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Research article

An Investigation of Hard Milling Performance Under MoS_2 Nanofluid-Assisted MQL Environment

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A B S T R A C T

The presented work aims to investigate the hard milling performance of Hardox 500 steel (49-50 HRC) under MQL environment using MoS_2 nano cutting oils. The impacts of input parameters including nanoparticle concentration, cutting speed, and feed rate on the total cutting force Fr and surface roughness Ra were studied and evaluated. The obtained experimental results indicate that the cutting efficiency and machinability of coated carbide inserts improved due to the better lubricating performance resulted from MoS_2 nano cutting oil. Feed rate has the most significant influence on the total cutting force and surface roughness. Morever, in order to achieve smaller the total cutting force Fr and surface roughness Ra, the appropriate value ranges of V=125-140 m/min, feed rate f = 0.012-0.013 mm/min, nanoparticle concentration NC= 0.2-0.3% were provided to contribute the technical guides in production practice..

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1. INTRODUCTION

In recent years, Hardox 500 steel plates are known for their superior abrasion resistance and have been widely used in construction and industrial applications. They provide superior strength and durability, making them ideal for heavy-duty applications that require long-lasting wear resistance [1]. Hardox 500 combines alloying elements, including manganese, nickel, chromium and molybdenum, making it three times tougher than ordinary carbon steel. In addition to its impressive impact tolerance, Hardox 500 has excellent weldability and machinability properties, making it easier to fabricate than other types of steel. It also does not require preheating before or postheating after welding due to its high-temperature strength, which reduces fabrication time and cost. Overall, Hardox 500 is an exceptionally strong yet lightweight alternative to traditional steels

such as regular carbon steel plates or even stainless steel, providing the most optimal solution when facing challenging working conditions where machinery needs maximum protection against wear and tear.

However, the possession of high strength, hardness, and ductility as well as good wear resistance makes Hardox 500 steel difficult for conventional cutting processes like grinding, milling, turning, and drilling [2]. The enormous heat and large cutting force generated from the cutting zone are the main issues to reduce the hardness and wear resistance of cutting tools. Combined with the good wear resisance of Hardox 500 steel, the tool wear rate accelerates, thereby strongly reducing the tool life and machined surface quality under dry condition. The use of flood condition faces difficulty in introducing the oil droplets deeply into contact faces and thermal shock phenonmena in hard milling. Besides, the environmental problems from the used cutting oils and their expensive treatment costs put the pressure to find out the suitable cooling and lubricating methods for these issues.

Among the likely cooling lubrication methods, minimum quantity lubrication (MQL) using nano cutting oil is emerging as a promising solution. This method shows high lubricating and cooling efficiency in the cutting zone while minimizing the use of cutting oil, so it is considered environmentally friendly. The effectiveness in reducing cutting heat and cutting force was recorded in hard turning of AISI 1045 steel under MQL condition using Al_2O_3 nano cutting oil [3]. Uysal and his colleagues [4] conducted an experimental study on the milling process of AISI 420 stainless steel under MQL method using MoS_2 nano cutting oil. The research results show that the friction coefficient on contact faces is reduced, helping to reduce tool wear and improve surface quality. Besides, the concentration of MoS_2 nanoparticles has a great influence on the results of the cutting process. A. K. Sharma et al. [5] studied the cooling lubrication mechanisms of different types of nanoparticles in the cutting zone and concluded that there are four main mechanisms (rolling, sliding, polishing and filming). These mechanisms depend on the shape, size, stiffness, etc. of each type of nanoparticles. R. W. Maruda et al. [6] studied the influence of Cu nanoparticle size and nanoparticle concentration on the turning efficiency of 316L stainless steel under MQL condition. The obtained experimental results show that smaller nanoparticle size is more suitable for higher machined surface quality. For Cu nanoparticles, the concentration of 0.5% gives better results in terms of surface quality and power consumption [7]. The introduction of nanoparticles into vegetable oil to create environmentally friendly nano cutting oil is a new research direction. This will enhance the cooling and lubricating performance of the based oil [8,9], enlarging the applicability of vegetable oils [10]. MoS_2 nanoparticles have the thin sheet structure, low friction coefficient, and high thermal conductivity among the most commonly used types of nanoparticles. Rahmati et al. [11] made an extensive study on the lubrication mechanism and MoS_2 nanoparticle concentration in MQL end milling process. The authors concluded that the efficiency of the end milling process was improved due to the good lubrication ability of MoS_2 nanoparticles. Besides, MoS_2 nanoparticle concentration affected the ability to form the tribo film. This film layer was continuously formed and lost during the cutting process, so the use of an unreasonable concentration of MoS_2 nanoparticles can lead to the difficulty in film formation [12] and the phenomenon of deposition and adhesion to the cutting edge, negatively affecting tool life [13].

After the literature review, there is little information reported in studying hard milling of difficult-to-cut materials like Hardox 500 steel under MQL environment using MoS_2 nano cutting oil. Accordingly, the authors made the experimental study on MoS_2 nanofluid-assisted MQL hard milling of Hardox 500 steel (49-50 HRC). Brand rice oil used as the base oil for MQL system will ensure the environmental friendly characteristic, which is suitable for sustainable production [14].

2. METHODOLOGY

The experimental set up for hard milling experiments is shown in Figure 1. The experiments was conducted on Mazak vertical center smart 530C. The APMT 1604 PDTR LT30 carbide inserts with TiAlCN coating layer were

used. The cooling and lubricating system includes MQL device with the designation of NOGA MiniCool MC1700, compressed air, the device for pressure stabilization, rice bran oil, and MoS_2 nanoparticles. Measurement devices include SJ-210 Mitutoyo for surface roughness and Kistler quartz three-component dynamometer 9257BA for cutting forces. MoS_2 nanoparticles (30 nm) made by Luoyang Tongrun Info Technology Co., Ltd., China were used. The samples are Hardox 500 steels (49÷50 HRC) with the dimensions of 150mm ×100mm ×15 mm. The chemical composition and mechanical properties of Hardox 500 steel are given in Tables 1, 2. Factorial experimental design was used to investigate the effects of nanoparticle concentration, cutting speed, and feed rate on surface roughness R_a and total cutting force F_r. The input variables and their levels were given in Table 3. The depth of cut was fixed at 0.12mm.

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

Element	Weight (wt%)
C	0.3
Si	0.7
Mn	1.6
P	0.0025
S	0.01
Cr	1.5
Ni	1.5
Mo	0.6
B	0.005

Table 2. Mechanical properties of Hardox 500 steel.

Yield strength, MPa	1250
Tensile strength, MPa	1400
Elongation, %	10
Hardness range, HBW	470 - 530
Hardness range, HRC	49 - 50

Table 3. Input variables and their levels.

Input variables	Low level	High level	Responses
Nanoparticle concentration, NC (%)	0.1	0.3	Surface roughness R_a (μm) Total cutting force F_r (N)
Cutting speed, V (m/min)	110	140	
Feed rate (mm/min)	0.012	0.016	



Fig. 1. The experimental set up.

The formation process of MoS_2 nanofluids was done by using 3000868 - Ultrasons-HD (JP SELECTA in SPAIN) shown in Figure 2 for 1 hour. The obtained nanofluids were immediately used for the experiments. The concentration of the nanofluids was calculated with the following equation and expressed in weight percent concentration (wt%).

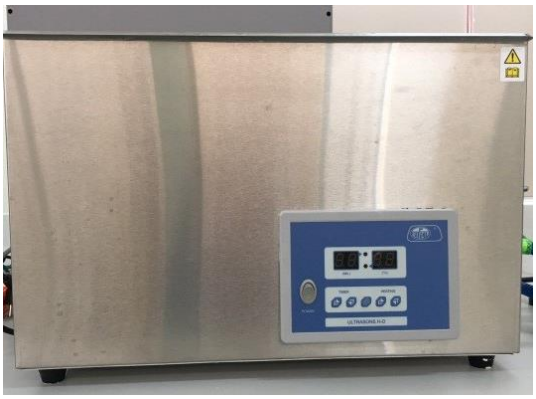


Fig. 2. The 3000868 - Ultrasons-HD (JP SELECTA in SPAIN) for MoS_2 nanofluid preparation.

$$\text{Weight percent concentration (wt\%)} = \frac{\text{Weight of solute (g)}}{\text{Weight of solution (g)}} \times 100\%$$

3. RESULTS AND DISCUSSION

The Pareto chart shows the influence of the investigated parameters on the total cutting force (Figure 3). It can be seen that the feed rate has the greatest influence on the total cutting force, followed by the MoS_2 nanoparticle concentration.

Meanwhile, cutting speed has a negligible influence. This is because the increase in feed rate increases the cutting layer area [15]. In Figure 4, it can be seen that the feed rate is the parameter that has the strongest influence on the surface roughness value R_a [16] while the influence of other parameters is insignificant.

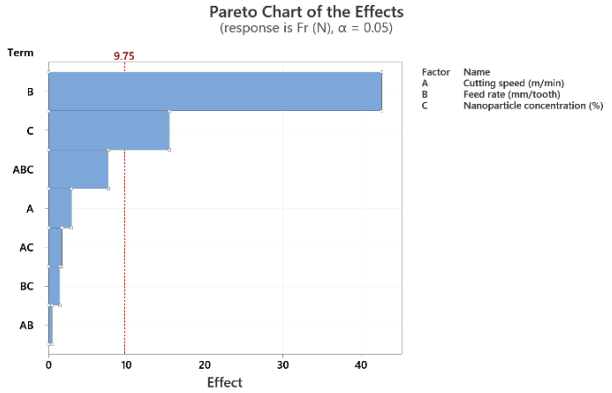


Fig. 3. The Pareto chart of the influence of the investigated parameters on the total cutting force F_r.

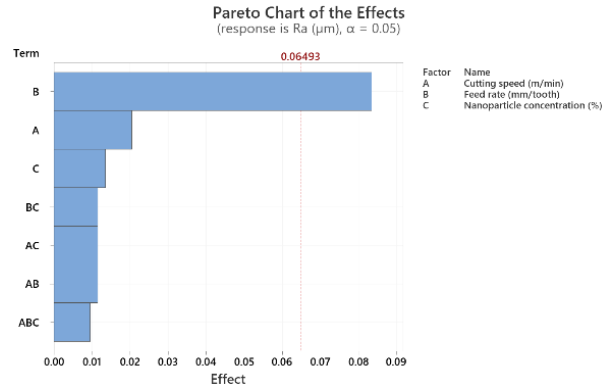


Fig. 4. The Pareto chart of the influence of the investigated parameters on surface roughness R_a.

The main effect of each investigated parameter is illustrated in Figure 5. It can be seen that increasing cutting speed and nanoparticle concentration contributes to reduce cutting forces, in which the effect of nanoparticle concentration is greater than that of cutting speed. This can be explained that the growing MoS_2 concentration nanoparticles from 0.1% to 0.3% increased the number of nanoparticles in the cutting zone and this is also a reasonable concentration value for MoS_2 nanoparticles [11,12] , thus creating suitable conditions to maximize the mechanism of tribo-film formation. From there, the friction coefficient in the cutting zone is reduced, helping to decrease cutting force and surface roughness values (Figure 6). Besides, when increasing the feed rate, the cutting force increases sharply due to the increase in cutting layer. A similar trend is also noted on the graph of the main effect of investigated parameters on surface roughness R_a (Figure 6).

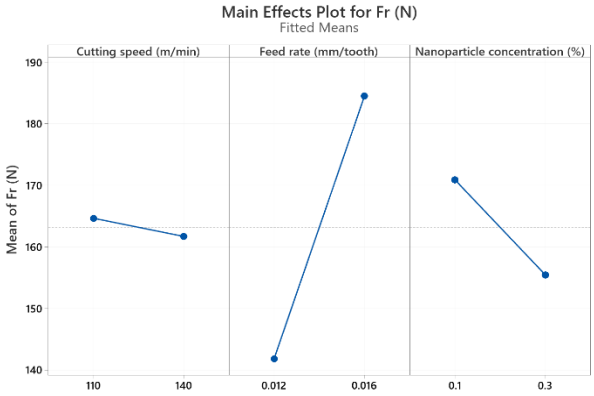


Fig. 5. Main effects of the investigated parameters on the total cutting force F_r.

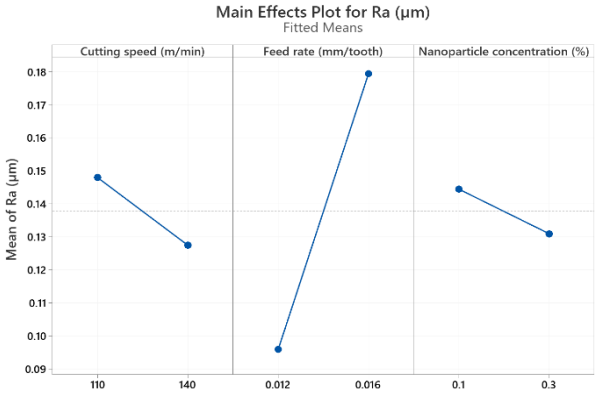


Fig. 6. Main effects of the investigated parameters on surface roughness R_a.

The contour plot in Figure 7 shows the influence of feed rate and cutting speed on the total cutting force when the MoS_2 nanoparticle concentration is fixed at 0.2%. The cutting speed V= 110-140 m/min and feed rate f = 0.012-0.013mm/min should be selected to achieve the smaller total cutting force values (F_r<150N).

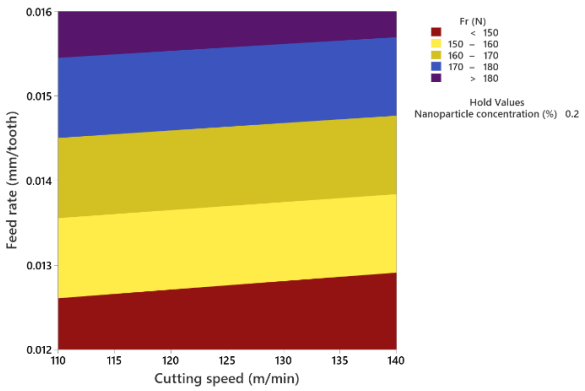


Fig. 7. Influence of feed rate and cutting speed on F_r.

In figure 8, the contour plot presents the influence of nanoparticle concentration and cutting speed on the total cutting force in case of the feed rate fixed at 0.014 mm/min. The cutting speed V= 136-140 m/min and nanoparticle concentration NC = 0.3% should be used to achieve the smaller total cutting force values (F_r<155N).

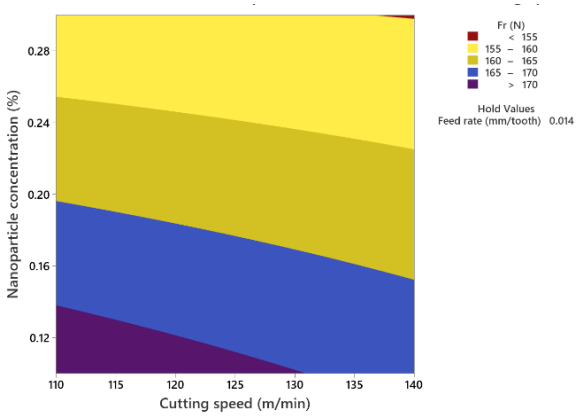


Fig. 8. Influence of nanoparticle concentration and cutting speed on F_r.

The contour plot in Figure 9 exhibits the effect of nanoparticle concentration and feed rate on the total cutting force when the cutting speed is fixed at 125 m/min. The feed rate f= 0.012-0.0125 mm/min and nanoparticle concentration NC = 0.23-0.3% should be selected to achieve the smaller total cutting force values (F_r<140N).

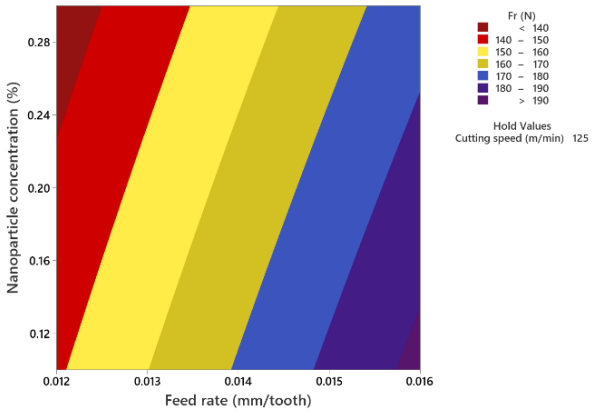


Fig. 9. Influence of nanoparticle concentration and feed rate on F_r.

The contour graph in Figure 10 shows the influence of feed rate and cutting speed on the surface roughness value R_a with nanoparticle concentration fixed at 0.2%. To achieve smaller surface roughness values R_a (R_a<0.08µm), feed rate f= 0.012-0.013 mm/min and cutting speed V= 122-140 m/min should be chosen.

Figure 11 shows the influence of nanoparticle concentration and cutting speed on the surface roughness R_a when the feed rate is fixed at 0.014 mm/min. The nanoparticle concentration NC =0.1-0.3% and cutting speed V= 135-140 m/min should be selected to achieve smaller surface roughness values (R_a<0.13µm).

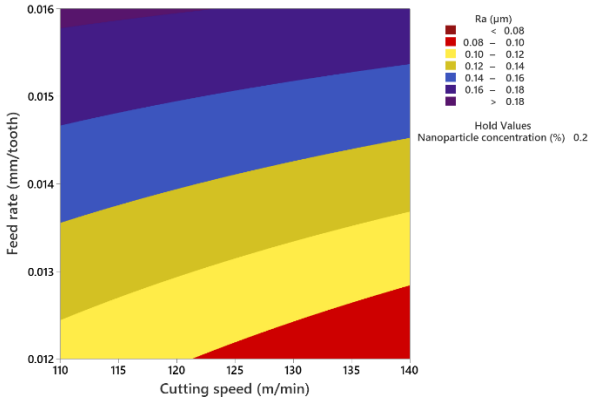


Fig. 10. Influence of feed rate and cutting speed on R_a.

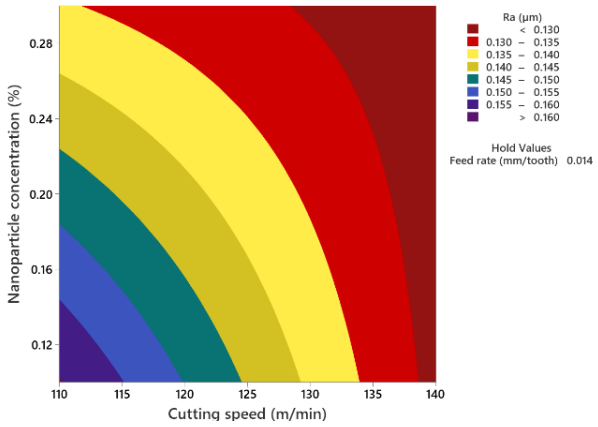


Fig. 11. Influence of nanoparticle concentration and cutting speed on R_a.

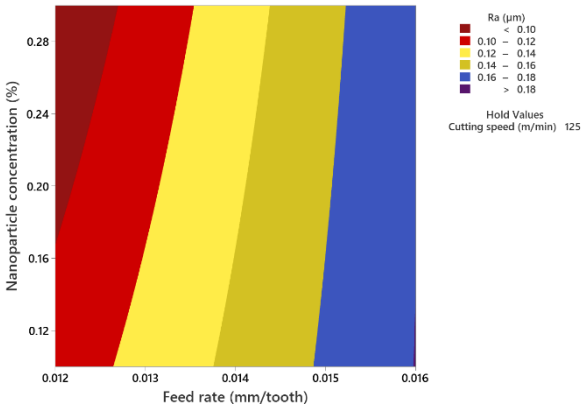


Fig. 12. Influence of nanoparticle concentration and feed rate on R_a.

Figure 12 is the contour plot showing the influence of nanoparticle concentration and feed rate on the surface roughness value R_a in case of V= 125

m/min. In order to achieve smaller surface roughness values (R_a <0.10μm), the nanoparticle concentration NC = 0.17-0.3% and feed rate f = 0.012-0.013 mm/min should be selected.

Thus, from the results obtained, it can be seen that for each specific requirement, the appropriate value ranges can be selected to achieve the desired output. These results have great scientific and practical significance, helping technologists quickly select parameters to apply in production practice. In general, V=125-140 m/min, f = 0.012-0.013 mm/min, NC= 0.2-0.3% can be used to simultaneously achieve smaller values of both F_r and R_a.

4. CONCLUSION

In this work, MQL technique using MoS_2 nano cutting oils was successfully applied for the hard milling process of Hardox 500 steel (49-50 HRC). The effects of nanoparticle concentration, cutting speed, and feed rate on the total cutting force F_r and surface roughness R_a were studied and evaluated. Experimental results show that MQL using MoS_2 nano cutting oil has improved the hard milling performance as well as machinability of coated carbide inserts. Thanks to MoS_2 nano cutting oil assisted to MQL method, the applicability of brand rice oil, a vegetable oil, was enlarged for hard milling process. Among the studied parameters, feed rate causes the strongest influence on the total cutting force and surface roughness, followed by nanoparticle concentration and then cutting speed. The appropriate value ranges were specified to provide the technical guides for technologists. The cutting speed V=125-140 m/min, feed rate f = 0.012-0.013 mm/min, nanoparticle concentration NC= 0.2-0.3% should be used for achieving smaller values of F_r and R_a.

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REFERENCES

[1] T. M. Duc, T. T. Long, and D. V. Thanh, "Evaluation of minimum quantity lubrication and minimum quantity cooling lubrication performance in hard drilling of Hardox 500 steel using Al2O3 nanofluid," *Advances in Mechanical Engineering*, vol. 12, no. 2, 2020, doi: 10.1177/1687814019888404.

[2] M. Kuntoglu, "Machining induced tribological investigations in sustainable milling of Hardox 500 steel: A new approach of measurement science," *Measurement*, vol. 201, p. 111715, 2022, doi: 10.1016/j.measurement.2022.111715.

[3] A. T. Abbas, M. K. Gupta, M. S. Soliman, M. Mia, H. Hegab, M. Luqman, and D. Y. Pimenov, "Sustainability assessment associated with surface roughness and power consumption characteristics in nanofluid MQL-assisted turning of AISI 1045 steel," *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 1-4, pp. 1311–1327, 2019, doi: 10.1007/s00170-019-04325-6.

[4] A. Uysal, F. Demiren, and E. Altan, "Applying Minimum Quantity Lubrication (MQL) Method on Milling of Martensitic Stainless Steel by Using Nano MoS2 Reinforced Vegetable Cutting Fluid," *Procedia Soc. Behav. Sci.*, vol. 195, pp. 2742–2747, 2015.

[5] A. K. Sharma, A. K. Tiwari, and A. R. Dixit, "Mechanism of Nanoparticles Functioning and Effects in Machining Processes: A Review," *Materials Today: Proceedings*, vol. 2, no. 4-5, pp. 3539–3544, 2015, doi: 10.1016/j.matpr.2015.07.331.

[6] R. W. Maruda, K. Arkusz, N. Szczotkarz, S. Wojciechowski, P. Niesłony, and G. M. Królczyk, "Analysis of size and concentration of nanoparticles contained in cutting fluid during turning of 316L steel in minimum quantity lubrication conditions," *Journal of Manufacturing Processes*, vol. 87, 2023, doi: 10.1016/j.jmapro.2022.12.065.

[7] N. Szczotkarz, R. Maruda, K. Leksycki, E. Feldshtein, S. Wojciechowski, P. Jurczak, and M. Waligóra, "Analysis of Power Grid Parameters Depending on the Variable Concentration and Size of Copper Nanoparticles and Aerosol Formation Parameters in the Minimum Quantity Lubrication Method During Turning of Ti6Al4V Titanium Alloy," *Advances in Science and Technology Research Journal*, vol. 17, no. 6, pp. 315-324, 2023, doi: 10.12913/22998624/174806.

[8] T. M. Duc, T. T. Long, and T. B. Ngoc, "Effectiveness of alumina nanofluid on slotting end milling performance of SKD 11 tool steel," *J. Comput. Appl. Res. Mech. Eng.*, vol. 9, no. 2, pp. 359–369, 2020, doi: 10.22061/JCARME.2019.4041.1484.

[9] T. M. Duc, T. T. Long, and P. Q. Dong, "Effect of the alumina nanofluid concentration on minimum quantity lubrication hard machining for sustainable production," *Proc. Inst. Mech. Eng. Part C: J. Mech. Eng. Sci.*, vol. 233, pp. 5977–5988, 2019, doi: 10.1177/0954406219861992.

[10] H. Hegab, H. A. Kishawy, U. Umer, and A. Mohany, "A model for machining with nano-additives based minimum quantity lubrication," *Int. J. Adv. Manuf. Technol.*, vol. 102, pp. 2013–2028, 2019.

[11] B. Rahmati, A. A. D. Sarhan, and M. Sayuti, "Morphology of surface generated by end milling AL6061-T6 using molybdenum disulfide (MoS2) nanolubrication in end milling machining," *Journal of Cleaner Production*, vol. 66, pp. 685–691, 2014, doi: 10.1016/j.jclepro.2013.10.048.

[12] P. Q. Dong, T. M. Duc, and T. T. Long, "Performance Evaluation of MQCL Hard Milling of SKD 11 Tool Steel Using MoS2 Nanofluid," *Metals*, vol. 9, p. 658, 2019, doi: 10.3390/met9060658.

[13] T. B. Ngoc, T. M. Duc, N. M. Tuan, and T. T. Long, "Influence of Al2O3/MoS2 hybrid nanofluid MQL on surface roughness, cutting force, tool wear and tool life in hard turning," *Forces in Mechanics*, vol. 16, p. 100285, 2024, doi: 10.1016/j.finmec.2024.100285.

[14] T. M. Duc and T. T. Long, "Investigation of Nano Cutting Oil Effects on Hard Milling Under Minimum Quantity Lubrication," *Journal of Materials and Engineering*, vol. 2, no. 4, pp. 323–328, 2024, doi: 10.61552/JME.2024.04.010.

[15] J. Paulo Davim, *Machining of Hard Materials*. Springer-Verlag London Limited, 2011.

[16] S. Pervaiz, I. Deiab, A. Rashid, and 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, no. 9, 2017, doi: 10.1177/0954405415599946.