Tran Minh D, Tran The L, Tuan NM. Novel uses of $\text{Al}_2\text{O}_3/\text{MoS}_2$ hybrid nanofluid in MQCL hard milling of Hardox 500 steel. *Lubricants*. 2021;9:45. DOI: 10.3390/lubricants9040045.
8. Tran Minh D, Tran The L, Van Thanh D. Evaluation of minimum quantity lubrication and minimum quantity cooling lubrication performance in hard drilling of Hardox 500 steel using Al_2O_3 nanofluid. *Advances in Mechanical Engineering*. 2020;12:1–12. DOI: 10.1177/1687814020909056.