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# Investigation of Hard Milling of 60Si2Mn Steel Under MQL Using Nano Cutting Oil

Tran The Long[1,]* and Tran Le Thu[2]
*[1]Department of Manufacturing Engineering, Faculty of Mechanical Engineering, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam*
*[2] Library Information Technology Department, Thai Nguyen University of Technology, Thai Nguyen, 250000, Vietnam*
**Corresponding author: Tran The Long*

***Abstract***
*In recent years, hard machining has been developed and increasingly applied in metal cutting field. The enormous amount of heat generated from cutting zone and high cutting forces are still the huge challenge, leading to reduce the surface quality and productivity because of the early worn tools. Hence, MQL technique using nano cutting fluid has been studied and developed to overcome these problems. This paper aims to present the investigation of cutting speed, feed rate, and nanoparticle concentration effects on surface roughness $R_a$, $R_z$ in hard milling process of 60Si2Mn steel (50-52 HRC) under MQL condition using $Al_2O_3$ nano cutting fluid. The results obtained show the main effect of each input parameter and the interaction influence, from which the technological recommendations are provided. The multi-objective optimization was done to bring out the optimal set is V=120 m/min, F =35 mm/min, and NC = 2.0%.*

***Keyword:*** *Hard milling; MQL; $Al_2O_3$ nanoparticles; nano cutting oil, surface roughness*

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## I. INTRODUCTION

Nowadays, the environmental problems from the use of cutting fluids adversely affecting human health in the metal cutting field have prompted researchers and manufacturers to find out alternative solutions to reduce the use of cutting oils [1]. There are many proposed studies in which minimum quantity lubrication (MQL) was proposed in the 1990s [2] as an alternative to dry and flood condition.

This technology shows efficiency in machining because it has many outstanding advantages such as high lubricating performance, which reduces cutting forces and tool wear leading to increase tool life as well as improve machined surface quality. In addition to that, the use of lubricants in MQL method is significantly reduced and it is considered an environmentally friendly technology [1]. Up to now, many studies have been carried out to prove the effectiveness and investigate the technological parameters for MQL.

However, the main disadvantage of MQL is low cooling performance [3], so its application to hard machining processes with high heat and cutting forces is limited [4]. There have been a number of solutions proposed to overcome the main drawback of MQL technology, one of which is the use of nano cutting oil as the based fluid [4]. Nano cutting fluid is formed from suspending various types of nanoparticles such as: $Al_2O_3$, $SiO_2$, $MoS_2$, $TiO_2$, CuO, etc. in the base oil at the reasonable ratio [5]. The presence of nanoparticles in the base oil has improved the lubricating and cooling properties, thereby helping to decrease the friction coefficient in the cutting zone. Accordingly, the reduction of cutting forces and tool wear and surface quality improvement was reported in [6]. The application of MQL technology using nanofluid is an up-to-date topic that is attracting much attention from researchers around the world. From there, the authors are motivated to make an experimental study to investigate the effect of cutting speed, feed rate and nanoparticle concentration on surface roughness $R_a$, $R_z$ in hard milling of 60Si2Mn steel under MQL condition.

## II. MATERIAL AND METHOD

### 2.1 Experimental design

Factorial experimental design with the help of Minitab 19.0 software is utilized for three input variables with two levels listed in Table 1.

***Table 1. Factorial design with three input variables and their levels***

| Input variables | Low level | High level | Response variables |
|---|---|---|---|
| Cutting speed, $V_c$ *(m/min)* | 120 | 130 | Surface roughness $R_a$, $R_z$ |
| Feed rate, *F (mm/min)* | 35 | 44 | |
| $Al_2O_3$ nanoparticle concentration, *nc* (%) | 1.0 | 2.0 | |

### 2.2 Experimental devices

The experiments were conducted on CNC milling center VMS 85S (Figure 1). The samples were 60Si2Mn with the hardness of 50-52 HRC, and the chemical composition is shown in Table 1. The APMT 1604 PDTR LT30 carbide inserts made by LAMINA Technologies (Sweden) was used. MQL system consists of MQL nozzle, air compressor, soybean oil and $Al_2O_3$ nanoparticles with the grain size of 30 nm. The MQL parameters consist of: air pressure of 6 bar, air flow rate at 200 l/min. The depth of cut was fixed at 0.2 mm. SJ-210 Mitutoyo (Japan) was used for measuring surface roughness. The values of surface roughness were measured 3 times and taken by the average value. Each experiment trial was repeated 3 times and taken by the average values.

**Table 1.** Chemical composition of 60Si2Mn steel

| Element | C | Si | Mn | P | S | Cr | Ni | Fe |
|---|---|---|---|---|---|---|---|---|
| **Weight (%)** | 0.56-0.64 | 1.50-2.00 | 0.60-0.90 | ≤0.035 | ≤0.035 | 0.35max | 0.35max | Rest |

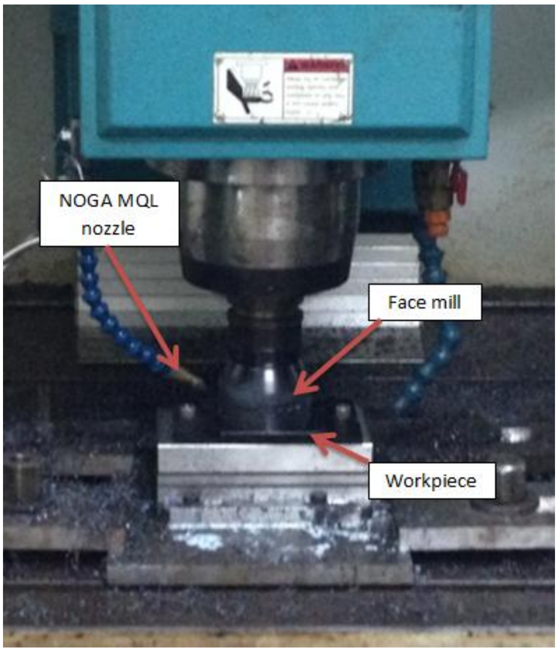


*Figure 1. Experimental set up*

## III. RESULTS AND DISCUSSION

Based on the experimental design, the experiments were carried out to collect and analyze the data. The main effects of cutting speed, feed rate, and nanoparticle concentration on surface roughness values $R_a$, $R_z$ are presented in Figure 2-3. The interaction influence between the input variables on the surface roughness is shown in Figure 4-6. Because the influence trend of $R_z$ is similar, the authors only investigate $R_a$.

From Figure 2, it can be seen that increasing the cutting speed and nanoparticle concentration will contribute to decrease $R_a$ values. The reason is that the growing cutting speed will contribute to reduce plastic deformation, thereby improving the surface quality, and increasing the concentration of $Al_2O_3$ nanoparticles will contribute to improving the lubricating and thermal conductivity of the based cutting oil, thereby reducing friction in the cutting zone, which is also observed for $R_z$ (figure 3). The feed rate still has the greatest influence on the machined surface roughness. As the feed rate increases, the roughness values $R_a$, $R_z$ increase sharply (Figures 2, 3) because the distance between the peaks on surface profile rises [7].

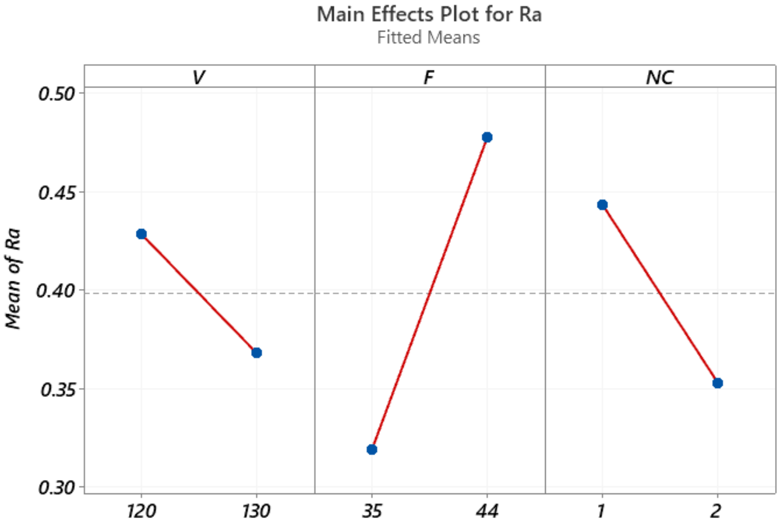


*Figure 2. Main effects of cutting speed, feed rate and nanoparticle concentration on $R_a$*

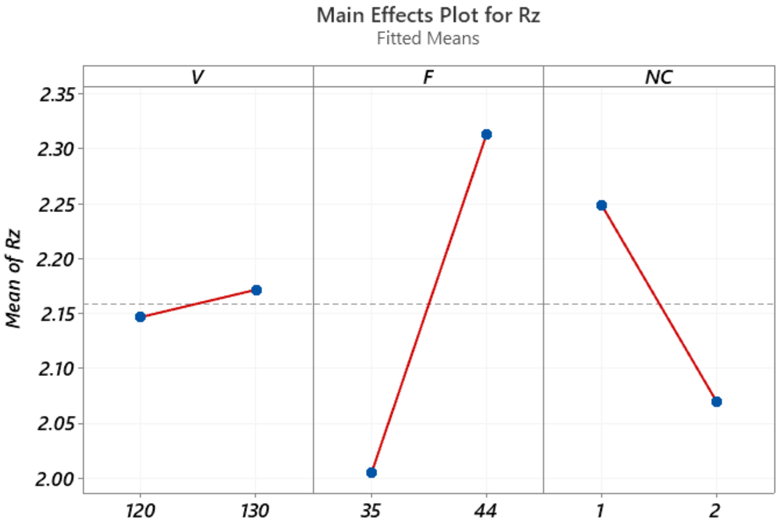


*Figure 3. Main effects of cutting speed, feed rate and nanoparticle concentration on $R_z$*

When the nanoparticle concentration is fixed at 1.5%, the combination of high cutting speed and low feed rate will give the smallest roughness value $R_a$ (Figure 4). For feed rate F=39.5 mm/min, the high level of cutting speed and nanoparticle concentration should be used to reduce $R_a$ value (Figure 5). When fixing the cutting speed V = 125 m/min, the combination of high nanoparticle concentration and low feed rate gives the best surface roughness $R_a$ (Figure 6). These results help to choose input parameters faster and easily apply in machining practice. Besides, this is also the basis for further studies. To get the exact values, multi-objective optimization was performed and the result is shown in Figure 7. To obtain the minimum value of surface roughness $R_a$, $R_z$ simultaneously, the optimal set of parameters should be used as V=120 m/min, F =35 mm/min, and NC = 2.0%.

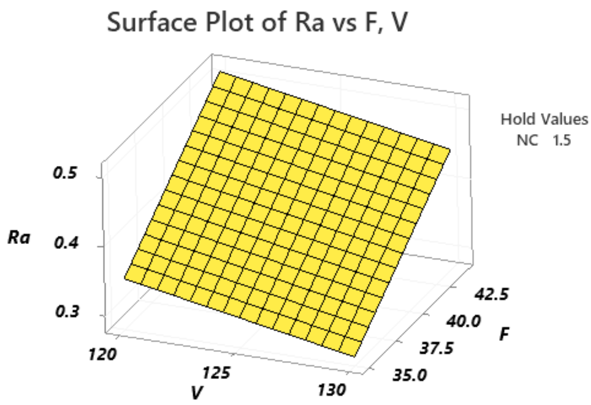


*Figure 4. Surface plot of cutting speed and feed rate on $R_a$ (nanoparticle concentration NC =1.5%)*

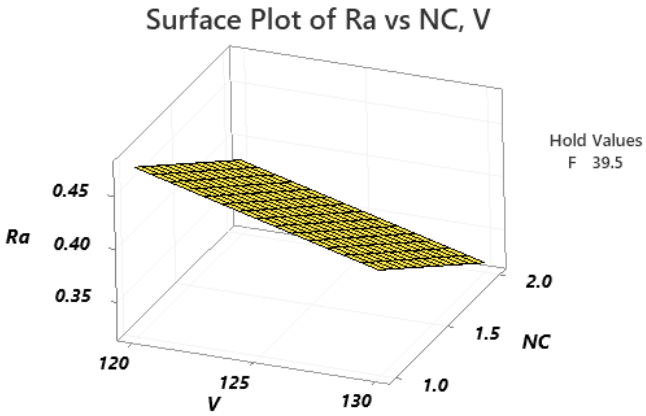


*Figure 5. Surface plot of cutting speed and nanoparticle concentration on $R_a$ (feed rate F=39.5 mm/min)*

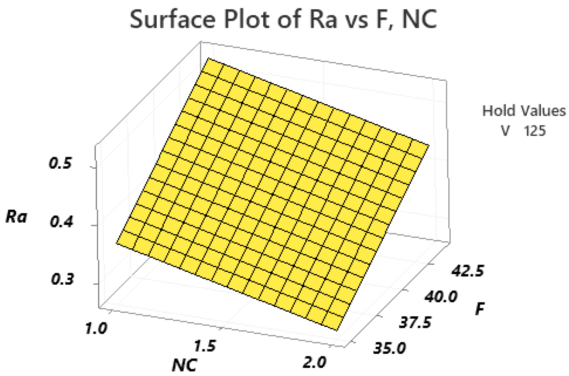


*Figure 6. Surface plot of nanoparticle concentration and feed rate on $R_a$ (cutting speed V=125 m/min)*

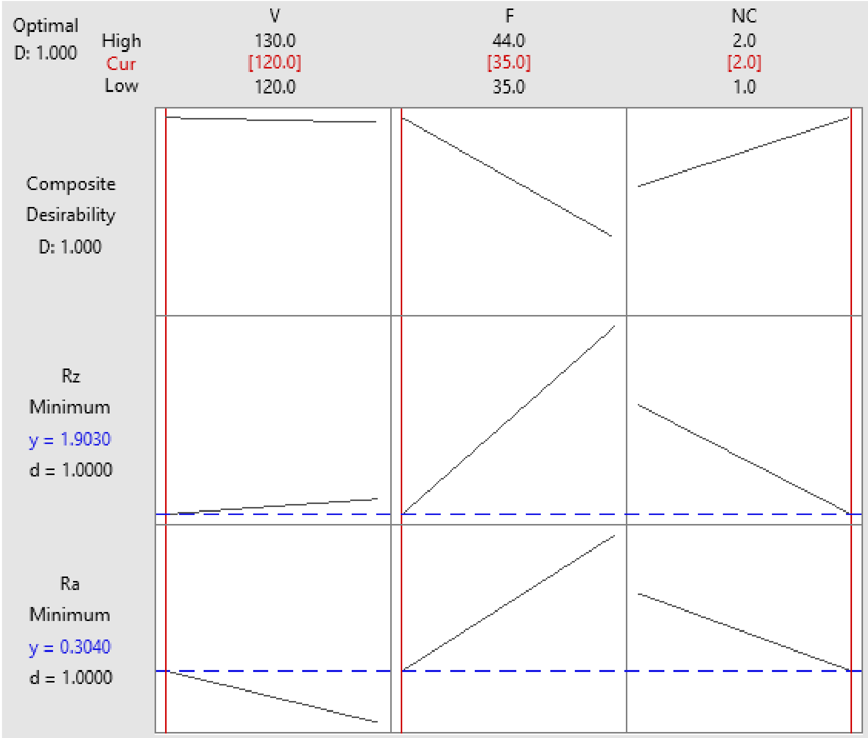


*Figure 7. Multi-objective optimization for surface roughness $R_a$, $R_z$*

## IV. CONCLUSION

In this work, the MQL technology using $Al_2O_3$ soybean-based nanofluid has been successfully applied for hard milling of 60Si2Mn steel (50-52 HRC). The influences of cutting speed, feed rate, and nanoparticle concentration on surface roughness were investigated and evaluated. The improvement of hard milling performance and carbide inserts was reported by using MQL with $Al_2O_3$ nano-cutting oil. Technological guidelines were provided to select input parameter value to achieve the good surface roughness. The multi-objective optimization was made to find out the optimal set of parameters including V=120 m/min, F =35 mm/min, and NC = 2.0%. Besides, the use of nanoparticles has improved the lubricating and cooling properties of soybean oil, an environmentally friendly vegetable oil, thereby expanding the application range of vegetable oil in hard milling. This will contribute to minimize the negative impact on the environment from the use of mineral oil.

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