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Experimental Investigation of Minimum Quantity Lubrication (MQL) as a Sustainable Cooling Technique

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Abstract

The use of mineral based cutting fluid in machining process induces negative effects especially to the environment, operator's health and the machining cost itself. In sustainable machining concept, the introduction of coolant techniques such as near-dry machining so called minimum quantity lubrication (MQL) and cryogenic coolant have shown promising performances especially in terms of cutting tool life. Nowadays, MQL is widely used in machining performances. This paper attempts to show the experimental results of using MQL based synthetic ester as the cutting fluid. Experimental investigations were carried out using orthogonal cutting process in which the efficiency of MQL technique was compared to dry technique with respect to cutting temperature, cutting force, tool-chip contact length and chip thickness. The experimental results showed that the application of MQL based synthetic ester as the cutting fluid was more efficient for the machining process as it reduced the cutting temperature, cutting force, tool-chip contact length and produced better chip thickness compared to dry machining technique.

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Keywords: Minimum Quantity Lubrication, Orthogonal Cutting, Near Dry Machining, Sustainable Manufacturing

1. Introduction

Sustainable manufacturing is defined as a creation of manufacturer products that uses a process which are economically sounds, minimizes the negative environmental impacts, conserves energy and natural resources ensuring the safety of the employees, communities and consumers.[1]. Nowadays, the sustainable manufacturing is needed in manufacturing industry to ensure the manufacturing process will become more sustainable, which in turn, increases the social, economic and environmental benefits [2].

There are many branches in sustainable manufacturing and one of them is sustainable machining. Sustainable machining is a process which helps to improve environmental friendliness, reducing machining cost, power consumption, and wastes. It would also lead to a more effective waste management, enhances operational safety and improves personal health. One of the concerns in sustainable machining process is associated with the application of mineral based cutting fluid. The metal working fluid (MWF) is used as a coolant and lubricant in machining process. There are various kinds of MWF, which include oil, oil-water emulsions, aerosols (mists) gels, pastes, air and other gases. Usually, the oil-water emulsions MWF are widely used in the machining industries. The microbial growth from MWF emulsions of oil and water creates environmental and occupational health problems. In order to overcome this problem, biocide is used as an additive to control the microbial growth. Additives are also being used to control the forming of foam and corrosion from the metals and other organic constituents that become entrained in the fluids during use. This setback requires MWF maintenance system that is expensive, energy consuming and leads to typical problem of degradation and disposal [3].

The sustainable machining has introduced various condition of machining which are dry machining, near dry machining so called minimum quantity lubrication (MQL) and cryogenic machining. In recent years, there are many

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researchers that have been doing researches about MQL technique. It was reported that the average cutting temperature could be reduced by 5-10% compared to dry machining [4]. Tool wear or tool life can also be improved by four fold with the use of MQL as the cutting fluid compared to dry machining [5]. The use of synthetic ester as optimal lubricant for MQL machining has been proven to produce better cutting performance than using vegetable oil and mineral oil [6,7].

The present work deals with experimental investigations of the efficiency of MQL as a sustainable machining cutting fluid compared to dry technique with respect to cutting temperature, cutting force, and chip thickness.

2. Experimental Setup

The experimental works were carried out by using an orthogonal cutting condition. AISI 1045 which is highly utilized in the manufacturing industry had been chosen as the work piece. The work piece was prepared in diameter and thickness of 150 mm and 2 mm respectively. The machining was carried out using NC lathe machine. The uncoated carbide insert was selected as the cutting tool. The machining was carried out with three levels of cutting speeds and feed rates on each coolant conditions which is dry machining and MQL technique. Table 1 shows the orthogonal cutting and MQL conditions.

Table 1 : Experimental condition

Experimental Condition	**Description**
Parameter	Cutting Speed, V_c (m/min) = 350, 450, 550 Feed Rate, F_r (mm/rev) = 0.08, 0.10, 0.12 Width of cut, d (mm) = 2
Coolant Condition	Dry, MQL
Cutting Insert	Uncoated Carbide , rake angle = 5º
MQL Parameter	Pressure = 0.2 MPa Nozzle distance = 4mm Nozzle angle = 45° Lubricant = Synthetic Ester

Kristler 9257 dynamometer was used to measure the cutting force. It was connected to the multichannel amplifier and the computer installed with Dynoware software to record the cutting force data.

The cutting temperature was measured close to the cutting zone using FLIR thermal imager. The surface of the work piece was assumed as a grey body where the emissivity was set as a constant value. Ten samples of chip from every experiment were collected and its thickness was measured using a tapered micrometre. The results of average chip thickness values from ten samples were recorded. The tool maker microscope was used to measure the tool-chip contact length. The difference between sliding and sticking zone was distinguished and the overall tool-chip contact length was measured. Figure 1 shows the full experimental setup for the machining process.

A 3D Dual Phase Doppler Anemometry (PDA) measurement was performed to determine the size of mist particles from the MQL. It was equipped with a transmitter, receiver, signal processor and a water-cooled argon-ion laser. The raw data from the PDA measurements were then exported to the Dantec software for further analysis. The result shows that the average droplet diameter of the mist was in the range of 35 µm to 45 µm.

In addition, four ball tests were carried out to determine the coefficient of friction for the synthetic ester. The measurement was according to the ASTM D4172. The applied force for the lever arm was set at 392N. The motor was driven at the speed of 1200 rpm with the test duration of 60 minutes. The temperature was maintained at 75^{o}C. It was observed that the coefficient of friction for the synthetic ester was approximately 0.08.

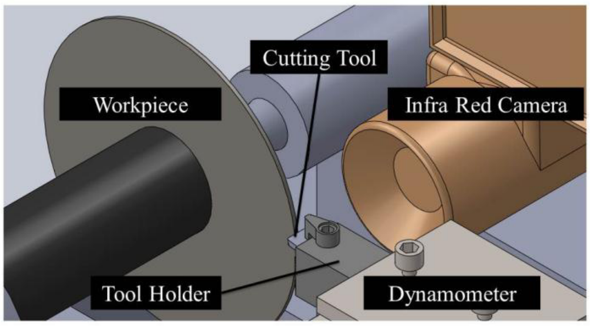

Figure 1 : Machine setup

3. Results and Discussion

3.1 Cutting temperature

The cutting temperature on the cutting zone was measured using FLIR thermal imager using temperature ranging from 0^{o}C to 1000^{o}C. Figure 2 shows the variation of the cutting temperature obtained at various cutting speeds and feed rates. It was observed that the cutting temperature increased as the feed rate and cutting speed increased. It was notable that higher cutting speed recorded the highest cutting temperature for both dry and MQL conditions. It was due to the increasing friction between work piece and tool insert. In addition, the feed rate played a significant role in the variation of cutting temperature. As the feed rate increased from 0.08 mm/rev to 0.12 mm/rev, the recorded value of cutting temperature increased for both dry and MQL conditions. It was expected that the required energy at higher feed rate would be greater subsequently accelerates the cutting temperature.

The use of MQL as a cutting fluid reduces the cutting temperature approximately 10% – 30% compared to the dry condition. The mixture of compressed air and lubricant from MQL facilitates the process by removing the heat efficiently. The mist of synthetic ester produced from MQL penetrates the cutting zone easily due to the tiny particles with high velocity. From the PDA analysis, the range of the particles size is recorded to be between 35 µm to 45 µm. From this result, it was found that tiny particles flowing at higher velocity will penetrate into the cutting zone more efficiently.

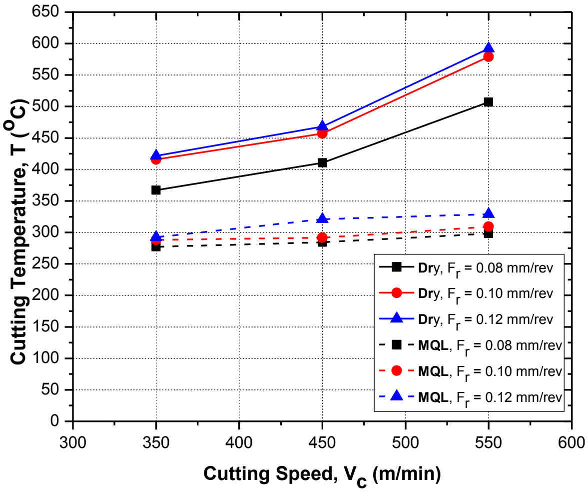

Figure 2 : Cutting temperature in different machining environments

3.2 Cutting force

Figure 3 shows the variation of cutting force at different cutting speeds, feed rates and machining conditions. It was observed that the cutting force increased as the feed rate increased. This was due to the increasing of tool-chip contact length which increased the chip load. By increasing the cutting speed from 350 m/min to 550 m/min, the cutting force was slightly decreased due to the reduction of removed material per revolution.

The cutting force was decreased approximately by 5% to 28% by using MQL technique. The lubrication effects from the synthetic ester assisted the cutting process to become smoother. From the four ball test analysis, it was observed that the measured coefficient of friction of synthetic ester was 0.08. This means that the contact between the tool-chip interface was smooth resulting in lower cutting force for the machining process. The application of lubricant was believed to reduce the friction coefficient between the tool–chip interfaces [8].

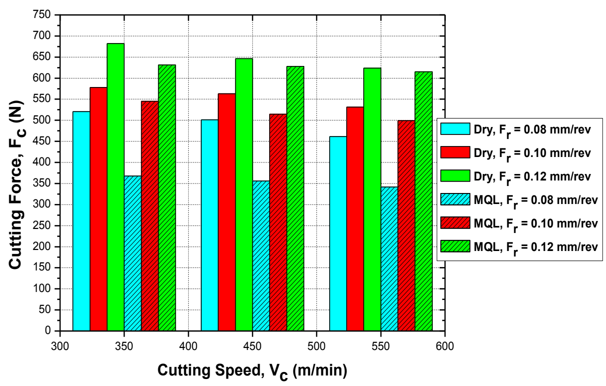

Figure 3 : Cutting force in different machining environments

3.3 Chip thickness

The major factors in chip breakability are chip shapes and sizes [9]. Figure 4 and Table 2 show the thickness of chips obtained in machining process at different cutting speeds and feed rates measured by using precision micrometre. It was observed that the feed rate significantly influenced the variation of thickness. It was noted that the chip thickness considerably increased due to increasing tool-chip contact length. It was also observed that at higher speeds the chip thickness decreased. This was due to decreasing material removed per revolution and decreasing tool-chip contact length.

MQL technique produced thinner chips compared to the dry condition. It could be observed that the cutting temperature under the MQL condition was lower than the dry condition. It reduced the adhesion and friction between the tool and chip efficiently thus reduced the chip thickness. The chips under MQL condition were 3% to 9% thinner than dry condition.

Table 2 : Chip thickness value

Cutting Speed (m/min)	Feed Rate (mm/rev)	Chip Thickness (mm) Dry	MQL
350	0.08	0.3043	0.2915
	0.10	0.3456	0.3346
	0.12	0.4023	0.3831
450	0.08	0.2897	0.2648
	0.10	0.3322	0.3212
	0.12	0.3545	0.3337
550	0.08	0.2643	0.2372
	0.10	0.3108	0.2898
	0.12	0.3398	0.3098

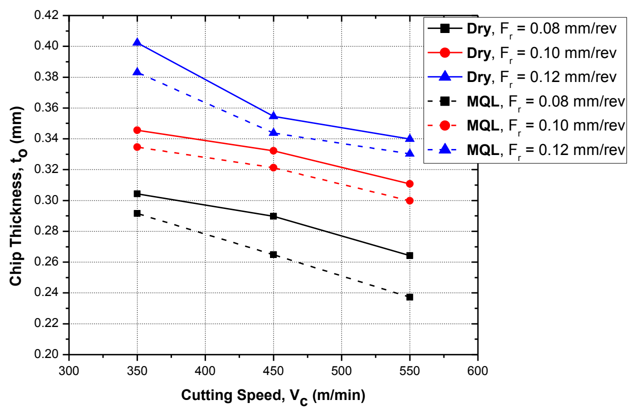

Figure 4 : Chip thickness in different machining environments

3.4 Tool-chip contact length

Figure 5 shows the variation tool-chip contact length at various cutting speeds, feed rates and machining conditions. It was observed that as the cutting speed increased, the tool-chip contact length was decreased. This was due to the decrease of removal material per revolution. Furthermore, the tool-chip contact length was increased as the feed rate increased.

Figure 6 shows the comparison of tool-chip contact length between MQL and dry condition. Under the MQL condition, the tool-chip contact length was decreased down to 12% compared to dry condition. This is due to the cooling effect from air constituent in the aerosol flow and the effectiveness of lubrication. In addition, it could be correlated with the low coefficient of friction value of synthetic ester which improved the machinability.

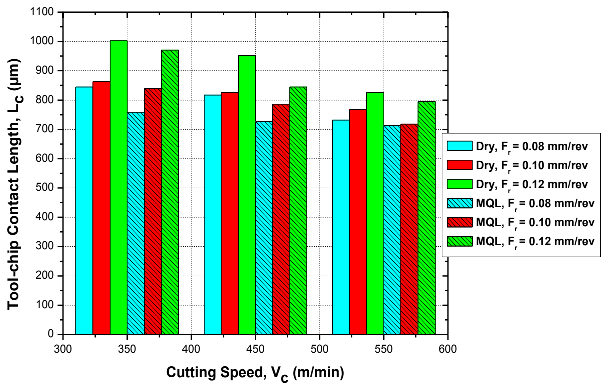

Figure 5 : Tool-chip contact length in different machining condition

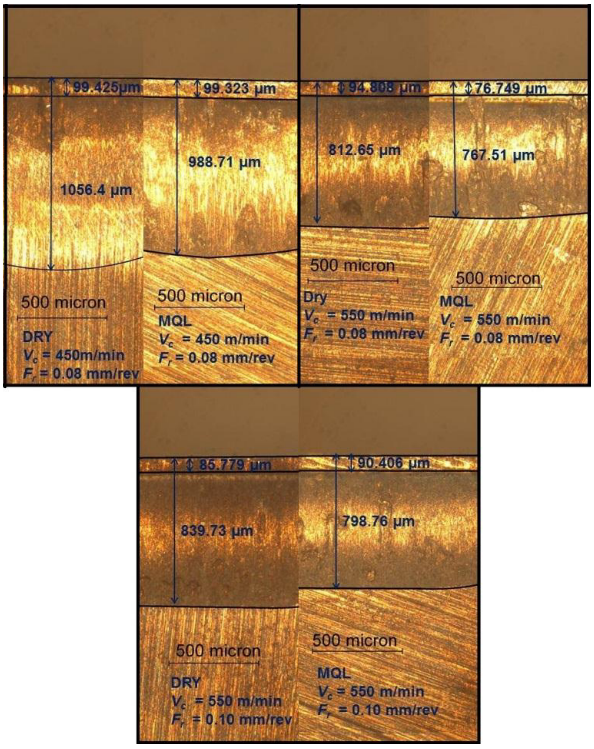

Figure 6 : Comparison tool-chip contact length between MQL and dry condition in different feed rate and cutting speed

4. Conclusion

The MQL was used as a cutting fluid for machining process and the major conclusions and the results can be summarized as follows:

i. The cutting temperature was reduced 10% to 30% for the MQL condition compared to dry condition. The reduction of temperature improved the tool life thus contributes to the sustainable manufacturing.
ii. Cutting force was reduced by 5% to 28% for the MQL condition compared to dry condition. This was due to the low coefficient of friction and smaller particle size that penetrates into the cutting zone.
iii. MQL machining technique was found to be more superior than dry condition. This phenomena can be correlates with the result of four ball test and PDA.

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