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# Research on the Effect of Minimum Quantity Lubrication (MQL) with $MoS_2$ Nanofluid on Surface Roughness in Hard Turning of 90CrSi Steel

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***Abstract***
*Minimum Quantity Lubrication (MQL) employing nanoparticle-enhanced cutting fluids has emerged as an effective approach for improving machining performance while supporting sustainable and environmentally friendly manufacturing. This study investigates the influence of MQL using $MoS_2$ nanofluid on the surface roughness (Ra) obtained during hard turning of hardened 90CrSi steel (60–62 HRC). Analysis of Variance (ANOVA) was applied to evaluate the effects of nanoparticle concentration (NC), compressed-air pressure (p), and fluid flow rate (Q) on surface roughness. The results revealed that nanoparticle concentration had the most significant effect on Ra, contributing 57.42% of the total variation. The flow rate Q was the second most influential factor contributed 27.10%, while air pressure p had the smallest influence at 15.48%.*

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## I. Introduction

Hard turning refers to the machining of hardened steels, typically within the hardness range of 45–68 HRC, using cutting tools with defined cutting edges. Over the past decades, hard turning has become widely adopted in industries such as automotive manufacturing, aerospace engineering, and mold production. The process has successfully replaced conventional grinding in many applications and is commonly employed for both rough and finish machining operations.

Hard turning can achieve surface roughness values ranging from 0.4 to 0.8 µm, roundness errors of 2–5 µm, and dimensional tolerances within ±(3–7) µm. When cubic boron nitride (CBN) tools are used in precision machining, dimensional accuracy can reach IT3 grade and surface roughness values as low as Ra = 0.1 µm. Previous studies have demonstrated that CBN tools generally produce superior surface quality compared with ceramic tools. However, ceramic inserts remain attractive because of their lower cost and acceptable machining performance [1,2].

To enhance the technical and economic performance of hard turning operations, various lubrication and cooling strategies have been developed. Among them, Minimum Quantity Lubrication combined with nanofluid cutting oils (NF-MQL) has attracted considerable attention and has become an important research trend in modern machining. The growing number of studies published on NF-MQL applications in hard machining processes highlights its increasing significance and industrial potential [3].

Numerous researchers have investigated the performance of NF-MQL in metal cutting processes. Their findings consistently indicate that NF-MQL provides superior lubrication conditions, resulting in lower cutting forces, reduced power consumption, and extended tool life compared with both dry machining and conventional flood cooling methods [5–11].

Duc et al. [12] conducted hard turning experiments using MQL with $MoS_2$ and $Al_2O_3$ nanoparticle-enhanced cutting oils. Their results showed that $MoS_2$ nanofluid significantly reduced the tangential cutting force (Fz), while generating higher thrust force (Fy) compared with $Al_2O_3$ nanofluid. Despite the reduction in cutting forces, better surface finish was achieved with soybean-oil-based $Al_2O_3$ nanofluid because of the lower thrust force produced during machining.

In a subsequent study, Duc et al. [13] further developed MQL technology by incorporating $Al_2O_3$ and $MoS_2$ nanoparticles into soybean oil and water-based emulsion lubricants for hard turning of 90CrSi steel hardened to 60–62 HRC. A factorial experimental design was employed to evaluate the effects of nanoparticle type, base oil, nanoparticle concentration, and cutting speed on cutting-force components and surface roughness. The results demonstrated that $MoS_2$ nanofluids were highly effective in reducing the cutting force components Fx and Fz, whereas $Al_2O_3$ nanofluids tended to produce lower thrust forces. Moreover, the lowest surface roughness values were obtained when using $Al_2O_3$ nanoparticles dispersed in soybean oil.

Considering the superior capability of $MoS_2$ nanofluids in reducing cutting forces, particularly Fx and Fz, further research is required to identify the optimal NF-MQL parameters that can simultaneously improve surface quality. Therefore, the present study aims to investigate the effects of nanoparticle concentration (NC), air pressure (p), and fluid flow rate (Q) in an MQL system employing soybean-oil-based $MoS_2$ nanofluid during hard turning of 90CrSi steel. The ultimate objective is to determine the optimal machining conditions for minimizing surface roughness.

## II. Materials and Methods

The experimental setup used for the hard-turning tests is illustrated in Figure 1. Machining experiments were carried out on a Chu Shin CS-460×1000 lathe (Shin Pin Machinery Co., Ltd., Taichung City, Taiwan). A Sandvik CBN insert, grade HW 7025 (Figure 2), was employed as the cutting tool. The insert had the following geometric characteristics: nose angle of 80°, nose radius (RE) of 0.8 mm, rake angle (GB) of −20°, clearance angle of 7°, and cutting-edge width (BN) of 0.1 mm.

The workpiece material was hardened 90CrSi steel (ISO DIN 4957), whose chemical composition is presented in Table 1. Cylindrical specimens with dimensions of Ø45 mm × 45 mm were prepared, with four test sections on each specimen. The hardness of the workpiece material was maintained at 60 ± 1 HRC.

Minimum Quantity Lubrication was supplied through a NOGA MiniCool MC1700 nozzle (Noga Engineering & Technology (2008) Ltd., Shlomi, Israel), which was positioned to direct the lubricant spray onto the tool flank face during machining. Surface roughness measurements were performed using a Mitutoyo SJ-210 surface roughness tester. The arithmetic average roughness (Ra) was evaluated over a sampling length of 0.08 mm. For each machining condition, surface roughness was measured three times after cutting, and the average value was used for subsequent analysis.

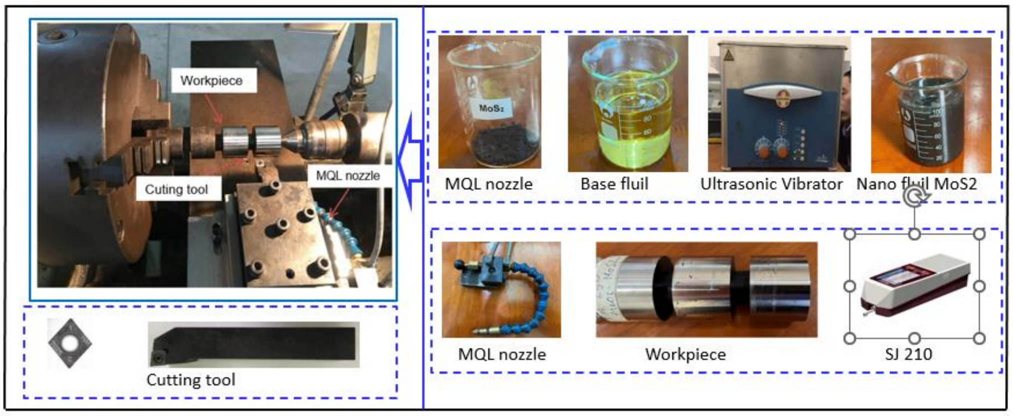


*Figure 1: Experiment set up*

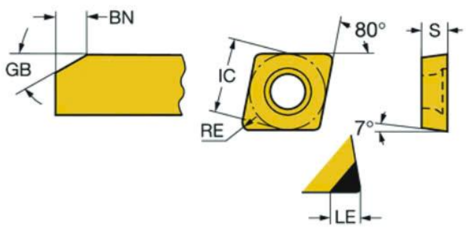


*Figure 2. Basic geometric parameters of the cutting insert.*

| | |
|---|---|
| Face land width(BN) | 0.1mm |
| Face land angle (GB) | $20^0$ |
| Hand(HAND) | NeutRal |
| GRade(GRADE) | 7025 |

$MoS_2$ nanoparticles with an average particle size of 30 nm were dispersed in soybean oil to prepare the $MoS_2$ nanofluid cutting lubricant. The nanofluid was produced by directly mixing the nanoparticles into the base oil, followed by mechanical stirring to achieve an initial dispersion. Subsequently, the mixture was subjected to ultrasonic agitation using an Ultrasons-HD ultrasonic homogenizer (JP Selecta, Abrera, Barcelona, Spain) for 1 hour at a frequency of 40 kHz to improve nanoparticle dispersion and stability.

The experimental design was developed using Minitab 21 software based on the Box–Behnken Design (BBD) methodology. Three process parameters were selected as input variables: nanoparticle concentration (NC), air pressure (p), and lubricant flow rate (Q). The levels of these variables are

presented in Table 2. A total of 15 experimental runs were generated and conducted, with each run repeated three times to ensure repeatability and reliability of the results.
Throughout the experiments, the cutting parameters were kept constant at a cutting speed of 160 m/min, a feed rate of 0.12 mm/rev, and a depth of cut of 0.12 mm . The experimental conditions and corresponding results are summarised in Table 3.

| Element | C | Si | Mn | P | S | Cr | Ni | Mo | W | V | Ti | Cu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Weight (%) | 0.85-0.95 | 1.20-1.60 | 0.30-0.60 | Max 0.03 | Max 0.03 | 0.95-1,25 | Max 0.40 | Max 0.20 | Max 0.20 | Max 0.20 | Max 0.03 | Max 0.03 |

*Table 1. Chemical composition of 90CrSi steel*

| No | Varieable | Name | Low level | High level |
|---|---|---|---|---|
| 1 | Particle concentration*(%)* | NC | 0,2 | 0,8 |
| 2 | Pressure*(Bar)* | p | 4,0 | 6,0 |
| 3 | Flow rate*(l/ph)* | Q | 150 | 250 |

*Table 2. Resource Planning Diagram with Three Survey Variables According to Box-Behnken Planning*

| StdOrder | RunOrder | PtType | Blocks | NC (wt%) | P (bar) | Q (l/min) | $R_a$ (µm) |
|---|---|---|---|---|---|---|---|
| 6 | 1 | 2 | 1 | 0.8 | 5 | 150 | 0.442 |
| 11 | 2 | 2 | 1 | 0.5 | 4 | 250 | 0.276 |
| 5 | 3 | 2 | 1 | 0.2 | 5 | 150 | 0.345 |
| 15 | 4 | 0 | 1 | 0.5 | 5 | 200 | 0.250 |
| 14 | 5 | 0 | 1 | 0.5 | 5 | 200 | 0.238 |
| 8 | 6 | 2 | 1 | 0.8 | 5 | 250 | 0.318 |
| 7 | 7 | 2 | 1 | 0.2 | 5 | 250 | 0.240 |
| 10 | 8 | 2 | 1 | 0.5 | 6 | 150 | 0.280 |
| 12 | 9 | 2 | 1 | 0.5 | 6 | 250 | 0.274 |
| 2 | 10 | 2 | 1 | 0.8 | 4 | 200 | 0.355 |
| 13 | 11 | 0 | 1 | 0.5 | 5 | 200 | 0.244 |
| 9 | 12 | 2 | 1 | 0.5 | 4 | 150 | 0.254 |
| 4 | 13 | 2 | 1 | 0.8 | 6 | 200 | 0.385 |
| 1 | 14 | 2 | 1 | 0.2 | 4 | 200 | 0.249 |
| 3 | 15 | 2 | 1 | 0.2 | 6 | 200 | 0.356 |

*Table 3. Summary of roughness R_a measurement results at 15 experimental points.*

## III. Results and Discussion

Preliminary analysis indicated that only the main factors, namely nanoparticle concentration (NC), air pressure (p), and lubricant flow rate (Q), together with their quadratic terms ($NC^2$, $p^2$, and $Q^2$), significantly affected the surface roughness (Ra). The interaction effects among the variables (NC×p, NC×Q, and p×Q) were found to be statistically insignificant and were therefore excluded from the final model. The experimental data were analyzed using Minitab 21 software.
The regression model describing the relationship between surface roughness Ra and the investigated process parameters is presented in Equation (1). The main effects of the process variables on Ra are illustrated in Figure 3. The adequacy of the developed model was evaluated using the coefficient of determination ($R^2$), as presented in Table 4. The obtained $R^2$ value of 79.87% indicates that the regression model provides a satisfactory representation of the experimental data and can reliably predict the surface roughness under the investigated conditions.

$$R_a = 0.958 - 0.746\ NC - 0.115\ p - 0.00269\ Q + 0.875\ NC*NC + 0.0135\ p*p + 0.000005\ Q*Q$$

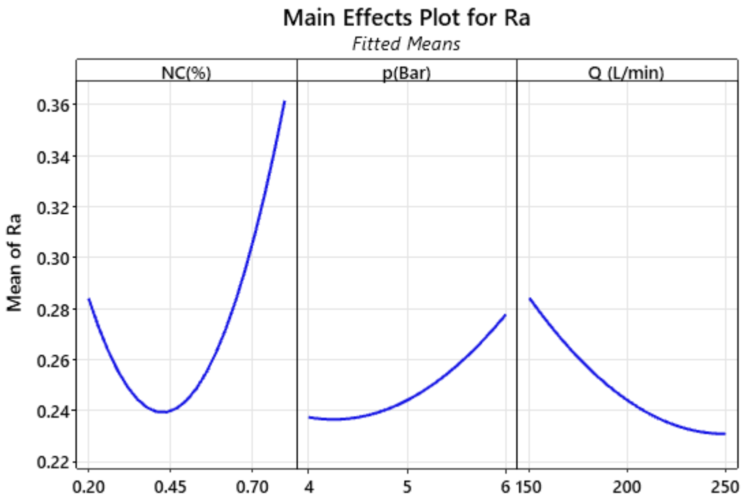


*Figure 3: The independent effect of survey variables on the objective function Ra*

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 0.0373158 | 79.87% | 64.78% | 19.72% |

*Table 4. Summary model of surface roughness evaluation parameters Ra*

Figure 3 shows the individual effects of nanoparticle concentration (NC), air pressure (p), and lubricant flow rate (Q) on surface roughness. All three parameters influenced Ra; however, their degrees of influence were different. Nanoparticle concentration exhibited the strongest effect, followed by lubricant flow rate, whereas air pressure had the least influence.

Regarding nanoparticle concentration, a relatively high surface roughness was observed at low concentrations (NC ≈ 0.2 wt.%). As the concentration increased, the roughness value gradually decreased and reached a minimum at approximately NC ≈ 0.4 wt.%. Beyond this level, further increases in concentration caused a rapid increase in surface roughness.

This result can be explained by the lubrication mechanism of $MoS_2$ nanoparticles. At moderate concentrations (around 0.4 wt.%), a sufficient number of nanoparticles are present in the cutting zone to form a stable tribological film, thereby reducing friction and improving cutting conditions. Consequently, the machined surface quality is enhanced, resulting in lower Ra values. At lower concentrations, the number of nanoparticles is insufficient to establish an effective lubricating film, limiting the beneficial effects of the nanofluid. Conversely, at excessively high concentrations, nanoparticle agglomeration and accumulation near the cutting edge may occur. These excess particles can adhere to the tool surface, impair cutting performance, and lead to a deterioration in surface finish, causing a significant increase in Ra [13].

The results demonstrate that nanoparticle concentration has a highly sensitive and dominant influence on surface roughness. Therefore, determining the optimal concentration of $MoS_2$ nanoparticles is crucial for maximizing the effectiveness of NF-MQL in hard-turning operations.

The ANOVA results presented in Table 5 further quantify the contribution of each factor to the variation in surface roughness. The developed model accounted for 79.87% of the total variation in Ra. Within the model, linear terms contributed 47.33% of the explained variation, while quadratic terms contributed 52.67%, indicating the strong nonlinear behavior of the process. Among the linear effects, nanoparticle concentration (NC) had the highest contribution ratio of 57.42%, followed by lubricant flow rate (Q) with 27.10%, and air pressure (p) with 15.48%. These findings confirm that nanoparticle concentration is the most critical parameter governing surface quality during hard turning under NF-MQL conditions.

| Source | DF | Adj SS | Adj MS | F-Value | P-Value | | % Contribution |
|---|---|---|---|---|---|---|---|
| Model | 6 | 0.044206 | 0.007368 | 5.29 | 0.017 | | ***79.87%*** |
| Linear | 3 | 0.020924 | 0.006975 | 5.01 | 0.030 | 47.33% | |
| NC | 1 | 0.012013 | 0.012013 | 8.63 | 0.019 | | 57,42% |
| p | 1 | 0.003240 | 0.003240 | 2.33 | 0.166 | | 15.48% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Q | 1 | 0.005671 | 0.005671 | 4.07 | 0.078 | | 27.10% |
| Square | 3 | 0.023282 | 0.007761 | 5.57 | 0.023 | 52.67% | |
| NC*NC | 1 | 0.022898 | 0.022898 | 16.44 | 0.004 | | 98.35% |
| p*p | 1 | 0.000673 | 0.000673 | 0.48 | 0.507 | | 2.89% |
| Q*Q | 1 | 0.000673 | 0.000673 | 0.48 | 0.507 | | 2.89% |
| Error | 8 | 0.011140 | 0.001392 | | | | ***20.13%*** |
| Lack-of-Fit | 6 | 0.011068 | 0.001845 | 51.24 | 0.019 | | |
| Pure Error | 2 | 0.000072 | 0.000036 | | | | |

*Table 5. Analysis of Variance*

## IV. General Conclusion

This study successfully applied the Minimum Quantity Lubrication (MQL) technique using $MoS_2$ nanofluid cutting oil to the hard-turning process of hardened 90CrSi steel (60–62 HRC) with a CBN cutting tool. The effects of three key MQL parameters, namely nanoparticle concentration (NC), air pressure (p), and lubricant flow rate (Q), on the surface roughness (Ra) were systematically investigated.

A Box–Behnken experimental design, supported by Minitab 21 software, was employed to analyze the influence of the selected process variables. The ANOVA results confirmed that all three factors significantly affected surface roughness. Among them, nanoparticle concentration was identified as the most influential parameter, contributing 57.42% to the variation in Ra. Lubricant flow rate was the second most significant factor with a contribution of 27.10%, while air pressure exhibited the lowest influence at 15.48%.

The experimental results further revealed that the minimum surface roughness was achieved at an intermediate nanoparticle concentration of approximately 0.4 wt.%. Surface roughness was found to be highly sensitive to changes in $MoS_2$ nanoparticle concentration, indicating the critical role of nanoparticle content in determining the effectiveness of NF-MQL lubrication. At optimal concentrations, the nanofluid improved lubrication conditions and enhanced surface quality, whereas excessive concentrations adversely affected machining performance.

These findings demonstrate the potential of $MoS_2$-based NF-MQL as an effective and environmentally friendly lubrication strategy for hard-turning applications. Furthermore, the strong influence of nanoparticle concentration suggests that additional studies should focus on optimizing nanofluid composition and lubrication parameters to further improve machining performance and surface integrity.

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