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Effect of nozzle distance and cutting parameters on MQL machining of AISI 1045

S A S Amiril^{1,2}, E A Rahim¹, A Z Hishamudin¹

¹ Precision Machining Research Centre (PREMACH), Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia

² Faculty of Manufacturing Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia

Abstract. Proper selection of nozzle distance during minimum quantity lubrication (MQL) machining can result in better performance of cutting force and tool life. This study emphasizes the effect of MQL nozzle distance from the cutting edge during the turning operation of AISI 1045 medium carbon steel. Machining operation at three levels of MQL nozzle distance with different cutting parameters are performed in order to evaluate the cutting force, tool wear and tool life of an uncoated cermet cutting insert. Results have shown significant reduction of the cutting force and tool wear progression which led to the improvement of the cutting tool life by keeping the distance of the MQL nozzle near to the cutting zone. Based from the experimental results, it is apparent that the appropriate MQL parameters including the nozzle distance showed a substantial contribution to the cutting performance and tool wear progression.

1. Introduction

The minimum quantity lubrication (MQL) technique supplies minimum quantity of lubricant, which was being atomized by a compressed air, which is then delivered into the cutting zone in the form of an aerosol or spray mist [1]. By using MQL technique, it reduces the consumption of lubricants since it uses very little lubricant during the machining operations, which was estimated to be between 0.005 to 1 l/hr of coolant compared to flood condition that uses 1.2 to 180 l/hr cooling fluid [1,2]. The MQL technique is also proven to provide better surface condition and longer tool life span when compared to dry and flood machining conditions [3-5].

Cutting fluids applications in the turning operations have been reported to cause many problems to the environment and human health [1,2]. Because of that, the uses of cutting fluids need to be reduced. However, the absence of cutting fluids in dry machining condition will increase the possibility of tool damage during the machining operation [1]. Lubricant starvation will increase the stress and heat generated at the tool-chip interfaces which will deteriorate the tool surface. In order to achieve best cutting performance, the cutting fluids are required to provide better surface quality [6]. The application of MQL technique can provide sufficient lubrication at the cutting zone and reduce tool damage. The important factor that affects the performance of the MQL supply performance are the pressure of compressed air, spray direction and the distance of the nozzle outlet directed towards the cutting zone. The optimum setting of the MQL spray mist delivery may provide better penetration of lubricants at the tool-workpiece surfaces [6-8]. The adequate amount of cutting fluid used when using MQL technique is aimed at reducing the cutting temperature, friction and cutting force, which in turn will improve the surface quality and tool wear.

From previous studies, MQL technique has proven to be the best solution to overcome the problem of bad environmental and health impacts in regards to the consumption of conventional flood cooling and dry cutting during the metal works [4,5]. However, the MQL technique requires improvements in order to further reduce the bad impact posed by the use of mineral-based cutting fluids as MQL lubricants. The floating mist generated in MQL machining may cause lung disease if oil mist smaller



than 10 mm in diameter being inhaled deep into the lungs [4,5,9]. Therefore, the factors that can affect the machining performance during MQL machining are being investigated in this study by using a synthetic ester, which was specially formulated for MQL machining [10].

The present study aims at evaluating the effect of the nozzle distance to the cutting edge, with the position and direction of the MQL mist as well as the pressure of the MQL supply were being fixed when machining AISI 1045 medium carbon steel at different cutting parameters. The cutting parameters namely cutting speed, feed rate, depth cut and various MQL nozzle strategy were selected as the investigational variables. The data of cutting force, tool wear and tool life of the uncoated cermet insert were discussed and comparative study was made against the set of cutting parameters selected for the machining experiments.

2. Experimental Set Up

The applicable cutting parameters have been considered prior starting the machining operation and according to the standard set by the tool's manufacturer. The details of the machining parameters are shown in Table 1. There are three levels of cutting speed and two levels of feed rate used in the current work, while the depth of cut was fixed to be constant throughout the machining experiments. For the MQL spray parameters, three levels of nozzle distance were selected with the input pressure, flow rate and nozzle inner diameter were fixed at constant value. Figure 1 shows the complete assembly of the MQL cooling unit for the experimental trials. A medium carbon steel cylinder of AISI 1045 with 100 mm width and 200 mm length was used as the workpiece material. An uncoated cermet tool insert of grade T1200A with chip breaker and negative rake angle of 14° was used as the cutting tool during the turning process [11].

Table 1. Machining Parameters

Cutting parameter	Values
Cutting speed, v_c (m/min)	100, 160, 220
Feed rate, f_r (mm/rev)	0.15, 0.30
Depth of cut, a_p (mm)	0.2
MQL parameter	Values
Input pressure (MPa)	0.2
MQL flow rate (l/hr)	0.04
Nozzle inner diameter (mm)	2.5
Nozzle distance (mm)	3, 6, 9
Lubricant properties	Values
Type	Synthetic Ester
Kinematic viscosity, ν at 40°C in mm ² /s	19
Kinematic viscosity, ν at 100°C in mm ² /s	4.3
Viscosity Index, VI	137

The machining experiments were carried out in two stages. The first stage focuses on measuring the cutting force during the material removal process and was conducted on an NC lathe machine (Harrison), which was equipped with a force dynamometer (Kistler 9257BA). The second stage was conducted on a CNC lathe machine (Mazak) for evaluating the tool wear and tool life of the cutting inserts. An optical microscope (Nikon) was used to measure the size of the flank wear on the cutting tool. The tool life criteria following the ISO 3685 was used when determining the tool life of the uncoated cermet inserts when machining AISI 1045 medium carbon steel bar as given in Table 2.

The flow rate of the MQL spray was determined prior to the machining process. The volume of lubricant consumed after half an hour continuous spray was recorded and the measurement was repeated twice to get the average value. The results of mist flow rate was calculated as the volume of fluid consumed in a litre over one hour spraying time. The lubricant used in the MQL system is a

synthetic ester and its properties are readily available in Table 1. Figure 2 shows the MQL nozzle located on an inclined angle of 45° when assembled on the lathe machine during the experimental trials.

Table 2. Tool life criteria

Description	Values
Average flank wear, VB	≥ 0.3 mm
Maximum flank wear, VB_{max}	≥ 0.6 mm
Maximum notch wear, VN	≥ 0.6 mm
Catastrophic failure	Chipping, fracture

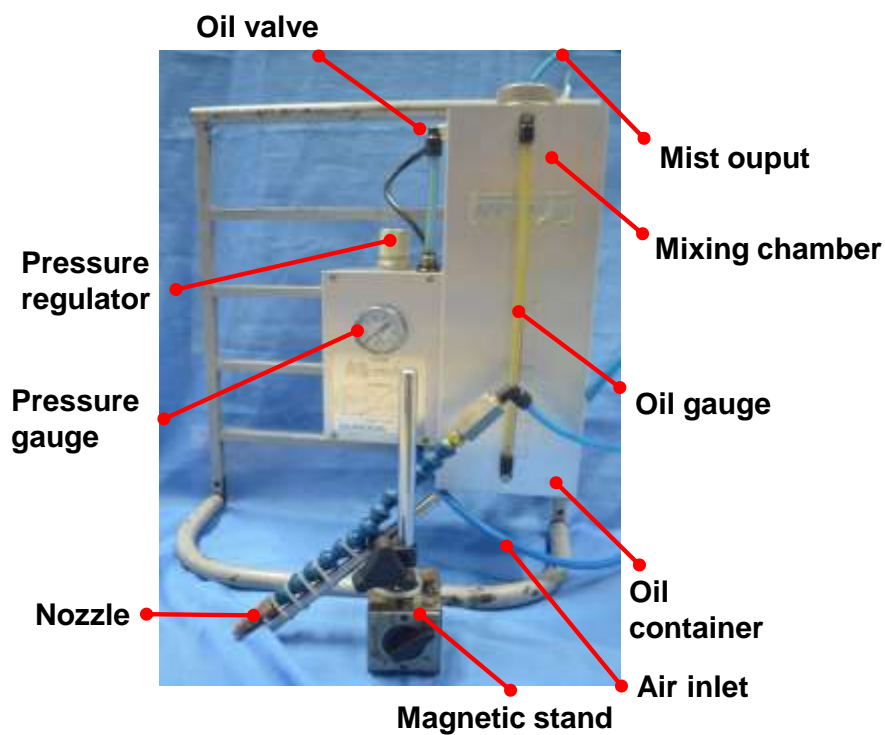


Figure 1. The MQL supply system type Kuroda KEP-R

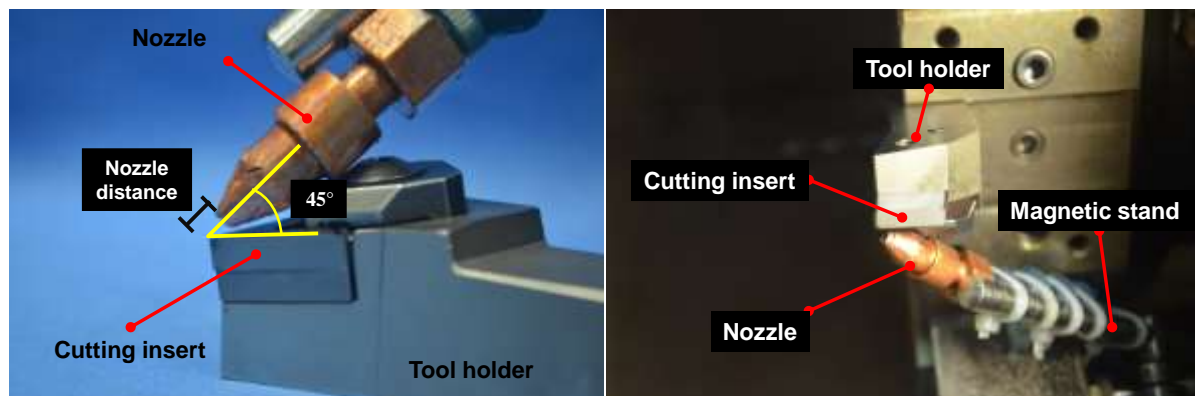


Figure 2. The location and setup of the MQL nozzle during the machining process

3. Results And Discussion

In this section, the results from the experimental design and methods used are presented and discussed. The turning operation was conducted with various MQL nozzle distance to the cutting tip and machining conditions.

3.1. Cutting force and feed rate

The machining experiment was performed in various cutting conditions of 3 levels of cutting speed, 2 levels of feed rate and 3 levels of MQL nozzle distance. Figure 3 shows that by increasing the cutting speed, the value of cutting force decreases. The results are similar for all feed rates and nozzle distances. This can be suggested by the fact that the increased cutting speed has decreased the apparent real contact surfaces between the tool-chip interfaces, which then lowering the contact friction and thus reducing the cutting forces [7,9]. Low cutting forces of 83 and 86 N are recorded at feed rate of 0.15 mm/rev and at the nozzle distances of 3 and 6 mm respectively. They are both recorded at the highest cutting speed of 220 m/min. Another low cutting force of 85 N is also presented at the cutting speed of 160 m/min, at the nozzle distance of 6 mm and feed rate of 0.15 mm/rev. For feed rate of 0.3 mm/rev, the lowest cutting force of 123 N was found at highest cutting speed of 220 m/min and shortest nozzle distance of 3 mm.

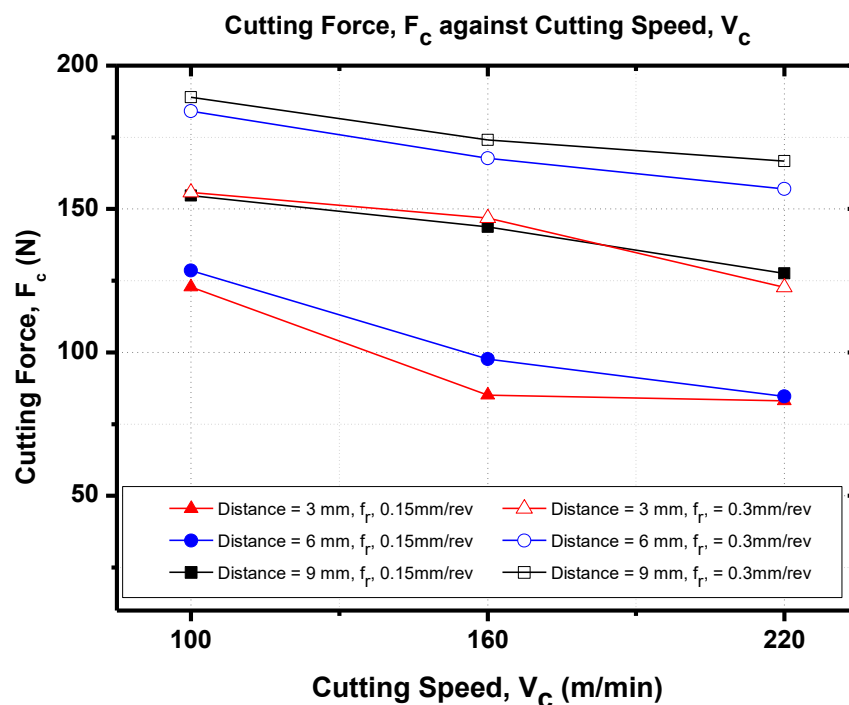


Figure 3. The results of cutting force, F_c against the cutting speed, V_c

The maximum values of cutting forces were obtained at the lowest cutting speed of 100 m/min for all cutting conditions. Moreover, the highest cutting force of 189 N was recorded at the highest feed rate of 0.3 mm/rev and the farthest nozzle distance of 9 mm. This could be explained by the increased built up edge formed on the cutting tool during the material removal process, whereas the metal debris formed by the chip formation process adheres on the tool surfaces and thus, increases the contact friction, which in turn produces high shear stresses and raises the cutting forces [4-8]. Moreover, Qian & Hossan also suggested that the cutting forces are highly influenced by the high value of feed rate [12]. By increasing the feed, the chip load will increase due to the large cross sectional area of the uncut chip formed during the material removal process [4,5,12].

3.2. Nozzle distance

Figure 3 also displays the influence of nozzle distance during the MQL machining experiments. It is seen that at the nozzle distance of 3 and 6 mm, low cutting forces of between 83 to 100 N are recorded in regards to the cutting speed of between 160 and 220 m/min and at the lowest feed rate of 0.15 mm/rev. The explanation is based on the lubrication and cooling effect of the MQL spray mist being delivered into the cutting zones [12,13]. With the low input air pressure at 0.2 MPa and flow rate of 0.04 l/hr, the closest distance of the nozzle to the cutting edge plays a significant role in supplying adequate amount of lubricants into the tool-chip interfaces. This is also true for the cutting conditions with higher feed rate of 0.3 mm/rev, whereby the highest cutting speed (220 m/min) produced lowest cutting force (123 N) at nozzle distance of 3 mm compared to the farthest nozzle distance of 9 mm at 167 N, a 36 % increments from the former.

From the results obtained, it can be suggested that, with the given MQL parameter setup, the nozzle should be placed as close as possible to the cutting edge between 3 to 6 mm distances. This happens due to the increase in total mass of oil mist particles accumulated on the tool-chip interfaces delivered by the nozzle, which was located close to the cutting edge [14]. The higher amount of oil mist penetrated into the cutting zone will provide better lubrication effect during the material removal process [12-14]. The good lubrication effects affect the reduction of frictional forces between the cutting tool and workpiece surfaces and lead to the reduction of cutting forces during the chip formation processes.

3.3. Tool life

Figure 4 shows that at feed rate of 0.15 mm/rev and nozzle distance of 3 mm, the cutting speed of 160 m/min produces the longest tool life with total machining time of 90 min compared with the other two cutting speeds. At the same feed and nozzle distance, the cutting speed of 100 m/min has produced the shortest tool life with a total machining time of 40 min. The rapid formation of notch wear trailing on the clearance edge is the reason of such occurrence, which has exceeded the maximum allowable notch wear, VN of 0.6 mm in a short period. The low cutting speed has influenced the increase of contact friction between the sliding surfaces, thus higher adhesion wear mechanism is expected [12,13]. The growth of notch wear due to oxidation and surface fatigue on the cutting tool surface are also contributing towards the reduction of the cutting tool life [13]. However, the farthest nozzle distance of 9 mm provided the shortest tool life due to lubricant starvation occurred on the cutting zones during the machining processes.

Figure 5 shows the results of tool wear at higher feed rate of 0.3 mm/rev. The shortest tool life are obtained at this feed rate with the accumulated time of 25 min at the cutting speed of 100 m/min and farthest nozzle distance of 9 mm. The longest cutting time of 55 min was recorded at cutting speed of 220 m/min and nozzle distance of 3 mm. Compared to Figure 4, the increase in feed rate have minimal effect on tool life than the effect by changing the cutting speed. At higher value of feed rate, the flank wear formations are decelerating, which leads to the improvement of the tool life at higher cutting speed [2]. The results have shown, that the feed rate gives minimal effect on the tool life because of the negligible changes on the notch wear progression.

In Figures 4 and 5, the nozzle distance is shown to be one of the main parameters that influence the cutting tool life. The longest tool life was obtained at the closest nozzle distance of 3 mm with the highest tool life achieved was at 90 and 55 minutes for cutting speed of 160 m/min and at feed rate of 0.15 mm/rev as well as at cutting speed of 220 m/min and at feed rate of 0.3 mm/rev, respectively. Meanwhile, the shortest tool life was recorded at the farthest nozzle distance of 9 mm. For the feed rate of 0.15 and 0.3 mm/rev, the tool life for cutting speed of 220 and 100 m/min was at 35 and 25 minutes, respectively.

The results obtained have shown that in the MQL machining processes, lubricant penetrations into the cutting zones provide significant tool life improvement by providing adequate lubrication effect at the sliding contacts [1,5,10]. By comparing the results of tool life at the same cutting speed of 160 m/min and the feed rate of 0.15 mm/rev, the tool life has improved up to 80 % increases between the nozzle

distance of 6 and 3 mm, respectively. The good lubrication effect provided by the nozzle located at the closest distance to the cutting zone has helped to reduce the abrasion wear mechanism and decelerate the tool wear progression, and therefore elongated the total cutting tool life span [15].

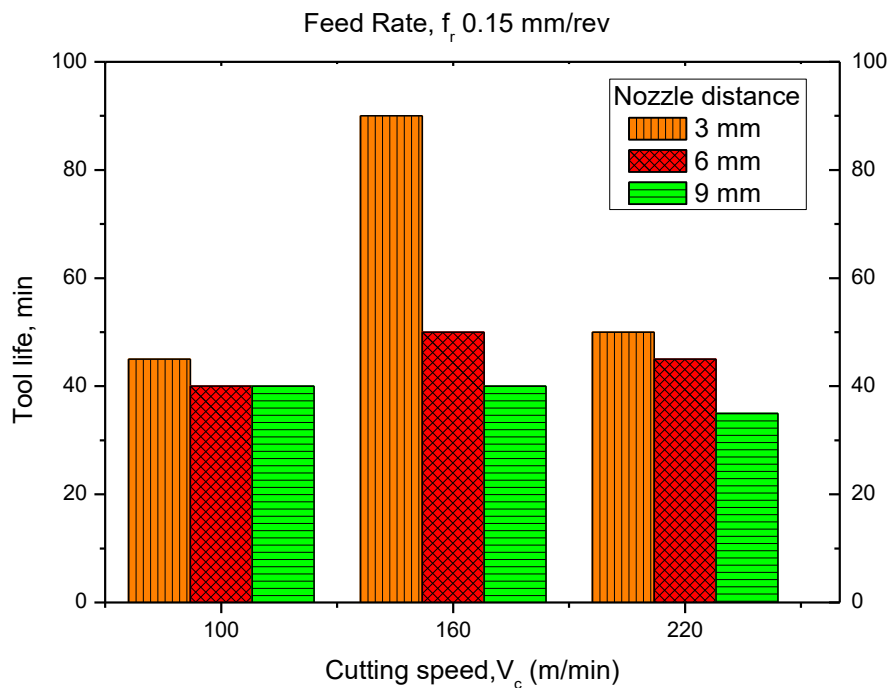


Figure 4. Tool life at different cutting speeds and feed rate of 0.15 mm/rev

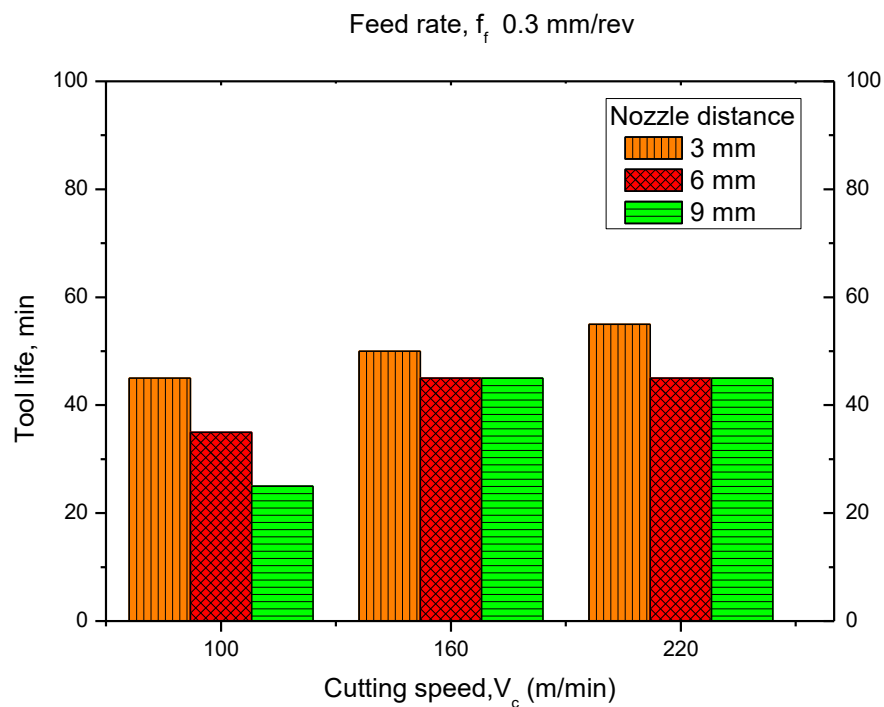


Figure 5. Tool life at different cutting speeds and feed rate of 0.3 mm/rev

4. Conclusion

Based on the investigation results, the effects of the nozzle distance in MQL machining on AISI 1045 medium carbon steel in terms of cutting force, tool wear progression and tool life at different cutting conditions have been successfully evaluated. The conclusions that can be drawn are:

- i. The cutting forces are minimum at higher cutting speed, low feed rate and closest nozzle distance to the cutting zone.
- ii. Higher cutting speed causes rapid wear due to abrasion that resulted in high flank wear, while at lower cutting speed, the dominant tool wear was caused by excessive notch wear as the main tool failure mode.
- iii. The closest nozzle distance provided better results in cutting force and improved the tool life.
- iv. With the combination of the given cutting parameters i.e. cutting speed of 160 m/min, feed rate of 0.15 mm/rev and nozzle distance of 3 mm, the best cutting performance was achieved.

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