IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 08, Issue 7 (July. 2018), ||V (II) || PP 51-57

Influences of minimum quantity lubrication parameters on cutting forces under cutting C45 carbon steel

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Abstract: In metal cutting, cutting fluids have been proved having significant effects on cutting performance for many decades. Many lubrication techniques have been developed and minimum quantity lubrication (MQL) is one of those which is considered as a renewable technology. This technique has many advantages in reducing production cost, environmental concerns and human health damages. This paper presents an investigation to the influences of MQL parameters on cutting force which is known having a considerable effect on machining cost and product quality. Three MQL factors (air pressure, ratio of emulsion in fluid, vertical angle of nozzle on rake face) were assessed by using fitted regression model and Taguchi analyzing method. A regression equation was built and an optimal data set of three parameters was found under the experiment setup. However, the study is still limited and need be developed more to gain a better understanding of MQL technique and cutting conditions interaction to more types of responses such as tool wear, cutting temperature and surface roughness.

Keywords: *Cutting forces, Minimum quantity lubrication, Nozzle position, Turning process*

Date of Submission: 28-06-2018 Date of acceptance: 13-07-2018

I. INTRODUCTION

In metal cutting industry, the primary goal of most production managers is lower the machining cost as well as enhancing productivity and quality. While the cost of machining strongly depends on metal removal rate (MRR), an increase in MRR can lead to the increase in friction and heat generation in cutting zones. The magnitude of the cutting temperature increases with the increase of cutting velocity, feed and depth of cut. At such elevated temperature the cutting tools if not enough heat strength may lose their form stability quickly or wear out rapidly resulting in increased cutting force, shorter tool life, and dimensional inaccuracy of the product.

During cutting process, almost all of the energy consumed in machining(~98%) is converted into heat [1], and it is waste of power consumption and causes tool failure, consequently affects the product quality. The application of cutting fluids is an effective solution for those issues due to their lubrication and cooling functions. The advantage of fluid application in metal cutting was first reported by F. Taylor in 1894 that cutting speed could be increased up to 33% without reducing tool life by applying large amounts of water in cutting area. Since then, an extensive range of cutting fluids have been developed in many techniques and covered most workpiece materials and operations [2].

In modern manufacture, more and more stricter laws have been posed on this industry, so companies need to concern not only about machining cost but also environment and human health issues. The advantages of cutting fluids have been questioned lately due to the several negative effects they cause. The inappropriate use of coolants during machining can lead to several techno-environmental problems such as environmental pollution, severe lungs and skin diseases for operators [3, 4].

On one hand, total elimination of coolants on conventional cutting fluids seems to be an effective solution; however, in most cutting situations (especially with high depth of cut), dry machining cannot be carried out as it shortens tool life [5]. On the other hand, flood cooling technique is very effective at lower cutting speeds, yet it seems to be ineffective at higher speeds because the amount of heat generation is greater and the coolant cannot reach the critical areas (tool - workpiece interface). Hence, the interface cannot be cooled [6].

For recent decades, minimum quantity lubrication (MQL) has been seen as an alternative green technique in metal cutting. MQL supplies lubricants under the form of atomized mist. The atomized droplets of lubricants are carried by high pressure which helps to penetrate deeply to the tool workpiece interface. It addresses the root of the heat generated in the contacting interface which is known as friction [7]. Researchers have had many studies about the effect of MQL on cutting forces, tool wear, surface roughness and dimension accuracy.

The effects of MQL in turning AISI 1040 steel were investigated again by Dhar et al. [8]. During the experiment, the factors: cutting forces, cutting temperature, chip reduction coefficient, average flank wear, auxiliary flank wear, surface finish and dimensional accuracy were measured to see the effect of MQL with different sets of cutting speeds (72, 94, 139 and 164 m/min) and feed rates (0.10, 0.13, 0.16, 0.20 mm/rev). Depth of cut 1.5mm Air pressure in MQL supply 8 bar Flow rate of MQL supply 200ml/h. In contrast to dry cutting condition, the authors found that MQL helped to reduce the cutting temperature and cutting forces approximately by 5-10% and 5-15% respectively compared with dry cutting for each combination of cutting speed and feed. Ali et al. [9] conducted experiments in turning medium carbon steel operation to study the effects of MQL on chip thickness ratio, cutting temperature, cutting forces, tool wear and surface roughness compared to dry cutting condition. Machining was carried out at different cutting parameters under MQL condition with high air pressure and VG-68 cutting oil. The results clearly indicated that MQL system successfully proved that MQL reduced the cutting force, effectively cooled the shear zone and the tool chip contact zone which reduced the heat generated there. Hence, the tool life and surface roughness were improved.

In another research, Hadad et al. [10] studied the effects of MQL (nozzle position) and cutting parameters on turning performance such as machining forces, surface roughness and temperature. The results indicated that at low cutting speeds and feed rates, oil droplets would penetrate more easily to the cutting area thus reduced the cutting forces. This also clearly showed that there was a significant decrease in cutting temperature (by more than 200^{o}C) accompanied with MQL compared to dry cutting condition. The authors concluded that cutting temperatures for dry, MQL and wet conditions were closely related to the difference in cutting forces. The greater the cutting forces led to the more heat was generated and consequently the higher cutting temperatures. Ekinovic et al. [11] investigated the influences of MQL parameters on cutting forces during turning of carbon steel St52-3. The experiment factors were quantity of oil and water, position of nozzle. The result showed that 1.7l/h of water and 10ml/h of oil were the optimized quantity for minimum forces. Furthermore, the cutting forces under MQL condition were 17% lower than those under dry cutting condition. Especially, the authors found that position of the nozzle did not significantly affect the cutting forces.

There were a number of researchers who studied the effects of MQL parameters and cutting parameters on the performance of machining processes with a wide range of materials. The typical factors of MQL chosen are air pressure, position of nozzle, quantity of lubricants [12-15]. Most of the researches showed that MQL has more advantages in reducing cutting temperature, cutting forces and also improving tool life and surface roughness. Researches' results show that tool breakage, tool wear and work piece deflection are strongly related to cutting forces. However, not many studies have been done to evaluate the effect of the concentration of MQL lubricants on the machinability, and unclearly showed the relationship between those to the desired outputs. This study intends to investigate the effects of MQL parameters (air pressure, concentration of the fluid, vertical angle of nozzle) on cutting forces during turning of carbon steel C45.

II. EXPERIMENTAL PROCEDURE

2.1 Experimental setup

2.1.1 MQL system

A minimum quantity lubrication system was built as the Fig. 1. In the system, pressure is supplied by the compressor and divided into 2 lines. The first one goes through valve 1 and lead gas (air) with pressure to the nozzle. The second one goes through valve 2 to supple pressure to the pressure tank that arm at pushing cutting fluid and lead to the rest input way of MQL nozzle. The nozzle used in the system is a product of the Spraying System [16] which has a needle helped to adjust fluid flowrate.

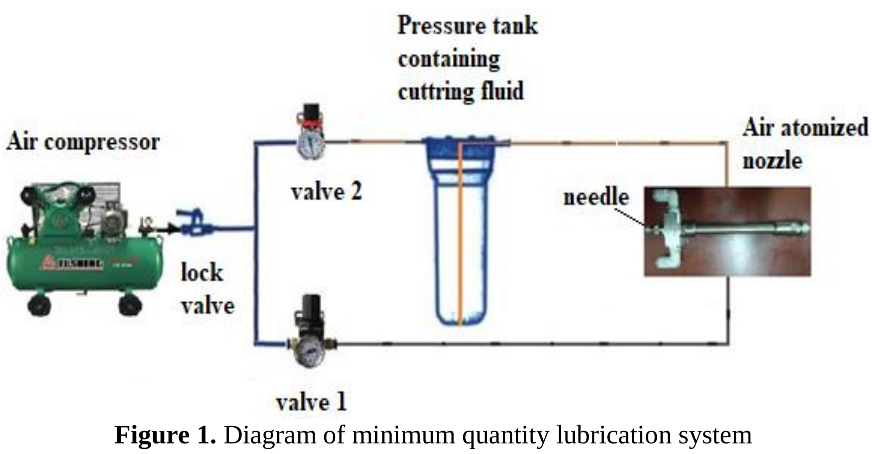

Figure 1. Diagram of minimum quantity lubrication system

2.1.2 Machine, tool and workpiece

Experiments have carried out on a turning machine MASCUT MA1880 located at the workshop of Tran Dai Nghia University, Vietnam. Cutting tool employed in the investigation is MITSUBISHI turning insert CNMG120408MA VP15TF and tool holder MCLR2525 M12 which are recommended using in medium cutting. For medium carbon steel (C45), the cutting parameters are in the range of 130 m/min-75m/min and 0.5-0.2mm/rev for cutting speed and feed rate respectively. In the present study, cutting conditions were set as in the Table 1.

Table 1: Cutting condition for experiment

Item	**Description**
Process parameters Cutting speed (Vc)	117 m/min
Feed rate (f)	0.2 mm/rev
Depth of cut (t)	1mm
MQL flowrate Lubricant	120 ml/h BLASOCUT 2000 Universal ; viscosity at 40^{o}C: 46 mm^2/s, density at 20^{o}C: 0.96 g/cm3, flash point: 154^{o}C.

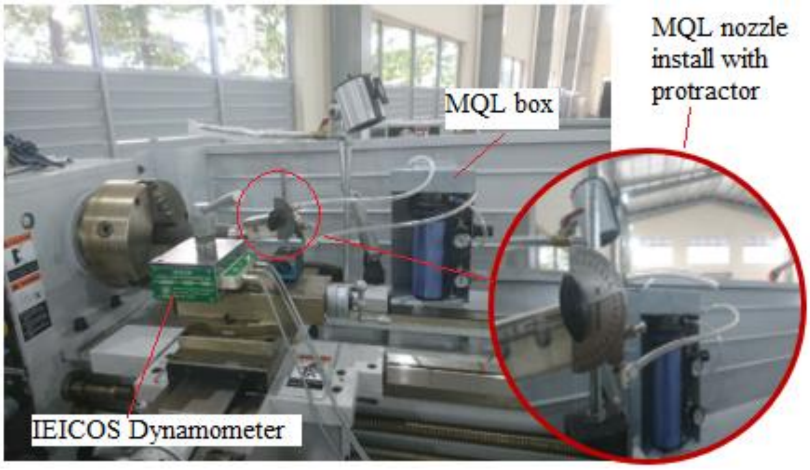

Figure 2. MQL system installed on the turning machine

As in Fig. 2, MQL system was installed in the turning machine with protractor to adjust the vertical angle of the nozzle on the rake face of the cutting tool while the horizon angle between nozzle and workpiece is set at 30 degrees. The job material used in the experiments is C45 carbon steel which has chemical composition and properties as in Table no 2 and Table no3. All experiments carried out on cylindrical samples with initial values of length and diameter equal to 200 and 50 mm, respectively.

Table 2: Chemical composition of C45 carbon steel

% Weight							
C	Si	Mn	P max	S max	Cr max	Mo max	Ni max
0.42-0.5	0,17 – 0,37	0.5-0.8	0.04	0.04	0.25	0.1	0.25

Table 3: Mechanical properties of job material.

Test temperature (^{o}C)	Ultimate tensile strength (MPa)	0.2% Yield (MPa)	% E long	Hardness (HRC)
Room	610	360	16	23

Cutting forces were measured by IEICOS Lathe Tool Dynamometer – Model 621B: 200 Kgf, Multicomponent digital force.

Figure 3. IEICOS Lathe Tool Dynamometer and Multicomponent digital force indicator

2.2 Experimentation

As mentioned above, the MQL parameters with three levels of air pressure, concentration of the fluid, and vertical angle of nozzle were used in the present study which sets of values shown in Table 4. Experimental design was planned by using L27 orthogonal array.

Table 4: MQL parameters in investigation.

MQL parameters	Level 1	Level 2	Level 3
Air pressure P (kg/cm^2)	3	5	7
Concentration of the fluid E (%)	6	8	10
Vertical angle A (degree)	20	25	30

2.2.1 The fitted regression model for MQL turning

The regression model regarding cutting force in the turning operation was fitted by pooling the interaction effects of PA, EA and the square terms AA which values were not significant. The fitted second –order response function is given by Eq. (1). The MQL parameter coefficients were estimated by the least square method.

$$F = 66.81 - 5.487P - 2.692E + 0.2556A + 0.0960PE + 0.4258P^2 + 0.1817E^2 \quad (1)$$

Where F is the total cutting force, P is the air pressure, E is the fluid concentration, A is the vertical angle.

2.2.2 Taguchi design analysis

The response is converted into signal-to-noise ratio (S/N ratio) for lower-the-better quality characteristic. Analysis of responses is carried out by MINITAB 17 software. S/N ratio for 'lower the better' type response is given by:

$$S/N \text{ ratio} = -10\log[1/n(y_1^2 + y_2^2 + ... + y_n^2)] \quad (2)$$

Where y_1, … y_n are the responses of values of quality characteristic for the trial condition repeated 'n' times.

Table 5: Experimental results

Exp. No	**Air pressure P (kg/cm2)**	**Fluid concentration E (%)**	**Vertical angle A (degree)**	**Total cutting force F (kgf)**	**S/N ratio for total cutting force**
1	3	6	20	51.30	-34.2023
2	3	6	25	52.71	-34.4379
3	3	6	30	54.02	-34.6511
4	3	8	20	52.72	-34.4395
5	3	8	25	52.72	-34.4395
6	3	8	30	53.91	-34.6334
7	3	10	20	54.02	-34.6511
8	3	10	25	53.91	-34.6334
9	3	10	30	55.76	-34.9265
10	5	6	20	47.74	-33.5776
11	5	6	25	50.02	-33.9829
12	5	6	30	51.30	-34.2023
13	5	8	20	48.73	-33.7559
14	5	8	25	50.24	-34.0210
15	5	8	30	51.30	-34.2023

16	5	10	20	51.30	-34.2023
17	5	10	25	52.92	-34.4724
18	5	10	30	53.91	-34.6334
19	7	6	20	48.73	-33.7559
20	7	6	25	50.24	-34.0210
21	7	6	30	51.30	-34.2023
22	7	8	20	48.73	-33.7559
23	7	8	25	51.94	-34.3100
24	7	8	30	53.03	-34.4904
25	7	10	20	52.72	-34.4395
26	7	10	25	53.36	-34.5443
27	7	10	30	54.46	-34.7216

III. ANALYSIS THE RESULTS

The medium turning experiments performed on C45 carbon steel for the response is total cutting force. The experimental results displayed in Table no 5. The obtained results were analysed by using Taguchi's lower the best signal to noise ratio(S/N ratio). The optimization study is performed by using Minitab17 software. Fig. 4 shows the effect MQL parameters on the S/N ratios of the cutting force. From the Fig. 4, it is found that higher S/N ratio could be achieved at middle level of air pressure and lower fluid concentration and lower vertical angle of MQL nozzle on rake face of the cutting tool. The optimal values of these factors is seen in table no 6, we can get the smaller cutting force by setting the control parameters at P2 E1 A1 (5 kgf/cm^2 and 6% and 20 degrees for input air pressure, fluid concentration and vertical angle, respectively).

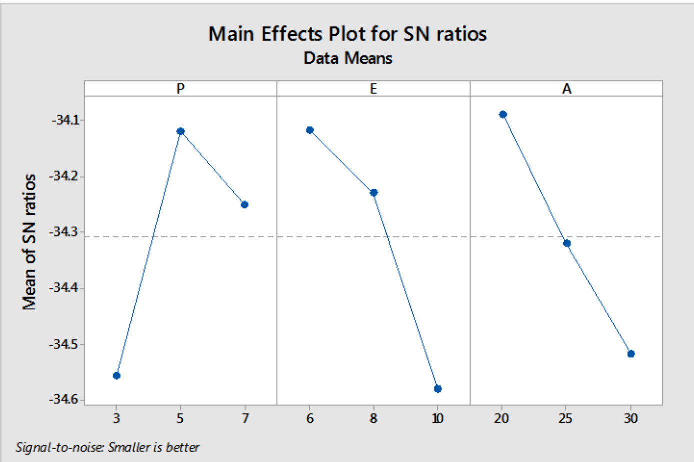

Figure 4. Main effects plot for S/N of total cutting forces

Table 6: Response table for signal to noise ratios

Level	P	E	A
1	-34.56	**-34.11**	**-34.09**
2	**-34.12**	-34.23	-34.32
3	-34.25	-34.58	-34.52
Delta	0.44	0.47	0.43
Rank	2	1	3

Furthermore, from the regression Eq. (1), we can evaluate the effects of sets of two controlling factors on the reponse by keeping one of the three at base level (level 2). The results show in Fig. 5.

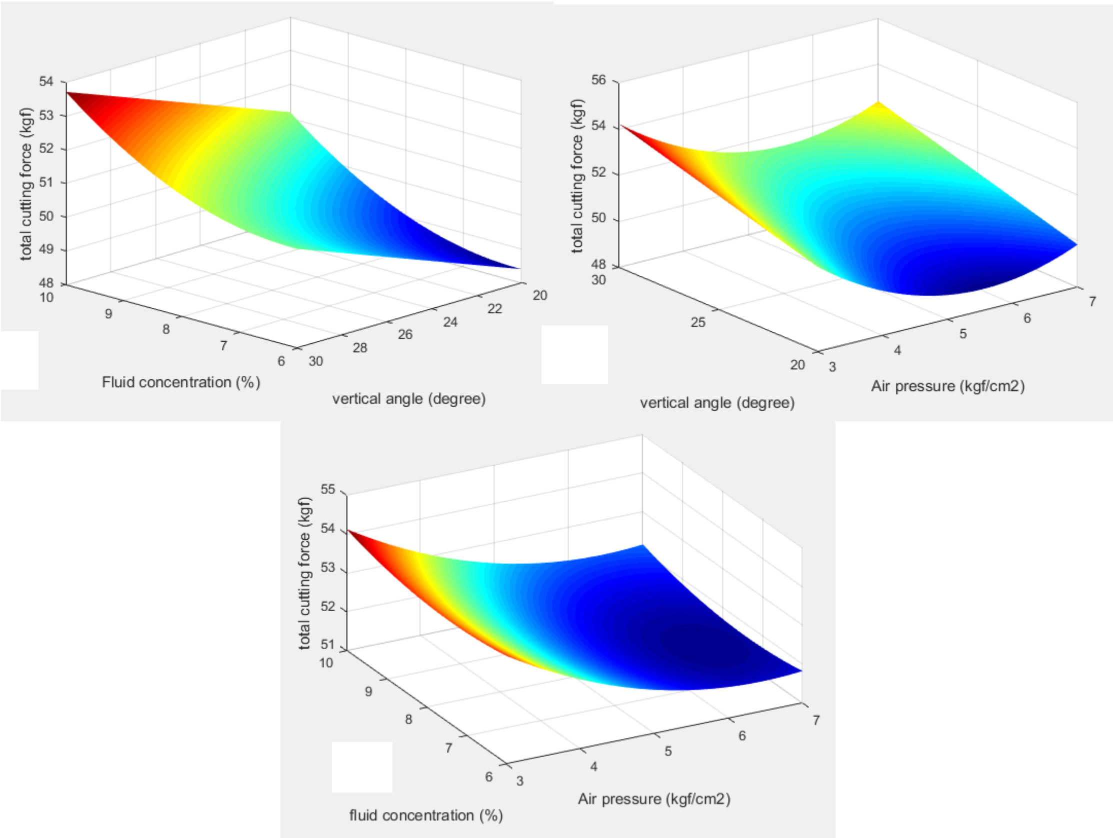

Figure 5. Influence of various parameters on cutting force

a) *Fluid concentration (%) and vertical angle (^{o})*
b) *Vertical (^{o}) angle and air pressure (kgf/cm^2)*
c) *Fluid concentration (%)and air pressure (kgf/cm^2)*

IV. CONCLUSION

The paper evaluated the influences of MQL parameters on cutting forces during turning C45 carbon steel. A fitted regression equation was built to describe the relationship of MQL controlling factors and cutting force. In addition, Taguchi method was used effectively to investigate the effects of input air pressure, ratio of emulsion in cutting fluid and vertical angle of MQL nozzle on the response. From the results, it is seen that those factors have significant influences on cutting force. Especially, among the three factors, the variation of fluid concentration causes a highest change in the output. For the above experiment conditions, the optimal MQL parameters are 5 kgf/cm^2 and 6% and 20 degrees for input air pressure, fluid concentration and vertical angle, respectively. However, the research is still limited with the small range of input parameters and experiments needed to expand to have more understanding of the combination effects of MQL technique and cutting conditions.

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IOSR Journal of Engineering (IOSRJEN) is UGC approved Journal with Sl. No. 3240, Journal no. 48995.

Le Van Canh . " Influences of minimum quantity lubrication parameters on cutting forces under cutting C45 carbon steel." IOSR Journal of Engineering (IOSRJEN), vol. 08, no. 7, 2018, pp. 51-57.