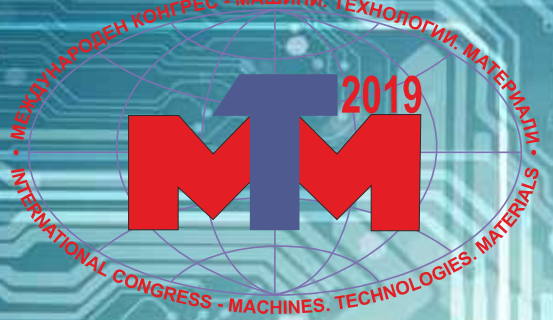
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AN EXPERIMENTAL STUDY ON CUTTING FORCES AND SURFACE ROUGHNESS IN MQL MILLING OF ALUMINUM 6061

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Abstract: *The minimum quantity lubrication (MQL) and dry machining operations are two types of environmentally friendly processes that have potentials to replace with conventional cooling methods. In recent years, the studies have been performed on the environment-friendly lubrication methods such as MQL method in machining operations. These studies have also focused on the usage of vegetable cutting fluids instead of mineral based oils due to increasing awareness to the environment and human health. In this experimental study, Aluminum 6061 was machined under dry and MQL conditions and the cutting force components and surface roughness values were measured. The experiments were carried out by CNC milling machine tool at three different cutting speeds and constant depth of cut and feed. The vegetable cutting fluid was pulverized to the rake face by using single nozzle and double nozzles at two flow rates during MQL milling. Cutting force components and surface roughness values were compared for minimum quantity lubrication and dry milling operations of Aluminum 6061.*

Keywords: CUTTING FORCE, SURFACE ROUGHNESS, MQL MACHINING, ALUMINUM 6061

1. Introduction

The challenge of modern machining industry is mainly focused on achievement of high quality in terms of workpiece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining, reducing environmental impact etc. [1]. In machining of ferrous and other high strength materials, the temperature rises with the cutting speed and the tool strength decreases, leading to faster tool wear and failure [2]. In order to reduce the temperature in the cutting zone, traditional flood cooling strategies have been commonly used. However, there are critical needs to reduce the usage of cutting fluids in machining process in order to decrease their environmental and cost effects [3]. As is known, the majority of cutting fluids is based on mineral oils and contains heavy chemicals which are hazardous to the human health and environment [4, 5]. Therefore, the usage of cutting fluids needs to be limited. For this purpose, minimum quantity lubrication (MQL) technique is utilized which is a promising, attractive, efficient and environmental friendly technique of cooling and lubrication [6].

In MQL technique, a very small amount of lubricant/coolant is mixed with air to form aerosol, which is sprayed at a high pressure in the cutting zone with the help of a nozzle. This system consists of an atomizer, cutting fluid pump, discharge nozzle, etc. The atomizer works as an ejector in which high pressure air is used to atomize the coolant. Atomized coolant is then delivered to the machining zone by the air in a low-pressure distribution system. Due to the venturi effect in the mixing chamber, partial vacuum sucks the cutting fluid from the oil pump where it is maintained at a constant hydraulic load. The air passing through the mixing chamber atomizes the coolant stream into aerosol of micron-sized particles. When this aerosol is sprayed in the cutting zone as mist, it works as coolant as well as lubricant and penetrates deep into the tool-workpiece interface [2]. In MQL method, the cutting fluid can be pulverized in the range between 0.01-2 l/h instead of the 50-1000 l/h in the case of conventional lubrication/cooling systems. Some MQL advantages against other lubrication/cooling systems are: reduction of cutting fluid consumption, cost and tool wear, improvement of surface roughness, diminution decrease of the environmental and worker health hazards and improve lubrication than conventional lubrication/cooling system. The cutting fluid is used in such small quantities that it is practically consumed in the process, eliminating the fluid disposal problems. In addition, chips produced are nearly clean from cutting fluid, which are easily recyclable [7].

In literature, there are several studies on MQL machining. Mulyadi et al. [8] compared to dry, flood, and MQL conditions and pointed that selecting MQL environment can be an intermediate strategy for reducing direct electrical energy requirements, global warming potential, human toxicity, and acidification in machining processes. The MQL method provides a good compromise in terms of tool life, when compared to dry machining. Also it performance was very close to machining under flood coolant environment. Ginting et al. [9] presented an industrial situation in a local small to medium sized enterprise (SME) in Western Australia to determine the technical, economic and environmental benefits of the replacement of traditional flood cooling with MQL. The use of MQL reduced the greenhouse gas emissions and eco-toxicity associated with the disposal of the contaminated liquid. It was found that this alternative cooling method increased the performance of the metal cutting operation. Finally, the replacement of traditional fluid cooling with MQL cooling system can help attain the three pillars of sustainability: economic, environmental, and social. Another implementation example of MQL is that Ford Motor Company began applying MQL to aluminum transmission components in 2005, and by 2008 had over 200 MQL machining centers in operation machining Aluminum transmission cases, torque converter housings, and valve bodies at two plants in North America. MQL machining is Ford's current standard machining method for these components, and is being implemented in new high-volume machining lines globally. Ford began machining aluminum engine heads and cast iron engine blocks at two plants in Europe in 2011; as in the case of transmissions, MQL is now the primarily standard method for machining cast iron engine blocks and aluminum engine blocks

and heads, although wet machining is still used for some specialized operations. New engine MQL modules have been installed in Brazil and China [10]. Berzosa et al. [11] reached better surface roughness results in MQL method than that in dry drilling of magnesium alloy. Sun et al. [12] observed better surface roughness in MQL turning of Ti-5553 alloy when compared to flood coolant and cryogenic cooling. Kumar et al. [13] performed turning experiments on AISI 4340 stainless steel under dry, flood cooling, and MQL conditions. Researchers reported that the surface quality improved by 7% to 10% with MQL when compared with flooded supply of lubricants. In Ramana's study [14], turning of Ti-6Al-4V alloy was performed under dry, flood cooling and MQL conditions. Based on the experimental results, the cutting performance of MQL condition showed better results as compared to dry and flood cooling conditions in reduction of surface roughness. Oliveira et al. [15] compared the influence of cryogenic cooling, MQL method, and flood cooling on end milling of Inconel 718 alloy and it was concluded that the MQL method provided the lowest levels of tool wear at the same cutting conditions and the resulting force levels were similar in both methods flood and MQL using water based cutting fluid. Joshi et al. [16] conducted turning experiments on Inconel 800 under dry, flood cooling, and MQL conditions and compared the surface roughness and flank wear results with each other. The MQL method showed the best performance. Aslantas and Cicek [17] determined that the use of MQL provides important advantages in terms of tool wear, burr formation and surface roughness for micro-milling of Inconel 718 superalloy.

In this experimental study, dry and MQL milling processes were performed on Aluminum 6061 to evaluate and compare the cutting force components and surface roughness values. In MQL milling, the cutting fluid was applied to the rake face through single nozzle and double nozzles at two flow rates.

2. Experimental Study

In experimental studies, slots were machined on Aluminum 6061-T651 parts by a CNC milling machine which chemical composition is given in Table 1. The workpiece parts were prepared in the dimension of 140x170x30 mm.

Table 1. *Chemical Composition of Aluminum 6061-T651*

Si %	Fe %	Cu %	Mn %	Mg %	Cr %
0.76	0.63	0.3	0.15	0.99	0.17

In milling operations, APHT 100308FR-27P uncoated cutting inserts were used and mounted two inserts on a diameter of 16 mm end mill. The milling experiments were conducted at a constant deep of cut of 1.5 mm, feed of 0.1 mm/rpm and three different cutting speeds as 200 m/min, 250 m/min, and 300 m/min under dry cutting and MQL conditions. In MQL method, milling experiments were performed by applying the cutting fluid to the rake face at total 26 ml/h and 52 ml/h through single nozzle and double nozzles as seen in Table 2 and Fig.1 due to understanding the effects of cutting fluid distribution on surface roughness and cutting force components.

In MQL milling, a micro lubrication system was used and a commercial vegetable cutting fluid was selected. The global lubricant is expected to reach 43.9 million tons in 2022. Cutting fluids represent about 5% of the global lubricant market, with Asia as the largest consumer. Availability of mineral based oils is limited as they are finite source and decreasing steadily whereas vegetable based cutting fluids are sustainable. Vegetable oils are evolving as metalworking fluids due to its higher biodegradability and ability to minimize the waste treatment costs. It also reduces the health risks to operators which were quiet common with petroleum based mineral oils due to their lower toxicity [18].

Table 2. *MQL conditions*

Conditions	Flow rate (ml/h)	MQL pressure (bar)	Nozzle distance (mm)	Nozzle angle (°)
Dry	-	-	-	-
MQL with single nozzle	26	5	30	45°
MQL with single nozzle	52			
MQL with double nozzles	13 13			
MQL with double nozzles	26 26			

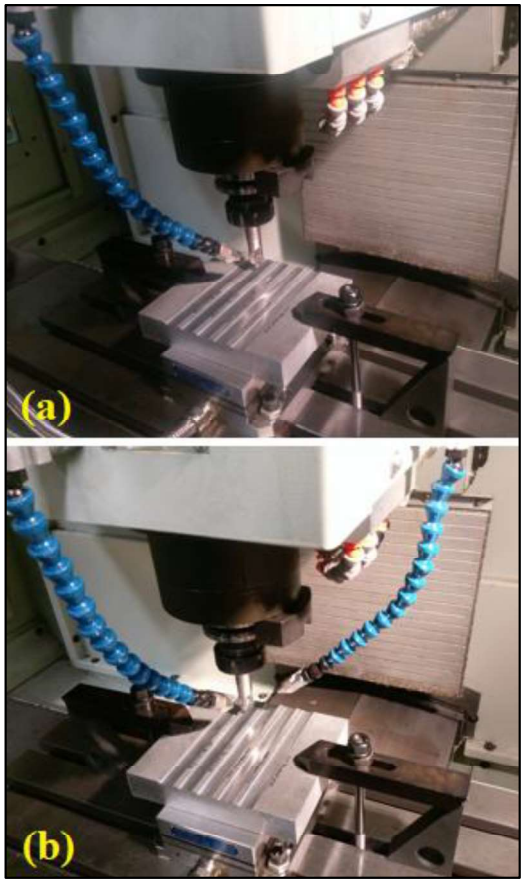


Fig.1. *Machine tool set-up for MQL milling with a) single nozzle and b) double nozzles*

Surface roughness (R_a) measurements of milled slots were performed by using Mitutoyo Surftest SJ-210 surface roughness tester. The dimension length was adjusted as 0.8 mm and the resolution of tester is 0.002 µm. During surface roughness measurements, 10 (ten) measurements were done on each surface and arithmetic means were calculated. The cutting forces were measured by Kistler 92578A dynamometer which the workpiece was mounted on.

3. Results and Discussion

3.1 Surface Roughness

Depending on the surface roughness measurement results, the minimum surface roughness was obtained at the cutting speed of 200 m/min in MQL milling with double nozzles at 26 ml/h of flow rate from each nozzle whereas the maximum surface roughness was measured in dry milling at the cutting speed of 300 m/min (Fig.2). The usage of MQL method gave better surface roughness results than that measured in dry milling. Additionally, it can be said that the surface roughness increased with increase of the cutting speed for all selected conditions.

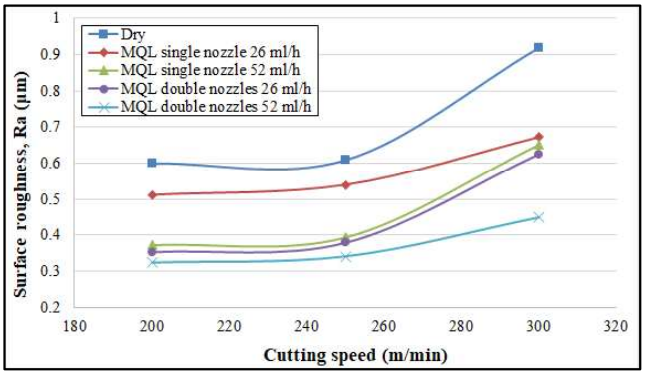


Fig. 2. *Variation of surface roughness with cutting conditions*

In MQL milling, the utilization of single nozzle or double nozzles affected the surface roughness. When the total flow rate is 26 ml/h, surface roughness decreased as 31%, 29.8% and 7% by using double nozzles at the cutting speed of 200 m/min, 250 m/min and 300 m/min, respectively as comparing with single nozzle. This is because of the reaching cutting fluid effectively to the cutting zone. Similarly, the effect of double nozzles on the surface roughness at the total flow rate of 52 ml/h, surface roughness decreased as 13%, 13.3%, and 31% at the cutting speed of 200 m/min, 250 m/min and 300 m/min, respectively, as comparing with single nozzle.

Additionally, surface roughness measurements showed that the flow rate of aerosol affected the surface roughness. In MQL milling by utilizing single nozzle, surface roughness decreased as 27.2%, 27.1%, and 3.2% at cutting speeds of 200 m/min, 250 m/min and 300 m/min, respectively, when the flow rate increased from 26 ml/h to 52 ml/h. At the same conditions, the decreases in surface roughness were determined as 8.2%, 9.9%, and 28.1% when the cutting speeds were 200 m/min, 250 m/min, and 300 m/min, respectively for double nozzles.

3.2 Cutting Force and Feed Force

As expected, the cutting force components decreased with increase of cutting speed. Based on the measurements, the minimum cutting forces and feed forces observed at the cutting speed of 300 m/min in MQL milling with double nozzles at flow rate of 13 ml/h from each nozzle whereas the maximum cutting forces and feed forces were measured in dry milling at the cutting speed of 200 m/min (Figs. 3, 4).

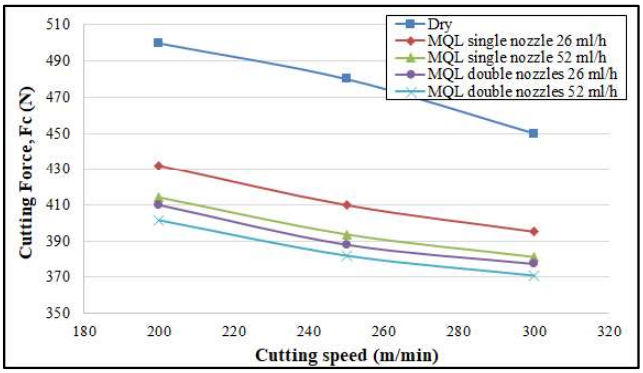


Fig. 3. *Variation of cutting forces with cutting conditions*

In MQL milling by utilizing double nozzles at the total flow rate of 26 ml/h, the feed forces decreased as 7.8%, 15.2%, and 18.2% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively when comparing the single nozzle. Under the same circumstances, the cutting forces decreased as 5.1%, 5.2%, and 4.5%. As investigating the effects of double nozzles on the cutting forces at the total flow rate of 52 ml/h, the cutting forces decreased by approximately 3% for the selected cutting speeds when comparing to single nozzle. In addition, the feed forces reduced by 14.4%, 17.5%, and 19.3% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively.

In MQL milling with single nozzle, the cutting force measurements showed that the cutting forces decreased as 4.1%, 3.9%, and 3.5% and the feed forces decreased as 3.5%, 7%, and 10% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively when the flow rate increased from 26 ml/h to 52 ml/h.

Regarding to the effects of aerosol flow rate on the cutting force components in MQL milling with double nozzles, the cutting forces decreased as 2.1%, 1.5%, and 1.7% whereas the feed forces reduced by 10.4%, 9.6%, and 11.6% at the cutting speeds of 200 m/min, 250 m/min, and 300 m/min, respectively when the flow rate increased from 26 ml/h to 52 ml/h.

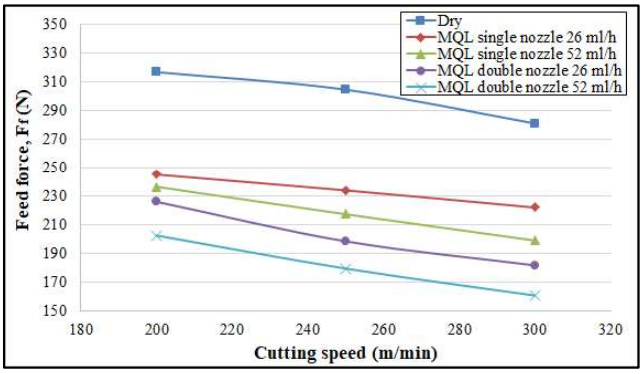


Fig. 4. *Variation of feed forces with cutting conditions*

4. Conclusion

In this experimental study, the effects of cutting conditions on the cutting force components and surface roughness were investigated in milling of Aluminum 6061. In experiments, three

different cutting speeds were selected while the depth of cut and feed rate were kept constant. Depending on the surface roughness and cutting force measurements, the conclusions could be expressed as follows;

- MQL milling gave lower surface roughness values than the dry cutting.
- In MQL milling, the increment of aerosol flow rate caused a reduction on surface roughness values.
- It was observed that lower surface roughness values were obtained by applying same total flow rate through double nozzles instead of single nozzle.
- The cutting force and feed force values were lower in MQL milling than those in dry cutting.
- In MQL milling, the cutting forces and feed forces decreased with increase of aerosol flow rate.
- Lower cutting forces and feed forces were observed by utilizing same total flow rate through double nozzles instead of single nozzle in MQL milling.

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