A Study on Influence of MQL Parameters on Cutting Heat Generated During Machining Based on Numerical Simulation

Van-Hung Pham[1], Thi-Thu-Ha Nguyen[2], Van-Huy Nguyen[1], Trung-Kien Quach[1], Trong-Nghia Nghiem[1], and Tuan-Anh Bui[1](✉)

[1] School of Mechanical Engineering, Hanoi University of Science and Technology, No. 1 Dai Co Viet Road, Hanoi, Vietnam
anh.buituan@hust.edu.vn
[2] Military Industrial College, Thanh Vinh, Phu Tho, Phu Tho, Vietnam

Abstract. In mechanical processing, to reduce the negative effects of Metal Working Fluid (MWF), it is possible to use the method of minimum lubrication (MQL - Minimum Quantity Lubrication) or Near Dry Machining (NDM). The MQL method is developed from the Micro-fog lubrication method used in the lubrication and cooling of high-speed spindle of CNC machine tools, providing very high lubrication efficiency. For the cutting of difficult-to-machine metals such as titanium alloys, a mist of air-oil mist will be sprayed on the back face of the cutting tool, greatly reducing the heat, and thus increasing the tool life. This writing presents a numerical simulation study on the influence of some basic parameters of the MQL, including the flow rate of the coolant from 2 to 150 ml/hr; feed rate from 0.05 to 0.14 mm/tooth; cutting speed from 50 to 300 mm/min to the heat generated during machining. The research results are the basis for choosing a suitable set of MQL parameters when machining titanium alloy, contributing to improving the quality of detailed machining.

Keywords: Numerical simulation · Minimum Quantity Lubrication · Machining · Cutting heat

1 Introduction

Machining is a technological process that plays a very important role in mechanical manufacturing. To speed up machining, fluids are used to lubricate and cool during cutting (referred to as "metalworking fluids" or "cooling fluids"). At that time, the cutting force can be reduced, and the heat generated during the cutting process can be reduced or eliminated at the same time. The most used method is overflow irrigation with some disadvantages, such as: cost of purchase and cost of handling the cooling solution after use; toxicity and non-biodegradable properties; affect human health and the environment. To reduce the amount of metalworking fluids used, it is necessary to choose liquids that are not harmful to the environment and human health, scientists have introduced the Minimum Quantity Lubrication (MQL).

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An MQL system usually consists of the following main components: Air compressor; Cooling liquid storage tank; Pipeline; Flow control system and nozzle. The MQL method uses a micro-fog technique that sprays a very small amount of the cutting liquid-pressurized air mixture, at a rate of less than 1000 ml/hr, directly into the cutting area. The volume of cutting fluid is 10,000 times less than the overflow technique. Therefore, an MQL system can bring economic efficiency up to 15%. When used in cutting machining, a very small amount of cutting lubricant is introduced into the cutting area, to reduce friction and heat between the cutting tool and the work surface. The MQL method involves misting or injecting a very small amount of the cutting lubricant into the working area, thereby reducing costs and industrial pollution. Currently, in Vietnam, this MQL method has begun to receive research attention, but it is still scattered. There have been some initial studies on the MQL method, performed alone in a few laboratories, on some commonly used mechanical materials to compare machined surface quality and tool life, did not pay attention to cost reduction and industrial environmental safety.

There are many types of metalworking fluids used in MQL systems. Typically, MQL uses a mixture in the form of an emulsion oil in different proportions in water to cool and lubricate the cutting edge of the tool [1]. Metalworking fluids for MQL have the following requirements: Must be biodegradable; High stability and high lubricating efficiency will be able to meet the requirements of durable machining with a low consumption of oil. Vegetable-based oils is one of the most widely used metalworking fluids in MQL because of their high biodegradability [2]. The advantages of using vegetable base oils over conventional metalworking fluids are greater pressure resistance, which can increase cutting speed, reduce losses due to evaporation and misting, etc. Similarly, synthetic esters have the same properties as vegetable-based including low viscosity, high boiling and burning points. Some studies also show that MQL processing with synthetic ester oils is superior to oils and mineral oils [3]. As such, both cooling oils can be better substitutes for other metalworking fluids. More importantly, those cooling oils are non-toxic and highly biodegradable, making them environmentally and health-friendly options for machining with MQL. Figure 1 shows a MQL system of K. Sundara Murthy et al. used for machining in a milling machine.

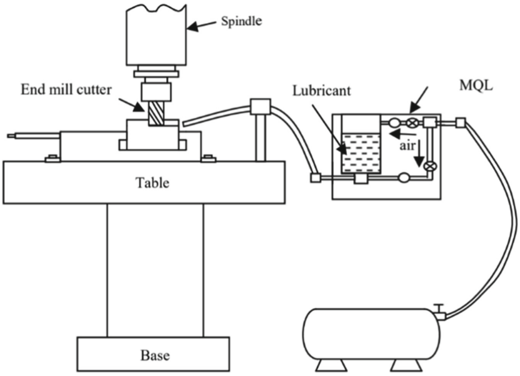


Fig. 1. MQL system model of K. Sundara Murthy [4]

There have been many publications on the use of MQL method in machining, the researchers mostly focus on the effectiveness of MQL method in improving surface accuracy, reducing cutting force and wear of cutting tool. Campatelli performed a test analysis of the machining MQL environmental impact for the AISI 1040 steel turning operation; cutting tools: CNMG 432; cutting depth 1.2 mm; cutting speed 200 m/min; MQL lubricants: Biocut-3000 at 60 ml/hr shows that the use of MQL can prolong tool life reducing production costs and machining time [5]. Kaynak [6] turned Inconel 718 material in three different cooling and lubricating environments (MQL, cryogenic and dry), which showed significant reduction in cutting forces at low cutting speeds. Tool wear when turning with the MQL method is also significantly reduced compared to dry turning. Pereira et al. [7] performed a comparative analysis of the machining efficiency in the dual-cooling method and near-dry cooling conditions. The results of the mixed cooling method study show that the tool life has been extended by more than 50% and a significant increase in cutting speed by up to 30% compared with dry machining. Studies also show that a combination of minimal cooling and lubrication methods is the solution for establishing a balance between engineering and the environment. Kyung-Hee Park [8] experimentally machining Ti-6Al-4V alloy with several different lubricating solutions such as cryogenic, MQL, LAM has shown that MQL and Cryogenic, especially the combination of Cryogenic and QML, will help reduce cutting force and reduce tool wear.

2 Influence of MQL Parameters on Machining Quality

Studies on the influence of MQL parameters on the surface quality of machine parts are also interested. Indeed, Alborz Shokrani et al. [9] studied the evaluation of surface quality when machining Ti-6Al-4V alloy with different lubrication methods such as overflow; MQL; Cryogenic (cooling) and Hybrid cryogenic MQL (MQL combined cooling), show that, within the experimental range, the MQL method gives the best machined surface roughness. Rabiei et al. [10] also showed that using the MQL system when machining high hardness steels, such as HSS and 100Cr6, the surface quality is higher with the overflow technique. Mozammel Mia has built a mathematical model of the relationship between average surface roughness (Ra) [11], energy consumption (Esp - Specific Energy) and MQL when experimentally machining 4140 steels (AISI) with a tool end milling (Fig. 3). The results show that with a cutting speed of 32 m/min, a feed-rate of 22 m/min and a minimum MQL of 150 mL/hr will give minimal surface roughness. Kedare S. B [12] used the MQL method (with a flow rate of 900 ml/h) to ensure a surface roughness equivalent to that of a conventional coolant (2 l/min). Alborz Shokrani proposed to use hybrid MQL (hybrid) [9] to improve tool life when milling Ti-6Al-4V alloy, the author conducted machining experiments using 04 different coolant solutions: Flooding, MQL, Cryogenic (cooling) and Hybrid (combining Cryogenic with MQL). Research results show that MQL and Hybrid Cryogenic MQL are both effective in extending tool life up to 30 times. Ashutosh Khatri [13] studied the effects of different quenching lubrication methods when milling Titanium Ti-6Al-4V alloy (Fig. 4), and showed that, when machining Titanium Ti-6Al-4V alloy with The MQL method has lower tool wear than the dry coolant or flood coolant methods. On the other hand, when studying chip samples collected after turning titanium with MQL, Gupta et al. [14] found that two types of chips were formed, the ribbon and the small spiral. The chip surface is smooth, flat, sparkling, and shiny. This is explained by the temperature drop at the tool cutting edge when MQL is present. K. Sundara Murthy [4] built a multi-objective optimization model to evaluate the influence of the technology regime on tool age and surface roughness with minimal lubrication conditions.

From the overview analysis of the above research situation, it can be seen that: (i) Using the coolant MQL method has better penetration at the cutting zone than other methods, the surface roughness and the cutting force are smaller. Tool life can be extended up to about 88% compared to dry machining while maintaining surface quality; (ii) When machining by milling, the MQL system usually uses a single nozzle. Metalworking fluids are usually vegetable-based or synthetic ester-based oils, which are non-toxic, highly biodegradable, environmentally friendly and do not harm operator health; (iii) Although published studies prove the ability and superiority of the MQL method, however, some issues related to MQL have not been elucidated such as its effectiveness in processing materials that are difficult in machining as titanium alloy (Ti-6Al-4V), the ability to remove chips in machining. Besides, the problem of optimizing technological parameters related to MQL in machining is also not to be announced. Therefore, more research is needed in reducing heat, expanding workpiece materials, easy chip removal, determining the optimal cutting mode and MQL parameter, and controlling it when machining conditions change. Table 1 is a summary of research results on MQL to machining quality that have been published.

Table 1. Summary of research results on MQL to machining quality

Documents	Cutting tool	Material of workpiece	Cutting parameters	Coolant solution	MQL	Results
Mozammel Mia (2017) [15]	Carbide endmill 12mm	AISI 4140	V = 32 (m/min) f = 22 (mm/min)	VG-68 ISO-grade	Q = 150 (ml/hr)	Ra = 0.67 (μm) Fn = 6.5 N
Mohammadjafar Hadad (2013) [16]	High speed steel for lathe	AISI 140 (340 HV)	V = 50.2, 100.4, 141.4 (m/min) f = 0.09, 0.22 (mm/rev) t = 0.5, 1, 1.5 mm	Este (RS-1642)	Q = 30 (ml/hr) P = 3 bar	T < 350° in comparison without lubrication, Ra = 3–4 (μm)
Kyung-Hee Park (2017) [8]	R245-12T3M, face mill 50 mm	Ti-6Al-4V	V = 47.7, 76.4, 100, 120 (m/min) f = 0.15 (mm/rev) t = 2 mm	Vegetable oil (with and without nano graphit)	Q = 180 (ml/hr) P = 5 bar φ = 1 mm	Wear_{min} = 0.153 mm with Q = 9 (ml/min)
Nilanjan Banerjee (2014) [17]	Chip SNMG 120408-TF, TiAlN carbide coating	C45 (AISI-1045)	V = 76, 190, 237 (m/min) f = 0.08, 0.27, 0.4 (mm/rev)	Accu-Lube LB 8000	Q = 50 (ml/hr)	HSMS: $\mu = 3.32 * V^{-0.45} - 0.24 * S$ T = 743 °C (V = 76), 818 °C (V = 190)

(*continued*)

Table 1. (*continued*)

Documents	Cutting tool	Material of workpiece	Cutting parameters	Coolant solution	MQL	Results
GuRaj Singh (2018) [18]	TiAlN carbide coating for Bridgeport BMC 1500	Inconel 718 superalloy	V = 100, 150, 200 (m/min) f = 0.1, 0.15 (mm/tooth) t = 0.5, 1.0 μm	Rhenus FU 60 with 1:20 H_2O	Q = 30 (ml/h) P = 6 bar D = 25mm $\alpha = 30°$	VB = 0.1, 0.28, 0.4 (mm) ~ V VBmax = −0.433 + 5.23e−3 Vc − 1.77f_z + 0.16a_e
Xiufang Bai (2018) [19]	For milling machine Dema ML1060B	Ti-6Al-4V	f = 500 (mm/min) t = 0.25 mm	Oil cottonseed + nano particles	Q = 85(ml/hr) p = 0.4 Mpa D = 30mm $\alpha = 30°$	Fx = 277.5 N, Fy = 88.3 N Ra = 0.594 μm (Al_2O3)
Anish Gupta (2017) [20]	Grinding, D126 C75	Inconel 751	V = 1413 (m/min) f = 0.4 (m/min) t = 10 μm	Cimtech D14 MQL oil	Q = 60, 80, 100 (ml/hr) p = 2, 4, 6 bar $\alpha = 30°$	Droplet diameters; Temperature concentration
Masato Okada (2014) [21]	Carbide coating for Milling machine	Ti64	f_z = 0.1 mm/tooth v = 50, 100, 200, 300 m/min t_R = 0,25 mm t_A = 5 mm	Vegetable oil	Q = 12 (ml/hr) p = 0.5 MPa	Ra = 0.25–0.2–0.2–0.15 μm T = 450–525–600–620
Z.Q Liu (2014) [22]	Titan coating for milling machine	Ti64	f_z = 0.05 mm/tooth V = 60, 150 m/min t_R = 1 mm t_A = 5 mm	MQL oil: LB-1	Q = 5 (ml/hr) p = 0.5 Mpa D = 25 mm $\alpha = 135°$	T = 225–295
M.J. Bermingham (2015) [23]	Carbide, milling machine	Ti64	f_z = 0,14 mm/tooth V = 69 m/min t_R = 1 mm t_A = 6 mm	Vegetable oil with 50 PSI	Q = 4 (ml/hr)	T = 400 V_{bmax} = 50 μm
Z Q Liu (2011) [24]	Milling machine PVD Titan	Ti64	f_z = 0.05 mm/tooth V = 150 m/min t_R = 1 mm t_A = 5 mm	Vegetable oil	Q = 2-4-6-8-10 (ml/hr) p = 0,5MPa $\alpha = 135°$ D = 20 mm	T = 276–270–261–254–252
M Jamil (2021) [25]	Milling machine	Ti64	f_z = 0.1 mm/tooth V = 110–185 m/min t_R = 0.5 mm t_A = 8 mm		Q = 150 (ml/hr) p = 6 bar D = 25 mm	T = 330–384

3 Numerical Simulation of the Influence of MQL Parameters on Heat During Machining

Based on the research results listed in Table 1, it can be seen that the above studies mainly focus on selecting some MQL parameters to achieve the best machining quality, reduce heat at the cutting area, or increase the life of tools. These data are used as the basis for establishing an empirical regression function describing the influence of some of the most basic parameters of MQL on the heat generated during machining titanium alloy. Thereby helping users quickly select the appropriate set of MQL parameters for a particular machining process.

The MQL parameters have been studied by the above authors, which can be listed as follows:

- Flow of cooling fluid: Q = 2; 4; 5; 6; 8; 10; 12; 150 (ml/hr);
- Feed rate: $f_z = 0.05; 0.1; 0.14$ (mm/tooth);
- Cutting speed: V = 50; 60; 69; 100; 110; 150; 185; 200; 300 (m/min);
- Radial cutting depth: $a_e = 0.25; 0.5; 1$ (mm);
- Axial depth of cut: $a_p = 5; 6; 8$ (mm);
- Injection pressure: p = 0.5 MPa;
- Nozzle distance: 25 mm;
- Spray angle: 45°.

Using mathematical tools and supporting software, the relationship between the heat generated when cutting and the quantities obtained is as follows:

- With feed rate $f_z = 0.05$ mm/tooth, cutting speed V = 150 m/min, $a_e = 1$ mm, $a_p = 5$ mm, and Q = 2–4–6–8–10 ml/hr, the heat function T depends on the flow Q obtained as:

$$T = 318.23 \times Q^{-0.06} \tag{1}$$

- When machining with Q = 4 ml/h; V = 69 m/min; $a_e = 1$ mm; $a_p = 5$ mm and $f_z =$ 0.05–0.1–0.14 mm/tooth, the interpolation function for cutting heat T depends on the feed-rate f_z as follows:

$$T = 875.01 \times f_z^{0.4276} \tag{2}$$

- With Q = 12 ml/hr; $f_z = 0.1$ mm/tooth; $a_e = 0.25$ mm; $a_p = 5$ mm; V = 50–100–200–300 m/min, the cutting heat interpolation function T depends on the cutting speed V as follows:

$$T = 222.56 \times V^{0.1833} \tag{3}$$

- With Q = 5 ml/hr; $f_z = 0.1$ mm/tooth; V = 100 m/min; $a_p = 6$ mm; $a_e = 0.25$–0.5–1 mm, the cutting heat interpolation function T depends on the radial depth t_R as follows:

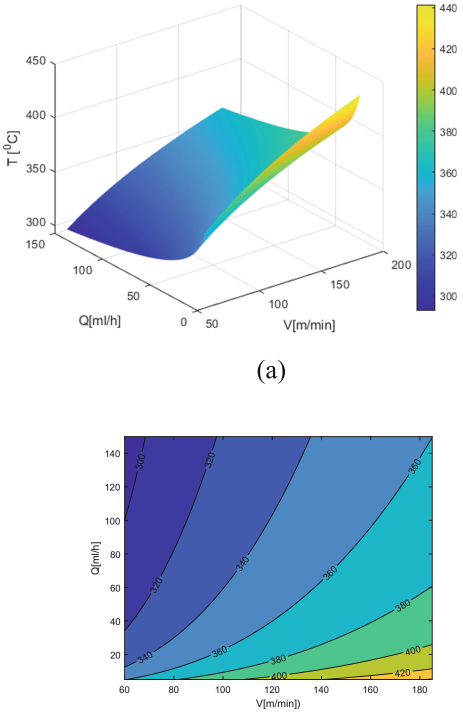
$$T = 449.83 \times t_R^{0.2925} \tag{4}$$

- With Q = 5 ml/h; $f_z = 0.1$ mm/tooth; V = 100 m/min; $a_e = 1$ mm; $a_p = 5$–6–8 mm, the cutting heat interpolation function T depends on the axial depth of cut as follows:

$$T = 186.45 \times t_A^{0.3682} \quad (5)$$

- Based on interpolation functions depending on each parameter, the generalized cutting heat function T can be obtained as follows:

$$T = 258.4 \times Q^{-0.06} \times f_z^{0.4276} \times V^{0.1833} \times a_e^{0.2925} \times a_p^{0.3682} \quad (6)$$

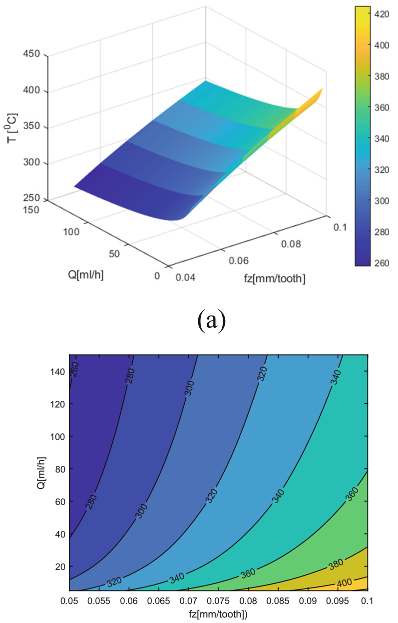


(a)

(b)

Fig. 2. Graph of cutting heat T depends on flow Q and cutting speed V with $f_z = 0.1$ (mm/tooth); $a_e = 1$ (mm); $a_p = 6$ (mm)

Based on the empirical regression function describing the relationship between the cutting heat and the basic parameters of the MQL system, the relationship graphs are built to have an overall view of the influence of each MQL parameter. to the cutting zone temperature. Assessing the strong or low influence of the main factors on the heat generated, it is the basis for choosing the most suitable set of parameters for processing a particular material. Figures 2, 3 and 4 depict the relationship between cutting heat and coolant flow and cutting speed, flow and feed rate, and cutting speed and feed rate, respectively. The temperature strongly depends on the cutting speed and the feed



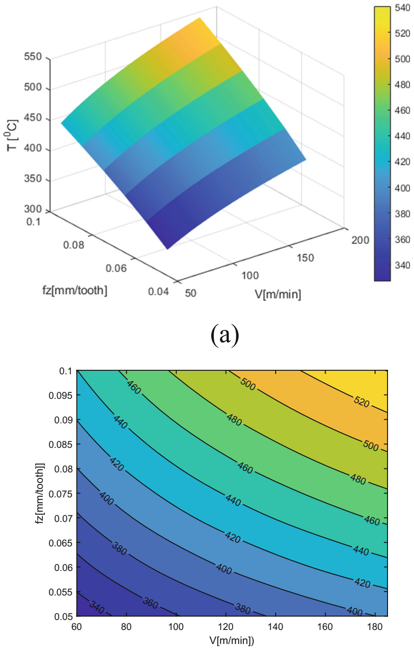
(a)

(b)

Fig. 3. Graph of cutting heat T depends on flow Q and feed rate f_z with V = 150 (m/min); a_e = 1 (mm); a_p = 6 (mm)

rate, while if the coolant flow is increased, the cutting zone temperature will decrease accordingly.

In addition, the larger flow rate will increase the degree of heat loss into the solvent and surrounding environment, reducing the heat at the cutting zone. This is also the reason to choose the right flow Q when machining a material for which the cutting mode has been calculated in advance. Similarly, the feed rate is also an important factor affecting the degree of heat generation in the cutting zone, whereby, with a certain flow rate, the cutting zone temperature will increase in proportion to the feed rate. This relationship is nonlinear and is shown in Fig. 3. A large feed requires a larger volume of material to be removed per unit time, i.e., the working intensity of the tool must be higher, resulting in a higher temperature generated here. Figure 4 also shows the influence of cutting speed and feed rate on the heat generated in the cutting zone. Accordingly, it is necessary to choose an appropriate flow rate to ensure that the temperature of the cutting area is within the allowable limit, without affecting the machining quality as well as the tool life. For example, with the Q flow limit of an MQL system of 150 ml/hr, a_e = 1 mm, and a_p = 8 mm, for the cutting temperature to be below 400 °C, the most feasible working range of the cutting mode parameters is selected as f_z = 0–0.116 (mm/tooth) and V = 0–140 (m/min).



(a)

(b)

Fig. 4. Graph of the cutting heat T depends on the cutting speed V and the feed rate f_z with Q = 1 (ml/hr); $a_e = 1$ (mm); $a_p = 8$ (mm)

Table 2. Calculation and experimental results of heat generated during cutting

Q (ml/h)	f_z (mm/tooth)	V (m/p)	a_e (mm)	a_p (mm)	$T_{calculation}$ (°C)	T_{actual} (°C)	Error (%)
5	0.05	60	1	5	249	225	9.6
		150			295	295	0
4	0.14	69	1	6	431	400	7.1
2	0.05	150	1	5	311	303	2.5
4					299	297	0.6
6					292	287	1.7
8					287	279	2.7
10					283	277	2.1
150	0.1	110	0.5	8	297	330	11.1
		185			326	384	17.7

Table 2 describes the results of calculation of cutting heat based on numerical simulation and actual temperature measurement results. The simulated value matches the measurement results with a rather small error. This small error is accepted in the technical calculation. Therefore, the problem of numerical simulation of the influence of some MQL parameters on the heat generated in the cutting zone has met the requirements. This is the basis for choosing a suitable set of MQL parameters when processing a material, ensuring the heat generation of the cutting zone within the allowable range. This contributes to ensuring the quality of the work part as well as the life of tools.

4 Conclusion

Based on published experimental results, a study on the influence of basic parameters of MQL on the heat generated at the cutting area was carried out. Simulation results clarify the relationship between cutting speed, feed rate and lubricant flow to cutting heat. Accordingly, cutting speed and feed rate are the main parameters causing heat in the cutting zone. Coolant flow is a decisive parameter to reduce the temperature of the cutting zone, contributing to improving the machining quality and the life of the cutting tool.

The simulation results can be used as a basis for selecting the most suitable set of MQL parameters for specific machining conditions, ensuring that the cutting temperature is within the allowable limits. When machining titanium alloys, to ensure that the cutting temperature is less than 400 °C, a flow rate Q of about 150 ml/hr, $a_e = 1$ mm, and $a_p = 8$ mm are required. Then the most feasible working range of the cutting mode parameters is selected as $f_z = 0–0.116$ (mm/tooth) and $V = 0–140$ (m/min).

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