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Experimental Investigation of Supercritical Carbon Dioxide ($SCCO_2$) Performance as a Sustainable Cooling Technique

E. A. Rahim[1,a], A. A. Rahim[1,b], M. R. Ibrahim[1,c], Z. Mohid[1,d]*

[1]*Advanced Machining Research Group, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 BatuPahat, Johor, Malaysia*

[a]erween@uthm.edu.my, [b]azizul.azdwan@yahoo.com, [c]rasidi@uthm.edu.my, [d]zazuli@uthm.edu.my

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 coolant techniques such as minimum quantity lubrication (MQL) and cryogenic coolant have shown promising performances especially in terms of cutting temperature and cutting force. Nowadays, the supercritical carbon dioxide has a potential to replace the mineral based cutting fluid. In this paper, the experiment were carried out using orthogonal cutting process in which the efficiency of $SCCO_2$ technique was compared to MQL technique with respect to cutting temperature, cutting force, chip thickness and tool-chip contact length. The experimental results showed that the application of $SCCO_2$ as the cutting fluid was more efficient for the machining process as it reduced the cutting temperature, cutting force, chip thickness, tool-chip contact length and specific energy compared to MQL machining technique.

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Keywords : Minimum Quantity Lubrication; Supercritical Carbon Dioxide; Orthogonal Cutting; Sustainable Manufacturing;

1. Introduction

In machining process, the cutting temperature and cutting force produced is an important parameter need to be control or reduce. The cutting temperature and cutting force will effected the tool life thus effected the tool cost. Metalworking fluids are essential coolants and lubricants used in material removal and deformation processes to improve manufacturing productivity by increasing process throughput and tool life. MWFs are ubiquitous in the machine tool industry, with estimates of world-wide annual consumption to be in the billions of liters [1]. There are various kinds of MWF, which include oil, oil-water emulsions, aerosols (mists) gels, pastes, air and other gases.

Nowadays, 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 of the coolant [2].

The sustainable manufacturing process has introduced various condition of machining to resolve the MWF problem which is dry machining, near dry machining also known as minimum quantity lubrication and cryogenic machining. 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 [3].

Dry machining process is a metal removing process does not involve the use of any cutting fluids and this will cause a very high cutting temperature was produced. Dry machining can eliminate of harmful from cutting fluid due to no cutting fluid using in this technique but this technique will reduce the tool life compare to the other technique effect from high cutting temperature produced [4]. Near dry machining also known as

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minimum quantity lubrication (MQL) supplied a very small particle of lubricant to the cutting zone by using compressed air. MQL technique also can reduce and eliminate of harmful from cutting fluid but this technique cannot reduce the cutting temperature effectively due to low heat transfer, especially in cutting operation that experience thermal problems [5]. The cryogenic machining is a machining process with using liquid nitrogen (LN_2) as coolant for tools and material. This technique is effectively in reducing cutting temperature and maintaining the cutting temperature of cutting tool and material due to the high heat transfer from the LN_2. However, this technique has less lubricating ability due to no lubricant used in this technique [6].

There are attempts to replace the current technique to the new technique that can improve the machining performance while emphasizing the sustainable manufacturing. The supercritical carbon dioxide has seen as potential to replace the mineral based cutting fluid and be a one of the sustainable cutting fluid. The carbon dioxide is a non-toxic gas and has excellent solubility with vegetable oils above its critical point (critical temperature = 31.2 ◦C, critical pressure = 7.38 MPa) [7]. Carbon dioxide also is a cheaper gas compare to nitrogen and easily available. $SCCO_2$ is widely used in dry cleaning process because this gas is environmentally friendly solvent. In food industries, the $SCCO_2$ is used as a solvent to remove caffeine from coffee bean. A very high thermal efficiency has led the nuclear plant to using $SCCO_2$ as a reactor coolant.

The rapid expansion of supercritical solutions for coating and spraying applications has been well-documented. The rapidly propagating mechanical perturbation resulting from the rapid expansion of $SCCO_2$ and oil produces a homogenous and finely dispersed spray of dry ice and frozen oil particles a few microns in size [8]. These rapidly expanding solutions of $SCCO_2$ can reach temperatures below –80°C with a uniform coating of the solubilized material forming on the spray target [9]. As a result it can be hypothesized that $SCCO_2$ as MWF sprays can provide sufficient heat removal and lubrication to replace conventional MWFs in a greater variety of machining operations than MQL or LN_2. $SCCO_2$ can dissolve lubricants unlike high pressure nitrogen or argon, while leading to colder sprays with higher heat removal potential and efficacy [10]. The Life Cycle Assessment (LCA) model has been develop and the results shows the $SCCO_2$-based MQL is better with respect to aquatic toxicity, solid waste, land use, non-renewable energy, and acidification since this system uses low amounts of oil. Air-based MQL using rapeseed oil is better with respect to global warming potential (GWP), by a magnitude that is largely driven by allocation assumptions about the use of CO_2 as a MWF. Water use is also higher in the $SCCO_2$ system than the air-based system but this use is quite small compared to water-based MWF systems [11].

There still lacking of research on $SCCO_2$ has used as a machining cutting fluids because this alternative is on early stage. In this paper, the experimental investigations of the efficiency of $SCCO_2$ as a machining cutting fluid compared to MQL technique with respect to cutting temperature, cutting force, tool chip contact length, chip thickness and specific energy.

2. Experimental Setup

The custom built system as shown in figure 1 has designed and developed to change the carbon dioxide phase from gas phase to supercritical fluid phase. The carbon dioxide is compressed and heated up to critical point of carbon dioxide (critical temperature = 31.2 ◦C, critical pressure = 7.38 MPa) to change the phase of carbon dioxide to supercritical carbon dioxide. The lubricant supplied has mixed with $SCCO_2$ inside this system and the flow rate of $SCCO_2$ and lubricant has controlled by metering valve before the mixed $SCCO_2$ and lubricants has used as a cutting fluids.

The experimental works were carried out with orthogonal cutting condition by using NC lathe machine. AISI 1045 medium carbon steel which is highly used 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. Uncoated carbide insert was selected as the cutting tool. Three levels of cutting speeds and feed rates on each coolant conditions which is $SCCO_2$ cooling technique and MQL technique had been choose to running this experiment. Table 1 shows the orthogonal cutting parameter, MQL and $SCCO_2$ conditions.

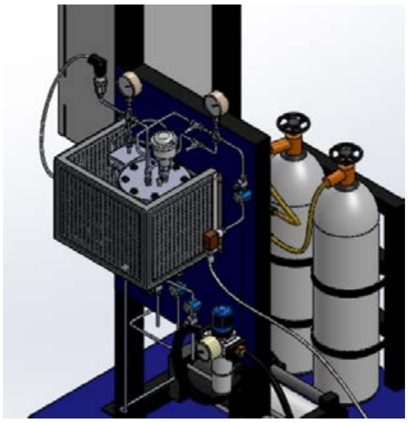

Fig. 1 : Supercritical carbon dioxide cooling system

The cutting force has measured by using Kristler 9257 dynamometer. It was connected to the multichannel amplifier and the computer installed with Dynoware software to record the cutting force data. The average force measured during the machining has taken as cutting force. The maximum cutting temperature was measured close to the cutting zone by using FLIR thermal imager with temperature ranging from 100 ºC to 650 ºC. 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 2 shows the full experimental setup for the machining process. The specific energy has calculated by using equation 1.

$$U = (Fc \times Vc) \div (Vc \times ti \times w) \ldots\ldots\ldots (1)$$

Table 1 : Experimental condition

Experimental Condition	Description
Machining 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	MQL, $SCCO_2$
Cutting Insert	Uncoated Carbide , rake angle = 5°
MQL Parameter	Pressure = 0.4 MPa Nozzle distance = 8 mm Nozzle angle = 45° Lubricant = Synthetic Ester Lubricant flow rate = 0.16 l/hr
$SCCO_2$ Parameter	Chamber pressure = 10.34 MPa Nozzle distance = 8 mm Nozzle angle = 45° Lubricant = Synthetic Ester Lubricant flow rate = 2.61 l/hr

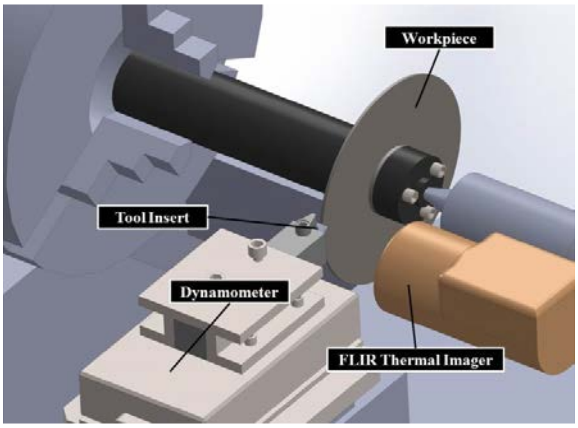

Fig. 2 : Experimental setup

3. Results and Discussion

3.1 Cutting Force, F_c

Figure 3 shows the variation of cutting force at different cutting speeds, feed rates and cooling condition. It was observed that the cutting force increased as the feed rate increased 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 14% by using $SCCO_2$ technique. The mixed $SCCO_2$ and lubricant assisted the cutting process to become smoother. The solubility of synthetic ester with $SCCO_2$ is very well. The mist of synthetic ester lubricates the tool-chip interfaces. From the four ball test analysis, it was observed that the measured coefficient of friction of synthetic ester was below 0.08 [12,13]. This means that the contact between the tool-chip interfaces 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.

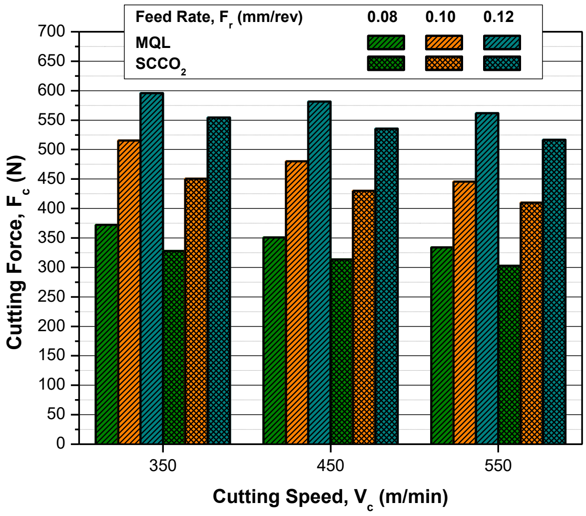

Fig. 3 : Cutting force in different type of cooling condition

3.2 Chip Thickness, t_o

The major factors in chip breakability are chip shapes and sizes [14]. Figure 4 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 and the shear angle. 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. The thickness of the chip will affects the cutting force during the machining.

$SCCO_2$ technique produced thinner chips compared to the MQL condition. The chips under $SCCO_2$ condition were 0.5% to 2.5% thinner than MQL condition. It could be observed that the cutting force under the $SCCO_2$ condition was lower than the MQL condition because the shear angle produced during machining on $SCCO_2$ condition is greater than MQL condition. It reduced the adhesion and friction between the tool and chip efficiently thus reduced the chip thickness and cutting force.

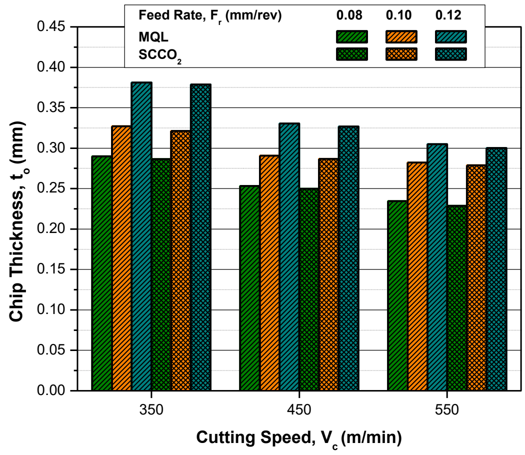

Fig. 4 : Chip thickness in different type of cooling condition

3.3 Tool Chip Contact Length, L_c

Figure 5 shows the variation tool-chip contact length between MQL and $SCCO_2$ condition 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 due to increasing of removal material per revolution. The tool chip contact length can be control by setting the feed rate and cutting speed. However, the material removal per revolution would effect and indirectly will effects the production time.

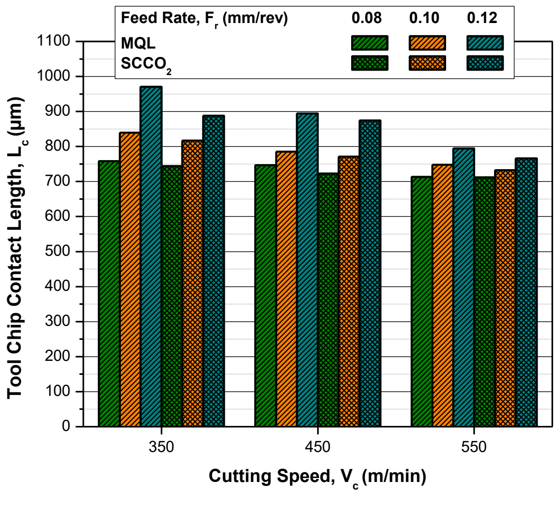

Fig. 5 : Tool chip contact length in different type of cooling condition

Under the $SCCO_2$ condition, the tool-chip contact length was decreased 1% to 10% compared to MQL condition under same cutting speed and feed rate. The mixture of $SCCO_2$ and lubricant reduce the coefficient of friction in cutting zone more effectively compare to MQL condition. Decreasing coefficient of friction can reduce the tool-chip contact length and indirectly can reduce the cutting force. The cutting force can be reduce without effecting the production time by applying $SCCO_2$ during machining as a cutting fluids.

3.4 Cutting Temperature, T

Figure 6 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 MQL and $SCCO_2$ 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 MQL and $SCCO_2$ conditions. It was expected that the required energy at higher feed rate would be greater subsequently accelerates the cutting temperature.

The use of $SCCO_2$ as a cutting fluid reduces the cutting temperature approximately 15% to 30% compared to the MQL condition. The very low temperature (less than - 70ºC) produce from $SCCO_2$ removing the heat efficiently. The mixture between $SCCO_2$ with lubricant (synthetic ester) also can reduce the cutting temperature by lubricate the tool-chip interfaces. The spray of $SCCO_2$ and synthetic ester penetrates to the cutting zone easily due to the tiny particles with high velocity. The size of the particle can affected the effectiveness of the lubricant penetrate to the cutting zone where the tiny particle more easily penetrate to the tool chip interface and reduce the temperature compare to the bigger particle such as on flood coolant condition. The lubricant particles transported to the rake face faster than the chemical reaction between the chip and lubricant.

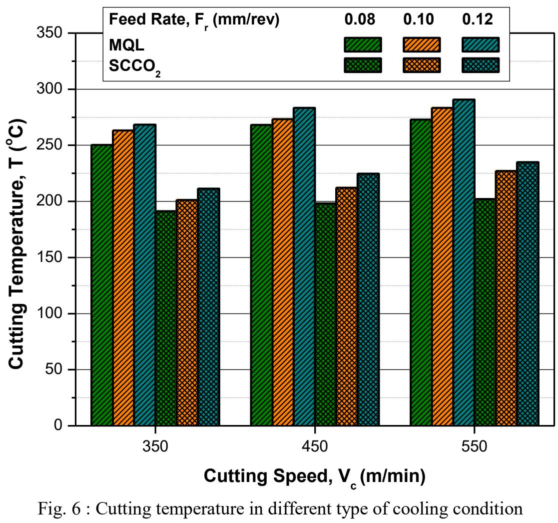

Fig. 6 : Cutting temperature in different type of cooling condition

3.5 Specific Energy, U

The variations specific energy results on figure 7 shows the specific energy obtained at various cutting speed, feed rate and different cutting condition. The increasing of cutting speed from 350 m/min to 550 m/min has reducing the specific energy during the machining. Increasing cutting speed will decreasing tool chip contact length as shown on figure 5 thus reducing the cutting force and cutting power and directly reduce the specific energy. As the feed rate increasing from 0.08 mm/rev to 0.12 mm/rev, the result of specific energy increase due to increasing of material removal per revolution during the machining.

The specific energy has reduced 20% to 30% under $SCCO_2$ condition compare to the MQL condition. The high velocity of the $SCCO_2$ spray has leads to high efficiency of lubricant and $SCCO_2$ particle to penetrate to the cutting zone thus reduced the cutting force and specific energy. The mixing of $SCCO_2$ with synthetic ester has seen as a high potential to become a sustainable cutting fluids due to reducing the specific energy.

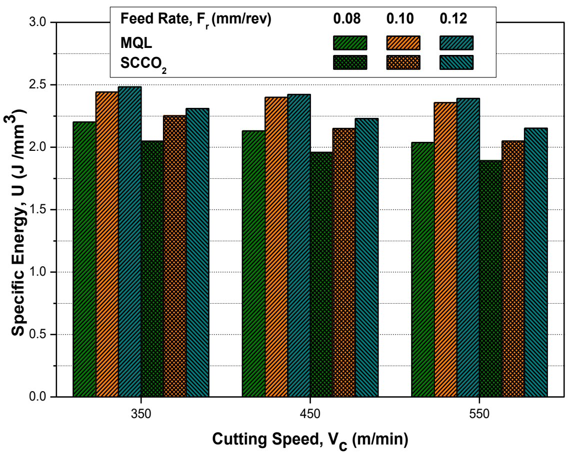

Fig. 7 : Specific energy in different type of cooling condition

4. Conclusion

The $SCCO_2$ 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 15% to 30% for the $SCCO_2$ condition compared to MQL condition. The reduction of temperature improved the tool life thus can reduce the production cost.

ii. Cutting force was reduced by 5% to 14% for the $SCCO_2$ condition compared to MQL condition. The reduction of cutting force reduced the specific energy thus reduce the production cost and become more economically.

iii. $SCCO_2$ machining technique was found to be more superior cutting fluids compare to MQL condition. The production cost can be reduce, environmentally friendly and no health effect to worker.

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