Evaluation of minimum quantity lubrication and minimum quantity cooling lubrication performance in hard drilling of Hardox 500 steel using \( \text{Al}_2\text{O}_3 \) nanofluid

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Abstract
The work in this study presents an experimental evaluation on minimum quantity cooling lubrication based on the Ranque–Hilsch vortex tube and minimum quantity lubrication performance in hard drilling of Hardox 500 steel (49–50 HRC) using coated carbide drills. \( \text{Al}_2\text{O}_3 \) nanoparticles are suspended in the based fluids including water-based emulsion and rice bran oil to enhance the cooling and lubricating effects. The response variables, consisting of drilling thrust force, surface roughness, surface profile and microstructure, and tool wear, are studied, and the analysis of variance is used for evaluating the input machining parameters under minimum quantity lubrication and minimum quantity cooling lubrication conditions. The results of this article indicate that minimum quantity cooling lubrication using \( \text{Al}_2\text{O}_3 \) nanofluid provides the better machining performance and gives out better surface quality and lower thrust force compared to minimum quantity lubrication with/without nanofluid and minimum quantity cooling lubrication with pure fluid. Also, based on the optimization results, the validation experiments are conducted to study more on drilling thrust force, chip morphology, and tool wear.

Keywords
Hard drilling, minimum quantity lubrication, minimum quantity cooling lubrication, emulsion, \( \text{Al}_2\text{O}_3 \) nanoparticles, nanofluid, concentration, surface roughness, Hardox 500 steel

Date received: 1 September 2019; accepted: 18 October 2019

Handling Editor: Diego Carou

Introduction
Machining is one of the various processes in which a workpiece is cut into the final shape and size following the technical requirements. Among these, the drilling process plays such an important role in creating holes. Heat dissipation and high friction in the contact zone usually limit cutting performance in drilling operations.\(^1\) High cutting temperature and cutting forces generated cause tool life and surface quality to reduce drastically,\(^2\) but it can be improved by using cutting fluids in high quantities to cool the drill bit, reduce the friction, prolong tool life, increase speeds and feeds as well as the surface finish, and aid in ejecting chips.\(^3\) Application of flood coolant with industrial cutting

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fluids is common in the drilling process, but it causes the negative effects on the environment, which has become one of the biggest issues in modern industry. Hence, the requirement of reducing environmental loads to achieve environmentally friendly manufacturing processes has been studied and developed. The reduction of metal cutting fluid in machining has been considered an effective way to encounter with this problem. Among many of the proposed alternative solutions, drilling processes under dry, compressed cold air, and minimum quantity lubrication (MQL) conditions have mainly been studied and categorized as the environmentally friendly machining methods. Dry drilling refers to machining without using cutting fluids, but it faced with several technical problems, including rapid tool wear, thermal deterioration on drill bit and machined surface, and so forth. A Diaz-Álvarez et al. estimated thermal effects in dry drilling of Ti6Al4V alloy using the TiAlN-coated carbide tool. The results indicated that the maximum temperature is reached in the material of the machined surface at the instant in which the contact with the drill tool and the cutting temperature is high due to no cooling and lubricating medium. Z Zhu et al. established a new three-dimensional (3D) schematic to understand the chip formation and morphology fully in dry drilling of Ti6Al4V alloys. The experimental results showed that the feed rate plays a more important role in chip macro morphology than cutting speed. The length of chip decreases with feed increasing and remains almost unchanged with increasing cutting speed. P Haja Syeddu Masooth and V Jayakumar studied the effect of three different coatings (TiN, AlCrN, and TiAlN) under dry drilling process of aluminum 5052 grade alloy on the surface finish of the holes. The authors pointed out that TiAlN-coated tools exhibited the better hole surface finish as well as lesser wear rate and enhanced productivity. FM Bordin and RP Zeilmann made the dry drilling experiments using carbide tools, coated with TiAlN and three configurations of tools (sharpened, polished with abrasive brushes, and treated with drag finishing surface treatment). The results indicated that the preparation of the cutting edge has a strong effect on the surface integrity of machined holes. However, the machining performance of dry drilling is low and always requires high-grade drilling tools, while the flooded lubrication technique is responsible for environmental and health issues as well as the high cost for the treatment of used cutting fluids.

Thus, Cryogenic and Minimum Quantity Lubrication conditions are the promising solutions to overcome the drawbacks of dry and flooded machining. S Joshi et al. developed a new approach to predict the delamination factor for dry and cryogenic drilling of carbon-fiber-reinforced polymer (CFRP) in terms of cutting speed and feed rate on thrust force, delamination, and surface roughness. The results of this article showed that drilling under cryogenic conditions exhibited a significant improvement on the surface quality compared to dry cutting. B Tasdelen et al. compared flood, MQL with emulsion, and compressed air cooling in drilling of gear wheel steel. The results exhibited that the tool wear in MQL and air cooling are lower than that in flood condition with emulsion but the wear with air cooling is little larger than that with MQL. Moreover, the authors also pointed out that the surface roughness in MQL is better and the cutting force is lower than those of air cooling. It is proven that MQL condition provides the better lubricating effect, while air cooling exhibits the good cooling characteristic. AT Kuzu et al. studied the thermal modeling of the deep-hole drilling process under MQL condition. From the obtained results, the heat flux is maximal at the chisel edge, which shows a decreasing trend along the cutting lip from the chisel to the periphery of the drill bit. G Le Coz et al. also studied on measuring cutting temperature in MQL drilling and dry milling of Ti6Al4V titanium alloy. The results demonstrated that the measurement system is very sensitive and reflects the cutting temperature more exactly.

S Niketh and GL Samuel studied drilling performance of microtextured tools under dry, wet, and MQL conditions. In this study, the authors used the drill tool having microtextures at the flute and margin side to reduce the sliding friction. This tool was found to be more efficient than the non-textured tool with thrust force reduction. The improvement of cutting performance of microtextured drill tools was found to be the underlying mechanism of contact length reduction and formation of micropool lubrication effect at the cutting regime. Furthermore, burr formation mainly affecting the machined hole quality seems to be minimum under wet and MQL conditions due to better cooling and lubricating effects. The inefficient cooling rate in the case of MQL is the main reason to cause roll back-type burrs, which is the main drawback of the MQL technique, especially for hard machining due to enormous heat generated from the cutting zone. In order to develop the MQL technique, the use of nanoparticles suspended in the base fluids is a promising solution and has gained much researchers’ attention. SS Chatha et al. studied the drilling performance of aluminum 6063 under nanofluid minimum quantity lubrication (NFMQL) condition using the high-speed steel (HSS) tool. The results showed that NFMQL significantly extends the tool life and reduces the drilling torques and thrust forces as compared to other coolant–lubrication conditions because of the reduction in friction force at contact face formed by the rolling effect of nanoparticles and superior cooling performance. In addition, the authors also pointed out that chips and burrs are eliminated to enhance the surface
quality of holes and reduce the tool wear. A similar observation was reported in end milling of the SKD11 tool steel using the HSS tool. R Rosnan et al. studied the effects of MQL using nanofluid on the performance of carbide drills for drilling nickel–titanium alloys. The results indicated that Al$_2$O$_3$ nanofluid was beneficial in improving tool wear resistance and decreasing the drilling thrust force of the coated carbide drills due to rolling effects as well as the formation of tribofilms in the contact zone. On the contrary, MQL nanolubricants were only suitable to control the tool wear rate within cutting speeds of 10–20 m/min. Moreover, drilling under MQL nanofluid conditions was found to be ineffective in terms of surface quality and tool life of uncoated drill bits compared to flood condition in machining difficult-to-cut materials. On the contrary, the MQL method has been proven to have low cooling effect, which is the main drawback and limits the applicability in hard machining due to enormous heat generated from the cutting zone. According to the alternative methods for hard machining of difficult-to-cut materials has been recently studied. The MQCL method is widely used by researchers for the cutting of difficult to machine materials such as nickel–titanium alloys. The results indicated that Al$_2$O$_3$ nanofluid was beneficial in improving tool wear resistance and decreasing the drilling thrust force of the coated carbide drills due to rolling effects as well as the formation of tribofilms in the contact zone. On the contrary, MQL nanolubricants were only suitable to control the tool wear rate within cutting speeds of 10–20 m/min. Moreover, drilling under MQL nanofluid conditions was found to be ineffective in terms of surface quality and tool life of uncoated drill bits compared to flood condition in machining difficult-to-cut materials. On the contrary, the MQL method has been proven to have low cooling effect, which is the main drawback and limits the applicability in hard machining due to enormous heat generated from the cutting zone. Accordingly, the alternative methods for hard machining of difficult-to-cut materials has been recently studied and developed to find the technological and economical solutions, which have drawn growing concern from not only researchers but also manufacturers worldwide. Hardox 500 steel cuts down on weight and extends the service life of parts and components in comparison with regular steel.

The type of steel turns out that the unique combination of hardness and toughness allows Hardox to perform as a load-carrying part in many industrial applications, and design structures can be designed to be wear-resistant, strong, and lightweight at the same time. However, metal cutting processes encounter the challenge when performing with normal cutting tools and dry condition, which limits the productivity and increase the machining cost. Recently, NFMQL and minimum quantity cooling lubrication (MQCL) have been considered the promising solutions to overcome the low cooling performance, the main drawback of the MQL technique. They give out the novel alternative machining techniques assisted to difficult-to-machine materials, but almost all the studies on machining under MQCL condition used emulsion-based fluid possessing the cooling property assisted to the MQL method. Hence, the study on MQCL using different nanofluids is among the newest topics and will give out promising results.

O Gutnichenko et al. recently carried out the study on the effect of graphite vegetable-based nanofluid for hard turning under MQCL condition. The obtained results showed that the turning performance much improved due to the reduction of the friction in combination created by nanoparticles in combination with cooling enhancement created by the MQCL technique. PQ Dong et al. studied the MQCL performance using MoS$_2$ nanofluid in hard milling of the SKD11 tool steel. The results indicated that the enhancement of cooling and lubricating effects is reported by using MoS$_2$ nanofluid, from which the white layer formation and burn marks significantly reduce and therefore the surface quality improves.

After the brief review, it may be concluded that there is little information reported in studying the MQCL performance in hard drilling of difficult-to-cut materials like Hardox 500 steel. Accordingly, the authors made the study on MQCL hard drilling of Hardox 500 steel (49–50 HRC). Moreover, this study also investigates the MQCL performance using Al$_2$O$_3$ nanofluid and then compares to NFMQL and dry conditions in terms of drilling thrust force, surface roughness, surface microstructure, and tool wear. It is also the first attempt to apply MQCL based on the principle of the Ranque–Hilsch vortex tube, used for separating hot and cold streams from ordinary compressed air combined with the MQL technique to create cooling and lubricating effects. The method presented in this study belongs to one of the environmental friendly machining processes, which is suitable for sustainable production.

### Materials and methods

#### Experimental set-up

The set-up model for hard drilling experiments is illustrated in Figure 1. The experiments were conducted on Mazak vertical center smart 530C. The multi drill MDS127SK carbide drill of Sumitomo Electric Industries (made in Japan) with the TiAlCN coating layer was utilized (Figure 2). The cooling and lubricating system includes the MQL device with the designation of NOGA MiniCool MC1700, MQCL device with the designation of Frigid-X Sub-Zero Vortex Tool Cooling Mist System (produced by NexFlow™), compressed air, the device for pressure stabilization, rice bran oil, emulsion oil 5 wt%, and Al$_2$O$_3$ nanoparticles. Measurement devices include SJ-210 Mitutoyo for surface roughness, KEYENCE VHX-6000 Digital Microscope for surface topography, and Kistler quartz three-component dynamometer 9257BA for cutting forces. Al$_2$O$_3$ nanoparticles made by Soochow Hengqi Graphene Technology Co., Ltd., Suzhou, China were used. The average grain size is 30 nm (Figure 3). In this research, Hardox 500 steels (49–50 HRC) with the dimensions of 150 mm × 100 mm × 15 mm were used. The chemical composition and mechanical properties of Hardox 500 steel are shown in Tables 1 and 2. To create uniform distribution of Al$_2$O$_3$ nanoparticles 1.0 wt% in the base fluids of rice bran oil and water-based emulsion, the based fluids with nanoadditives are placed in the Ultrasons-HD ultrasonicator produced by JP SELECTA for 6 h with 600 W ultrasonic pulses.
at 40 kHz and directly used for MQL and MQCL systems.\textsuperscript{23}

**Experimental design**

The drilling experiments are conducted by following the factorial design $2^{k-1}$ with five variables ($k = 5$). The control factors and their levels are given in Table 3. The experiment design is $N = 2^{5-1} = 8$.

Minitab 18.0 software is applied for the experimental design of $2^{5-1}$. The experimental design with trial run order and response variables is shown in Table 4. The air pressure of 6 Bar and flow rate of 30 mL/h are fixed for MQL and MQCL systems. For room temperature of 24–27°C, the temperature of output cool air of the MQCL nozzle is about 4–8°C. Each experimental trial is repeated by three times under the same machining parameters.

**Results and discussion**

**The effects on drilling thrust force $F$**

Minitab 18 software is used with a confidence level of 95\% (i.e. 5\% significance level) to analyze the experimental data. The effect of input machining parameters on drilling thrust force is given by equation (1) with a coefficient of determination ($R^2$) equal to 99.80. The results of analysis of variance (ANOVA) are given in Table 5 in Appendix 1. Pareto chart for evaluating the variable influence on axial force is shown in Figure 4,
and effects of investigated variables on the values of drilling thrust force are shown in Figure 5.

The regression function of drilling thrust force \( F \) is given by the following equation

\[
F = 220.8 + 148.83 x_1 + 4.25 x_2 - 34.92 x_3 \\
+ 17.02 x_4 + 6838 x_5 - 41 x_2 x_3 - 1867 x_2 x_5
\]

\[(1)\]

From the Pareto chart in Figure 4, all the values of the investigated variables exceed the reference line, which means they have strong influences on the drilling thrust force \( F \). The influence level of each input machining parameter is reflected by its coefficient in equation (1). The conclusion has the scientific and practical meanings because the fluid type, cooling and lubricating methods (MQL and MQCL), nanoparticles, and

Table 3. Input machining factors and their levels.

| Control factor                  | Low level (–1)          | High level (+1)       | Response variables |
|---------------------------------|-------------------------|-----------------------|--------------------|
| Type of cutting fluid \( x_1 \) | Emulsion (Em)           | Rice bran oil (RO)    | Thrust force \( F \) |
| Cooling and lubricating method \( x_2 \) | MQL                    | MQCL                  | Surface microstructure |
| Based fluid \( x_3 \)           | Without nanoparticles (no) | With nanoparticles (yes) | Surface roughness \( R_z \) |
| Cutting speed \( V_c \) \( x_4 \) | 15 m/min                | 25 m/min              |                    |
| Feed rate \( f \) \( x_5 \)     | 0.02 mm/rev             | 0.06 mm/rev           |                    |

MQL: minimum quantity lubrication; MQCL: minimum quantity cooling lubrication.

Table 4. The experimental design with run order, input parameters, and response variables.

| Run | Input parameters | Output variables |
|-----|------------------|------------------|
|     |                  | \( F \) (N) \( R_z \) (\mu m) |
|     | \( x_1 \) \( x_2 \) \( x_3 \) \( x_4 \) \( x_5 \) |
| 1   | Em MQL No 25 0.06 | 1006 3.17 |
| 2   | RO MQCL No 25 0.02 | 980 2.22 |
| 3   | Em MQCL No 15 0.06 | 700 2.35 |
| 4   | Em MQL Yes 25 0.02 | 670 2.87 |
| 5   | RO MQCL Yes 15 0.06 | 780 2.64 |
| 6   | RO MQCL Yes 15 0.06 | 1150 2.86 |
| 7   | RO MQCL Yes 15 0.06 | 1135 2.76 |
| 8   | Em MQCL No 15 0.06 | 710 2.38 |
| 9   | RO MQCL No 25 0.02 | 975 2.21 |
| 10  | RO MQCL No 25 0.02 | 800 2.54 |
| 11  | Em MQCL Yes 15 0.02 | 550 2.02 |
| 12  | Em MQCL Yes 25 0.02 | 1022 3.28 |
| 13  | Em MQCL Yes 25 0.02 | 682 2.67 |
| 14  | Em MQCL Yes 25 0.02 | 668 2.76 |
| 15  | Em MQCL Yes 25 0.02 | 1000 3.01 |
| 16  | Em MQCL Yes 25 0.02 | 570 1.86 |
| 17  | Em MQCL Yes 25 0.02 | 565 1.95 |
| 18  | Em MQCL Yes 25 0.02 | 1000 2.26 |
| 19  | Em MQCL Yes 25 0.02 | 1050 2.67 |
| 20  | Em MQCL Yes 25 0.02 | 1162 2.88 |
| 21  | Em MQCL Yes 25 0.02 | 707 2.31 |
| 22  | Em MQCL Yes 25 0.02 | 969 2.08 |
| 23  | Em MQCL Yes 25 0.02 | 1015 2.88 |
| 24  | Em MQCL Yes 25 0.02 | 786 2.58 |

Em: emulsion; MQL: minimum quantity lubrication; MQCL: minimum quantity cooling lubrication.

Figure 4. Pareto chart of effects of investigated variables on drilling thrust force \( F \).
cutting condition have significant effects on the hard drilling process of Hardox 500 steel.

The results of ANOVA in Table 5 in Appendix 1 indicate that the investigated parameters and their interaction in equation (1) have p-values smaller than the significance level \( \alpha = 0.05 \), from which they have strong influences. The regression model is judged by a coefficient of determination \( (R^2) \) equal to 99.80, which means that the obtained model is suitable.

Among the input machining parameters, the fluid type \( (x_1) \) and feed rate \( (x_5) \) have strongest influences, followed by nanoparticles \( (x_3) \) and cooling and lubricating methods \( (x_2) \). Hence, when the cutting force need to be controlled, the fluid type and feed rate should be modified.

The interaction effects of \( x_2 \times x_3 \) (cooling and lubricating methods and nanoparticles) and \( x_2 \times x_5 \) (cooling and lubricating methods and feed rate) have significant influence shown in equation (1) and Figure 4.

The effects of input parameters on drilling thrust force \( F \) (Figure 5) are as follows:

- The effects of fluid type \( (x_1) \): the cutting force in the case of emulsion 5% is smaller than that of rice bran oil. The reason is that compared to emulsion fluid, rice bran oil has the higher viscosity, which makes it difficult to enter to the cutting zone, and its cooling and lubricating property is reduced by the enormous generated cutting temperature of the hard drilling process due to lower ignited temperature, which is suitable to the previous study.\(^{16}\)
- The effects of cooling and lubricating methods \( (x_2) \): the performance of MQCL is better than that of MQL due to the better cooling effect.
- The effects of nanoparticles \( (x_3) \): compared to the case of using pure fluid, the axial drilling force reduces by using nanofluid, which indicates the better lubricating performance of \( \text{Al}_2\text{O}_3 \) nanofluid.\(^{16,19,27}\)
- The effects of cutting speed \( (x_4) \) and feed rate \( (x_5) \): the axial drilling force \( F \) rises with the increase in cutting speed and feed rate.

From the analysis of the effects for input parameters, the combination of emulsion fluid, MQCL, \( \text{Al}_2\text{O}_3 \) nanofluid, cutting speed \( V_c = 15 \text{ m/min} \), and feed rate of 0.02 mm/rev should be used for the objective of reducing drilling thrust force \( F \).

The effects on surface roughness \( R_z \)

Geometrically, drilling is a complex process and is traditionally categorized as the rough machining process. It is usually performed before threading, tapping, boring, reaming, and so on. Therefore, the requirements for machined hole quality are not high, so the authors use surface roughness criteria \( R_z \).

Minitab 18 software is used with a confidence level of 95% (i.e. 5% significance level) to analyze the experimental data. The effects of input machining parameters on surface roughness \( R_z \) are given by equation (2) with a coefficient of determination \( (R^2) \) equal to 91.39. The results of ANOVA are given in Table 6 in Appendix 1. Pareto chart for evaluating the variable influence on values of surface roughness is shown in Figure 6, and the effect of investigated variables on the values of surface roughness is shown in Figure 7.

The regression function of surface roughness \( R_z \) is given by the following equation

\[
R_z = 1.691 - 0.0021x_1 - 0.3354x_2 - 0.0138x_3 + 0.02458x_4 + 9.19x_5 + 0.0212x_2 \times x_3 + 1.27x_2 \times x_5 \tag{2}
\]

After the drilling process, the samples are cut by wire electrical discharge machining to take the cross-section faces, which are examined under the KEYENCE VHX-6000 Digital Microscope (Figure 8). The effects of machining parameters on surface profile and microstructure in the hard drilling process are shown in Figure 9.

From the Pareto chart in Figure 6, among the investigated variables, the cooling and lubricating method has a strongest influence, followed by feed rate and cutting speed. The fluid type and \( \text{Al}_2\text{O}_3 \) nanoparticles also
have interaction effects with the cooling and lubricating method, but they influence very little on surface roughness $R_z$.

The results of ANOVA in Table 6 in Appendix 1 indicate that the investigated parameters have $p$-values smaller than $\alpha = 0.05$, so they cause strong influences. The regression model is judged by a coefficient of determination ($R^2$) equal to 91.39, which means that the obtained model is suitable.

From Figure 9, all the investigated parameters have strong impact on surface roughness $R_z$, surface profile, and surface microstructure. In general, the $R_z$ values and the surface microstructure are good and fulfill the requirements of rough machining.

The influences of input variables on surface roughness $R_z$ (Figure 7) are as follows: the effects of fluid type, cooling and lubricating methods, nanoparticles, cutting speed, and feed rate on surface roughness are similar to those on drilling thrust force mentioned earlier. The cooling and lubricating method, cutting speed and feed rate have strong influences on $R_z$ values. The combination of MQCL, cutting speed $V_c = 15 \text{ m/min}$, and feed rate of $0.02 \text{ mm/rev}$ should be used for the objective of reducing the values of surface roughness $R_z$.

**Multioptimization results**

The optimization plot for both drilling thrust force and surface roughness $R_z$ is shown in Figure 10.

From the multi-optimization result, MQCL using emulsion-based nanofluid combines with a cutting speed of $15 \text{ m/min}$ and a feed rate of $0.02 \text{ mm/rev}$. In order to achieve the productivity and quality characters, cutting speed and feed rate can be increased. Further studies are needed to evaluate chip formation, tool wear, and tool life more accurately.

**Study of the machinability of drilling Hardox 500 steel**

The aim is to evaluate the machinability of the drilling process of Hardox 500 steel through chip formation, tool wear, and tool life. The experimental set-up is the same as in “Experimental set-up” section and is conducted under MQCL condition using Al$_2$O$_3$ emulsion-based nanofluid with a nanoconcentration of 1.0 wt%. The cutting speed is $20 \text{ m/min}$ and the feed rate is $0.04 \text{ mm/rev}$ (the average values of investigated range). The graph exhibits the relation between drilling thrust force and cutting time shown in Figure 11 with 7.5 min for each measurement. Chip morphology and flank wear are shown in Figures 12 and 13, respectively.

Although Hardox 500 steel has high hardness (49–50 HRC), it also has ductility and toughness properties. Accordingly, the continuous chip is formed (Figure 12(a)) with folded long ribbon on chip surfaces due to high level of plastic deformation character (Figure 12(b) and (c)), which also makes the chip break process difficult.

The fresh drill tool is shown in Figure 13 (a). It is clearly seen from Figure 13 (b) that the flank face of carbide drill under MQCL using nanofluid 1 wt% after 20 minutes of cutting occurs burned area, and the wear land is very small. The burned marks are caused by the cutting fluid ignition adhered to the flank face. In contrast, the wear land under dry condition is large (about 0.25–0.3 mm) even in the same cutting condition and time. The wear mode is mainly the crater, and the tool life ends. The tool life under MQCL using Al$_2$O$_3$
Figure 8. The cross-section faces of machined holes to study surface profile and microstructure.

| No. | Input parameters | Surface profile | Surface microstructure |
|-----|------------------|-----------------|------------------------|
| 1   |                  |                 |                        |
| 2   |                  |                 |                        |
| 3   |                  |                 |                        |
| 4   |                  |                 |                        |
| 5   |                  |                 |                        |
| 6   |                  |                 |                        |
| 7   |                  |                 |                        |
| 8   |                  |                 |                        |

Figure 9. Surface profile and microstructure of machined holes following the experimental design.
nanofluid is about 90 min with the critical value of the flank wear (VB) of 0.3 mm.\(^\text{14}\)

**Conclusion**

In this study, the usage of ANOVA for the design of experiment to study the effects of input machining variables including the based fluid type, cooling and lubricating methods (MQL and MQCL), Al\(_2\)O\(_3\) nanoparticles, cutting speed, and feed rate on drilling thrust force, surface roughness, and surface microstructure in hard drilling of Hardox 500 steel (49–50 HRC). Then, the multi-optimization is done to predict the optimal machining parameters, which provide the technical guides and research direction.

In this work, the Frigid-X Sub-Zero Vortex Tool Cooling Mist System, an MQCL device, is used for creating the cool air stream to improve cooling performance, which is successfully applied in hard drilling using coated carbide tools. It is the first experimental work to study the novel MQCL performance using Al\(_2\)O\(_3\) nanofluid, which is also compared to the MQL technique to prove the effectiveness in hard machining of Hardox 500 steel, one of the difficult-to-cut materials.

Compared to MQL and MQCL using pure fluid, the surface roughness and microstructure improve in the case of the MQCL technique using emulsion-based fluid with Al\(_2\)O\(_3\) additives. The significant improvement in cooling lubrication of MQCL using Al\(_2\)O\(_3\) nanofluid is reported.

Based on the multi-optimization results, the validation experiment is done to not only have a deeper view but also study chip morphology and tool wear. The results show that the better cooling and lubricating performance of MQCL using Al\(_2\)O\(_3\) nanofluid is observed through the chip morphology and the significant reduction of flank wear. Therefore, the tool life in the case of cutting speed of 20 m/min and feed rate of 0.04 mm/rev much extended to 90 min, which is about 4.5 times longer than that with dry condition.

The extreme wear resistance has always been the typical property of Hardox steel. Today, it is harder and tougher than ever and able to withstand heavy impact without permanent deformation or cracking; therefore, it is grouped in difficult-to-cut materials. The application of MQCL with nanofluid assisted to the hard drilling process using the coated carbide tool contributes to improve the machining performance of

Figure 10. The optimization plot.

Figure 11. The relation between drilling thrust force \(f\) and cutting time.

Figure 12. Chip morphology under MQCL using Al\(_2\)O\(_3\) nanofluid: (a) continuous chip, (b) chip surface uncontacted with rake face, and (c) chip surface contacted with rake face.
Hardox 500 steel while retaining the good surface quality and tool life. It will be a promising sustainable solution for machining practice.

From the obtained results, the combination of the MQCL method utilizing emulsion-based nanofluid with a cutting speed of 15 m/min and a feed rate of 0.02 mm/rev brings outs the low values of surface roughness $R_z$ and drilling thrust force $F$. On the contrary, the external mist delivery rather than internal mist delivery as recommended by manufacturers can be used while fulfilling the technical requirements, which contribute to simplify the machine tool and drill bits and reduce the manufacturing cost. In further research, more studies are necessary to focus on the influences of other parameters such as nanoparticle concentration, cutting temperature, and MQCL parameters.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The study had the support of Thai Nguyen University of Technology - Thai Nguyen University with the project number of DH2018-TN02-01.

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### Table 5. Results of ANOVA of drilling thrust force F

| Source          | DF | Adjusted SS | Adjusted MS | F-value | p-value |
|-----------------|----|-------------|-------------|---------|---------|
| Model           | 7  | 1,376,245   | 196,606     | 1152.27 | 0.000   |
| Linear          | 5  | 1,302,451   | 260,490     | 1526.68 | 0.000   |
| x<sub>1</sub>   | 1  | 531,633     | 531,633     | 3115.80 | 0.000   |
| x<sub>2</sub>   | 1  | 119,004     | 119,004     | 697.46  | 0.000   |
| x<sub>3</sub>   | 1  | 29,260      | 29,260      | 171.49  | 0.000   |
| x<sub>4</sub>   | 1  | 173,740     | 173,740     | 1018.26 | 0.000   |
| x<sub>5</sub>   | 1  | 448,814     | 448,814     | 2630.41 | 0.000   |
| Two-way interactions | 2 | 73,795      | 36,897     | 216.25  | 0.000   |
| x<sub>2</sub>×x<sub>3</sub> | 1 | 40,344      | 40,344      | 236.45  | 0.000   |
| x<sub>2</sub>×x<sub>5</sub> | 1 | 33,451      | 33,451      | 196.05  | 0.000   |
| Error           | 16 | 2730        | 171         |         |         |
| Total           | 23 | 1,378,975   |             |         |         |

ANOVA: analysis of variance; DF: degrees of freedom; MS: mean squares; SS: sum of squares.
Table 6. Results of ANOVA of surface roughness $R_z$.

| Source                  | DF | Adjusted SS | Adjusted MS | F-value | p-value |
|-------------------------|----|-------------|-------------|---------|---------|
| Model                   | 7  | 3.14763     | 0.44966     | 24.25   | 0.000   |
| Linear                  | 5  | 3.12129     | 0.62426     | 33.67   | 0.000   |
| $x_1$                   | 1  | 0.00010     | 0.00010     | 0.01    | 0.941   |
| $x_2$                   | 1  | 1.94370     | 1.94370     | 104.83  | 0.000   |
| $x_3$                   | 1  | 0.00454     | 0.00454     | 0.24    | 0.628   |
| $x_4$                   | 1  | 0.36260     | 0.36260     | 19.56   | 0.000   |
| $x_5$                   | 1  | 0.81034     | 0.81034     | 43.70   | 0.000   |
| Two-way interactions    | 2  | 0.02634     | 0.01317     | 0.71    | 0.506   |
| $x_2 \times x_3$        | 1  | 0.01084     | 0.01084     | 0.58    | 0.456   |
| $x_2 \times x_5$        | 1  | 0.01550     | 0.01550     | 0.84    | 0.374   |
| Error                   | 16 | 0.29667     | 0.01854     |         |         |
| Total                   | 23 | 3.44430     |             |         |         |

ANOVA: analysis of variance; DF: degrees of freedom; MS: mean squares; SS: sum of squares.