Investigation of hard milling performance of 60Si2Mn steel under nanofluid minimal quantity lubrication environment

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ABSTRACT

One of the promising solution to improve the hard machining performance is the application of Nanofluid Minimal Quantity Lubrication (NF MQL). The presence of nanoparticles not only improve the cooling lubrication of the based cutting oil but also create more lubricating mechanisms in the cutting zone. This paper aims to study effect of MQL using nano cutting oil on the hard milling process. The Box-Behnken experimental design was utilized to investigate the effects of input variables on the responses. The obtained results indicated that the concentration of nanoparticles, cutting speed and feed rate cause the strong influences on the surface roughness and cutting forces. Also, the appropriate ranges of input variable values can be determined for the required outputs. Moreover, the better cooling and lubricating effects were reported and the machinability of carbide inserts was improved by using Nanofluid Minimal Quantity Lubrication.

Keywords: Hard milling; Cutting force; Surface roughness; Nano cutting oil; MQL; NF MQL.

1. INTRODUCTION

Cutting processes still play an important role in industrial production because of their outstanding advantages such as high dimensional accuracy and surface quality, and being able to create many profiles [1]. In the machining field, the solution to finishing steels after heat treatment is grinding, but low productivity and environmental pollution problems from using coolants have created new requirements for developing alternative technologies. One of the technological solutions that is being developed and increasingly widely applied is hard machining technology [2]. Hard machining processes use cutting tools with geometric defined cutting edge to directly cut the heat-treated steels with high hardness [2]. Thanks to developments in the field of materials and machine tools, it is now increasingly easier to carry out the hard machining process. Besides, this technology shows advantages such as high productivity, machining accuracy and very good surface quality, so it is being increasingly widely used and replaces or supports the grinding process. Among them, hard milling technology has attracted great attention from manufacturers and researchers, especially in the field of mold manufacturing [3]. Due to the intermittent cutting process combined with high cutting force and cutting heat, flood technology is not suitable [4]. When performing hard milling in dry condition, high cutting force and cutting heat accelerate tool wear, greatly affecting tool life, surface quality and productivity [5]. Several solutions have been proposed to improve lubrication and cooling in the cutting zone during hard milling, including minimum quantity lubrication (MQL) [6], minimum quantity cooling lubrication (MQCL) [7, 8], nanofluid MQL (NF MQL) [9, 10], and so forth. Among these solutions, MQL technology using nano cutting oil is an up-to-date research topic and has proven its suitability when applied to hard milling [11]. Besides, using nano cutting oil has overcome the disadvantage of low cooling capacity of MQL method [12]. However, the publications following this topic in Vietnam are limited, so the authors are motivated to make an experimental study on the influence of MQL environment using Al_2O_3 nano-cutting oil based on soybean oil on hard milling of 60Si2Mn steel (50-52 HRC).

2. MATERIAL AND METHOD

The experiments were carried out on a VMC 85S machining center. The BAP 400R-80-27-6T face mill head was used with APMT 1604 PDTR LT30 PVD submicron carbide inserts (flank angle (11º), nose radius (0.66 mm)) made by LAMINA Technologies (Switzerland). The MQL system includes: NOGA MiniCool MC1700 combined with the air pressure regulator, and air flow rate valve, PT-0136 compressed air, soybean oil, and Al_2O_3 nanoparticles (30 nm). To reach the uniform distribution of Al_2O_3 nanoparticles in the soybean oil, Ultrasons-HD (JP SELECTA in Spain) is used to create the ultrasonic vibration. Kistler quartz three-component dynamometer (9257BA) and SJ-210 Mitutoyo (made by Japan) were used for measuring cutting forces and surface roughness (cut-off length of 0.08 mm). The 60Si2Mn steel samples were austenitized at 850 °C, then tempered at 400 °C and finally were oil quenched to the room temperature to reach the hardness of 50 - 52 HRC. The chemical composition of steel samples is presented in table 1.

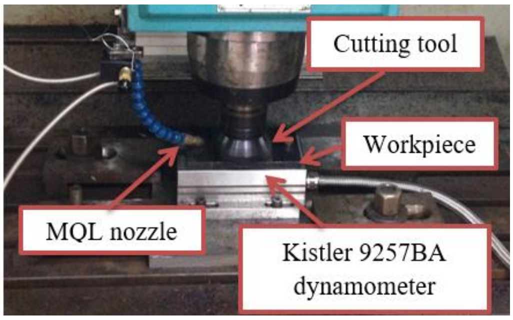


Figure 1. *Experimental set up [13].*

The Box-Behnken design of experiment was shown in table 2. The three input variables include nanoparticle concentration (NC), cutting speed (V) and feed rate (f). The responses are the resultant cutting force F_r and surface roughness R_a. The fixed parameters include the depth of cut t_0 = 0.2 mm, air pressure p = 6 bar, and air flow rate Q = 200 l/min, which were based on the previous studies [11, 13]

Table 1. *Elemental composition of 60Si2Mn steels.*

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

Table 2. *Design of experiment.*

No.	Input parameters	Symbol	Low level	High level	Responses
1	Nanoparticle concentration (%)	NC	0.5	1.5	- Resultant cutting force F_r - Surface roughness R_a
2	Cutting speed (m/min)	V	90	130	
3	Feed rate (mm/tooth)	f	0.08	0.16	

The cutting trials were implemented by following the experimental matrix built by Minitab 19 software. The surface roughness R_a values were measured 03 times and the average value was taken after each cut. The cutting force components F_x, F_y, F_z were measured directly during cutting process by Kistler quartz three-component dynamometer (9257BA). The resultant cutting force F_r is calculated by equation (1).

$$F_r = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (1)$$

3. RESULTS AND DISCUSTION

In figures 2 and 3, it can be seen that the strongest impact on R_a and F_r is the nanoparticle concentration, followed by the cutting speed, and then the feed rate. For surface roughness R_a, when increasing the nanoparticle concentration from 0.5% to 1.2%, the surface roughness value increases rapidly and tends to decrease slightly when increasing NC to 1.5%. However, the graph for F_r is the opposite. It can be explained that increasing the nanoparticle concentration helps improve the lubrication ability because Al_2O_3 nanoparticles have high hardness and nearly spherical shapes. However, the growing density of nanoparticles in the cutting area causes impedance and scratching of the machined surface, causing R_a to increase. For increasing V from 90 to 105 m/min, both surface roughness and cutting force decrease, and this result is completely consistent with the study [2, 14]. When cutting speed V goes up to 130 m/min, R_a and F_r rapidly rise. In case of increasing the feed rate, R_a and F_r grow because the distance between cutting path and the area of the cross-section of a cut layer increase [15].

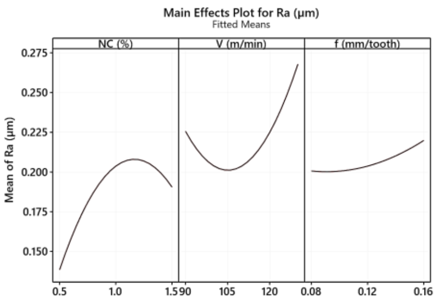


Figure 2. *Main effect of investigated variables on surface roughness R_a.*

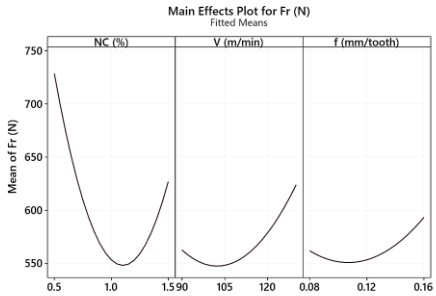
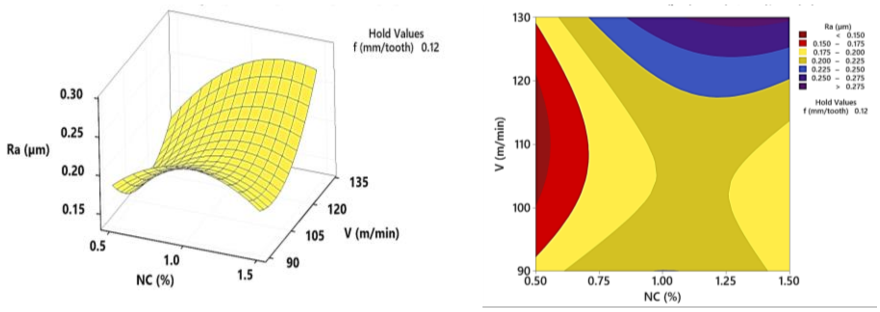
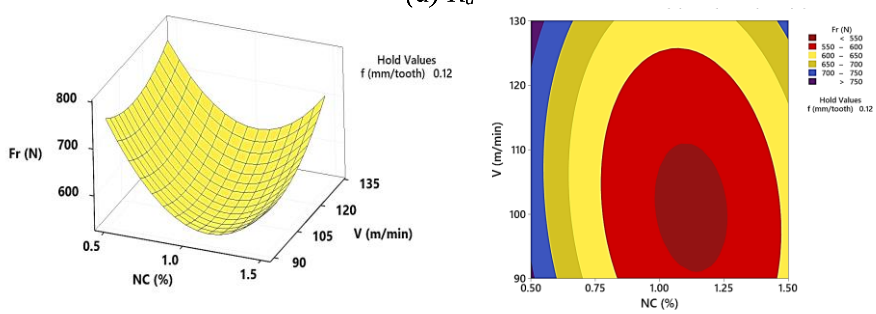


Figure 3. *Main effect of investigated variables on resultant cutting force F_r.*

The surface and contour plots in figure 4 show the influence of the nanoparticle concentration and cutting speed on the objective functions R_a and F_r when the feed rate f is fixed at 0.12 mm/tooth. Figure 6a shows that the optimal R_a value domain is the region with R_a < 0.15 µm when the nanoparticle concentration is from 0.50 ÷ 0.55% and the cutting speed V = 100 ÷ 120 m/min. Figure 6b shows that the domain for the smaller F_r value is the region with F_r < 550 N when using NC = 1.00 ÷ 1.25 % and V = 92 ÷ 110 m/min. Similarly, for cutting speed fixed at 110 m/min. the optimal R_a value domain (R_a < 0.14 µm) can be achieved with NC = 0.50 ÷ 0.60% and f = 0.08 ÷ 0.16 mm/tooth. From figure 7b, NC= 1.00 ÷ 1.25% and f = 0.09 ÷ 0.12 mm/tooth should be chosen for smaller F_r (F_r < 550 N). When NC is fixed at 1.0%, the optimal R_a value domain (R_a < 0.20 µm), V = 102 ÷ 110 m/min and f = 0.08 ÷ 0.11 mm/tooth should be recommended. From figure 8b, for smaller F_r value (F_r < 550 N), it should be chosen with V = 90 ÷ 110 m/min and f = 0.08 ÷ 0.12 mm/tooth. The obtained results help technicians quickly choose the investigated parameters in the optimal domain depending on the objective functions. Specifically, for smaller surface roughness R_a, the nanoparticle concentration NC=0.5% ÷ 0.55%, cutting speed V= 100 ÷ 110 m/min, feed rate f = 0.08 ÷ 0.16 mm/tooth should be chosen. For smaller resultant cutting force F_r, the nanoparticle concentration NC = 1.0% ÷1.2%, cutting speed V = 90 ÷ 110 m/min; feed rate f = 0.08 ÷ 0.12 mm/teeth should be selected. In order to achieve the smaller values of both surface roughness R_a and the resultant cutting force F_r, the cutting speed can be selected in the range of 100 ÷ 110 m/min. However, if the exact optimal values of the nanoparticle concentration, cutting speed and feed rate, the more specific calculation will be needed and the obtained results are presented in the next section.



(a) R_a



(b) F_r

Figure 4. *Effect of nanoparticle concentration and cutting speed on:*
(a) R_a and (b) F_r at f = 0.12 mm/tooth.

4. CONCLUSIONS

In this study, the influence of MQL using nano cutting oil on the hard milling process was investigated and evaluated. It can be seen that the hard milling efficiency as well as the machinability of coated carbide inserts have been improved due to the good lubrication and cooling effect obtained from nanofluid MQL technique. This expands the applicability of vegetable oil, a naturally biodegradable and environmentally friendly oil, in the hard machining process.

The important technological guidelines are also provided for further research and production practice. In order to achieve the smaller surface roughness R_a, NC = 0.5% ÷ 0.55%, V = 100 ÷ 110 m/min, f = 0.08 ÷ 0.16 mm/tooth should be chosen. For smaller F_r values, the NC = 1.0% ÷1.2%, V = 90 ÷ 110 m/min; f = 0.08 ÷ 0.12 mm/tooth should be selected.

In further study, deep investigation should be made on the cutting mechanism, wear mechanism, and machined surface integrity when using nanofluid MQL.

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TÓM TẮT

Khảo sát hiệu quả của quá trình phay cứng thép 60Si2Mn với chế độ bôi trơn tối thiểu dùng dầu cắt nano

Một trong những giải pháp đầy hứa hẹn để cải thiện hiệu suất gia công cứng đó là ứng dụng Bôi trơn tối thiểu dùng dầu cắt nano (NF MQL). Sự có mặt của các hạt nano không chỉ cải thiện khả năng bôi trơn làm mát của dầu cắt gốc mà còn tạo ra thêm các cơ chế bôi trơn trong vùng cắt. Bài báo này này nhằm mục đích nghiên cứu ảnh hưởng của MQL sử dụng dầu cắt nano đến quá trình phay cứng. Thiết kế thử nghiệm Box-Behnken được sử dụng để nghiên cứu tác động của các biến đầu vào đến các thông số đầu ra. Kết quả thu được cho thấy nồng độ hạt nano, tốc độ cắt và tốc độ tiến dao có ảnh hưởng mạnh mẽ đến độ nhám bề mặt và lực cắt. Ngoài ra, có thể xác định dải giá trị thích hợp của các biến đầu vào cho các kết quả đầu ra theo yêu cầu. Hơn nữa, hiệu quả làm mát và bôi trơn tốt hơn đã được ghi nhận và khả năng gia công của mảnh hợp kim cứng được cải thiện bằng cách sử dụng bôi trơn tối thiểu dùng dầu cắt nano.

Từ khoá: Phay cứng; Lực cắt; Nhám bề mặt; Dầu cắt nano; MQL; NF MQL.