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PERFORMANCE OF TURNING OPERATION BY USING SUPERCRITICAL CARBON DIOXIDE ($SCCO_2$) AS A CUTTING FLUID

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ABSTRACT

The minimum quantity lubrication (MQL) machining is capable to reduce the machining cost and cutting fluid consumption, while enhancing machining performance. However, the performance of MQL technique to reduce the machining temperature is still ineffective. In recent study, the use of supercritical carbon dioxide ($SCCO_2$) cooling technique has seen to give a very high effectiveness. This technique can reduce the machining temperature and cutting force subsequently prolong the tool life and surface quality. In this paper, the performance of $SCCO_2$ as a cutting fluids has been compared with MQL technique. The results showed that the $SCCO_2$ cooling technique was more effectiveness in reduce the cutting force and cutting temperature thus improve the surface roughness compare to the MQL technique.

Keywords: supercritical carbon dioxide, turning operation, minimum quantity lubrication.

INTRODUCTION

The cutting temperature and cutting force produced during the machining processes is an important parameter needed to be controlled or reduced. This parameter affected the quality of surface roughness and tool life thus affected to the tool cost. To control or reduce the cutting temperature and cutting force, the metalworking fluids was used during machining process.
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 (Cheng *et al*., 2005). There are various kinds of MWF, which include oil, oil-water emulsions, aerosols (mists) gels, pastes, air and other gases.

The oil-water emulsions MWF are widely used in the machining industries. This oil-water emulsion MWF requires frequently maintenance that is expensive, energy consuming and leads to typical problem of degradation and disposal of the coolant (Clarens *et al*., 2006). The microbial growth on oil-water emulsion MWF also creates environmental and occupational health problems. Near dry machining has introduced as sustainable MWF to overcome this problem. Near dry machining also known as minimum quantity lubrication supplied a very small fine lubricants particle to the cutting zone by using compressed air. MQL technique can reduce and eliminate of harmful from oil-water emulsions MWF but this technique cannot reduce the cutting temperature effectively due to low heat transfer, especially in cutting operations that experience thermal problems (Rahim and Sasahara, 2011).

There are attempts to replace the existing technique to the new technique that can improve the machining performance while emphasizing the sustainable manufacturing. The application on liquid nitrogen (LN_2) at -196°C to the cutting zone during the machining process, known as cryogenic machining, is effective in reducing the cutting temperature and maintaining the temperature of cutting tool (Vans and Bryan, 1991). Liquid nitrogen evaporates harmlessly into the air, and no residual oil left on the chip. However, this is an energy-dissipating technique. The price of LN_2 is expensive and needs proper procedures to use as the cutting fluid. It was reported that the LN_2 only reacts as a cooling, mostly dominated at lower cutting velocity because of more effective penetration at the tool-chip interface (Dhar *et al*., 2002).

The $SCCO_2$ has seen as potential to replace the mineral based cutting fluid and be a one of the sustainable cutting fluid. It 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) (Hyatt, 1984). Carbon dioxide 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 rapidly disseminating mechanical disruptions 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 (Tom and Debenedetti, 1991). 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. $SCCO_2$ also leading to colder sprays with higher heat removal potential and efficacy (Supekar *et al*., 2012). There still lacking of research on the application of $SCCO_2$ as a machining cutting fluids. In this paper, the efficiency of $SCCO_2$ at various input chamber pressure and nozzle distance was evaluated and compared with MQL

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technique with respect to cutting temperature, cutting force and surface roughness

EXPERIMENTAL SETUP

The custom system has been designed and developed to exchange 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 into supercritical carbon dioxide. The supplied lubricant was mixed with $SCCO_2$ inside the mixing chamber. The flow rate of $SCCO_2$ and lubricant were controlled by the metering valves before they were released via the nozzle.

The experimental works were carried out under the turning operation using NC lathe machine. AISI 1045 which is highly used in the manufacturing industry had been chosen as the workpiece. The workpiece was prepared in diameter and length of 100 mm and 100 mm respectively. Uncoated carbide insert was selected as the cutting tool. Table-1 shows the machining parameters, MQL and $SCCO_2$ conditions.

The cutting force was measured by using Kristler 9257 dynamometer. It was connected to the multichannel amplifier and software data logger to record the cutting force data. The maximum cutting temperature was measured close to the cutting zone by using FLIR thermal imager with temperature. The surface roughness tester has used to measured the R_a value. The R_a value has taken in 4 difference line with total measuring length is 4 mm. Figure-1 shows the full experimental setup for the machining process.

Table-1. Experiment condition.

Experimental Condition	Description
Machining Parameter	V_c (m/min) = 350 F_r (mm/rev) = 0.12 *doc* (mm) = 1
Cutting Insert	Uncoated Carbide , rake angle = 5°
MQL Parameter	Pressure = 0.4 MPa Nozzle distance = 8 mm Nozzle angle = 45° Lubricant = Synthetic Ester
$SCCO_2$ Parameter	Chamber pressure = 7.58, 8.96, 10.34 MPa Nozzle distance = 8, 22, 36, 50 mm Nozzle angle = 45° Condition = With lubricant, without lubricant Lubricant = Synthetic Ester

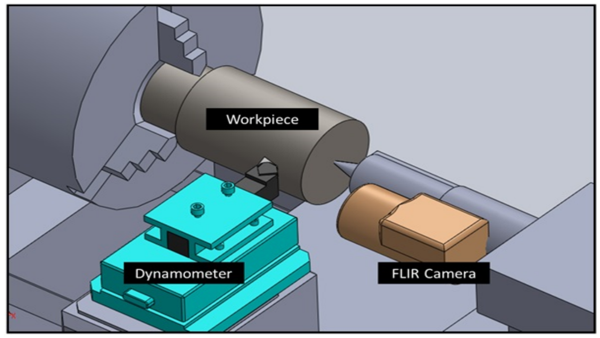

Figure-1. Experimental setup.

RESULTS AND DISCUSSION

Cutting temperature, *T*

Figure-2 shows the cutting temperature at various nozzle distance, $SCCO_2$ pressure chamber comparison between MQL technique and $SCCO_2$ technique. The result shows the cutting temperature produce by using $SCCO_2$ as cutting fluids is reduced 6% - 30% compare to the MQL technique. The rapid expansion process on $SCCO_2$ produced a very low temperature (-80 °C) and has increased the heat transfer rate between $SCCO_2$ and cutting zone. It was observed that the cutting temperature reduces with increasing the pressure inside the chamber from 7.58 MPa to 10.34 MPa.

The different pressure inside the chamber effects the rapid expansion process where the higher pressure inside the chamber was produced the lowers expansion temperature thus effects the heat transfer rate. The concentration of focus length in the $SCCO_2$ spray also significantly affects $SCCO_2$ and lubricants penetrated into the tool-chip interface. The distance of nozzle has affected the efficiency of $SCCO_2$ to penetrate and reduced the cutting temperature in cutting zone during the machining. The 8 mm nozzle distance has recorded the lowest cutting temperature compare to others nozzle distance. The $SCCO_2$ without lubricant produce lower cutting temperature compared to the $SCCO_2$ with lubricant. This is due to the lower cooling efficiency when the $SCCO_2$ has mixed with lubricant.

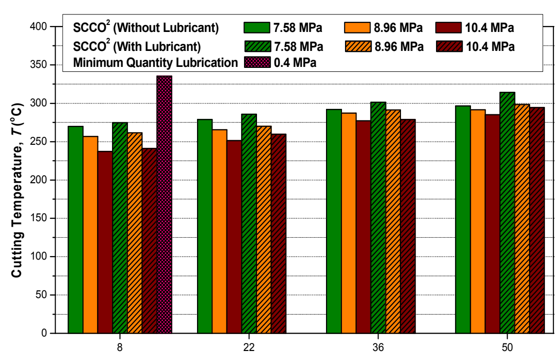

Figure-2. Cutting temperature at various conditions.

Cutting force, F_c

The cutting force in Figure-3 shows the significant results between $SCCO_2$ mixed with lubricant and $SCCO_2$ without lubricant. Furthermore, the use of $SCCO_2$ with lubricant as cutting fluid reducing the amount of cutting force approximately 5 to 17% compare to MQL condition. The mixture of $SCCO_2$ and lubricant increase the machinability of AISI 1045. The formation of 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 (Rahim *et al*., 2015) (Talib and Rahim, 2015).

This means that the contact between the tool-chip interfaces was lubricated by synthetic ester resulting in lower cutting force. Application of lubricant reduce the friction coefficient between the tool– chip interfaces.

The $SCCO_2$ without lubricant has show the cutting force produce during the machining is higher than MQL condition. This is due to the dry ice produce during the rapid expansion of $SCCO_2$ has reduce the machinability of the material. The cutting force was increases when the nozzle distance was increased. The efficiency of lubricant to penetrate to the cutting zone was decrease when the nozzle distance increased thus effects the cutting force.

$SCCO_2$ without lubricant condition has recorded the different results trend compare to $SCCO_2$ with lubricant. Increasing of nozzle distance was decreasing the cutting force due to the dry ice produce during the rapid expansion process has melt before its entering the cutting zone. Increasing the chamber pressure was decreasing the cutting force. The velocity of lubricant particle was increase when chamber pressure increased and has affected the penetration efficiency of lubricant and $SCCO_2$.

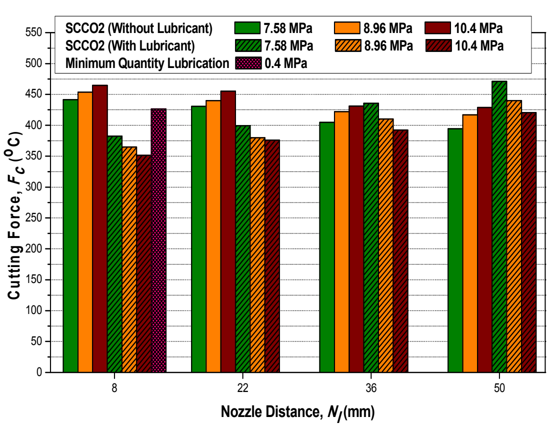

Figure-3. Cutting force at various conditions.

Surface roughness, R_a

Figure-4 show the surface roughness of the AISI 1045 material after the machining process. The observation shows the surface roughness results is similar with cutting force results trend in figure-3. The relationship between cutting force and surface roughness can be make where the higher cutting force produce higher R_a that's mean rough surface roughness compare to the lower cutting force was produces the lower R_a value.

The lubrication was increase the machinability of materials and reduce the force thus the better surface roughness was produces. The higher pressure from $SCCO_2$ also removing the chip produced during machining that distracting the surface roughness result.

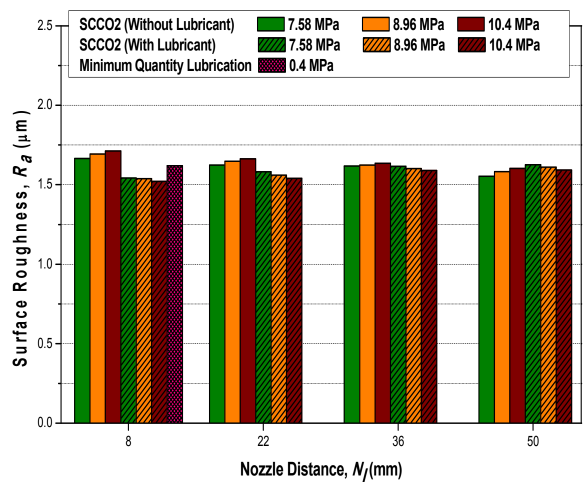

Figure-4. Surface roughness at various conditions.

CONCLUSIONS

The $SCCO_2$ was used as a cutting fluid for machining process and the major conclusions can be summarized as follows:

- The cutting temperature was reduced 6 to 30% for the $SCCO_2$ condition compared to MQL condition. The reduction of temperature can be able to improve the tool life thus reduce on tool budget.
- Cutting force was reduced by 5 to 17% for the $SCCO_2$ with lubricant condition compared to MQL condition. The reduction of cutting force was increase the surface roughness quality.
- The $SCCO_2$ technique has improve the surface quality by 5% compare with MQL technique. By using $SCCO_2$ technique, the finishing work can be minimize.

$SCCO_2$ with lubricant condition was better than MQL condition and $SCCO_2$ without lubricant condition. The production cost can be reduce, environmentally friendly and no health effect to worker.

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