A Study on Cryogenic Supercritical Carbon Dioxide Coolant Delivery Technique when Machining of AISI 1045 Steel

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ABSTRACT

The machining operation involves a material removal process and develop high temperature due to the friction force. The heat generated at the region of cutting edge has critical influences on machining process. It can increase cutting tool wear, reduce tool life, get rise to thermal deformation and might consequence to microcracks. The application of cutting fluid at the cutting zone by conventional process could overcomes the aforementioned problems to some extent via cooling and lubrication process. However, the waste of cutting fluid might be profuse and its impact on the environment. A new efficient process, cryogenic cooling using carbon dioxide gas (CO_2) has been introduced on improving the cooling process. This technique is more economical in coolant usage while maintaining significant performance including cutting temperature, cutting force and surface roughness. The pulse mode of CO_2 cooling spray under supercritical state has been used to corroborate the machining process by reducing the cutting zone temperature as to reducing coolant usage.

Keywords: *Cryogenic cooling, Carbon dioxide, Turning, Sustainable machining.*

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Introduction

Huge demands for the manufacturing industry means the manufacturer has to double up their production, while maintaining the quality of the product at the same time. The challenge for the manufacturer is to increase the productivity and lowering the cost of operation. In the context of machining, to increase the productivity means higher value of cutting parameter is used. The higher value of cutting parameters will increase the machining energy, subsequently increases the cutting temperature. The temperature increment during machining will affect the surface finish and tool life of the cutting tool. The most major issue in machining process is the usage of petroleum based cutting fluid. Despite of it benefits, increases cutting tool life, better product quality and good chip evacuation, it drawbacks diminishing the overall manufacturing process especially to the impact to the environment [1]. Therefore, it is essential to seek for an alternative coolant-lubricant techniques to preserve the environment.

Environmental concern has become a motivating factor in developing of a products. Growing level of environmental awareness by the consumers contributed to the eco-friendly product. The sustainable machining process has introduced various condition of machining to resolve the cutting fluid problem which is dry machining, near dry machining also known as minimum quantity lubrication and cryogenic machining.

There is no application of lubricant or coolant in dry machining. This process generates very high of cutting temperature, subsequently reduces the cutting tool life. However, dry machining process poses its benefit which could be able to eliminate of harmful from cutting fluid. Near dry machining supplies a tiny particle of lubricant to the cutting zone by the aid of compressed air. This technique reduces and eliminates the harmful from the cutting fluid. However, it insignificant in reducing the cutting temperature effectively due to low heat transfer.

In machining process, cryogenic cooling technique shows a promising performance and addressed the benefits towards the environment impact. There are many types of cryogenic gasses such as helium, hydrogen, neon, nitrogen, oxygen, argon and etc. The advantages of the gasses use of this cooling technique are low temperature, colourless, non-toxic and readily vaporizes into a gas [2]. Cryogenic machining using liquid nitrogen effectively reduces the cutting temperature due to the high heat transfer from the gas itself. However, it shows a drawback, whereby there is less lubricating ability. Supercritical carbon dioxide ($SCCO_2$) cooling technique is one of cryogenic cooling category. It is one of an essential coolant in machining process that could minimize the generation of cutting temperature.

Carbon dioxide is an environmental benign natural working fluid, thus could solve the aforementioned problem. The systems operated using carbon dioxide provides many advantages compared to the systems that operate with other working fluids. Carbon dioxide is inexpensive and abundant in the nature. Compared with other natural working fluids, it is more chemically stable and reliable. Further, due to its relatively high working pressure, the carbon dioxide system is more compact than the system operating with other working fluids. Supercritical fluids exist at a temperature and pressure which are equal to or greater than the critical temperature and pressure of the fluid, that is 31.2^{o}C and 7.38 MPa respectively. Sprays of $SCCO_2$ are function to cool and lubricate machining processes by spraying a mixture of dry ice mix with lubricant into the cutting zone [3]. At this level, carbon dioxide has properties between liquid and gas with lower surface tension than the water. $SCCO_2$ coolant providing a better results in machining performance in terms of cutting temperature, cutting force, surface quality and tool life compared to minimum quality lubrication (MQL) and dry machining technique.

When the production of the machining industry is increasing, the machinability will rise and the usage of carbon dioxide increases. The increase of carbon dioxide usage during the machinability will surge the cost to operate [4]. High consumption of $SCCO_2$ occurs due to the opening of the metering valve was set at fully open (100% open). The metering valve opening parameters can be applied to analyze which combination of opening has the best effect during machinability. Furthermore, through the alteration of the metering valve opening, the consumption of $SCCO_2$ for a machining process can be reduced. According to Rahim and his co-workers [4], the pulse spray mode is beneficial to reduce the gas consumption without subside its machining performance. At the same time, the $SCCO_2$ sprayed with lubricant was better than MQL condition [5]. It was also reported that $SCCO_2$ significantly reduced the production cost, environmentally friendly and no harm to the worker [6].

$SCCO_2$ has been used as a working fluid in many applications such as on refrigerators, heat pumps and power production. Moreover, research efforts have focused on the rapid expansion of supercritical conditions, especially in coating and cleaning applications. At supercritical condition, the gas was rapidly expanding and recording the temperature of less than –80°C [7]. It also permit the oil to easily penetrate into the machining zone due to the reduction of surface tension of the vegetable oil [8]. In this paper, the performance of $SCCO_2$ on delivering a good surface quality through reducing the cutting temperature in the different condition of pulse spray mode will be investigated. A research study in pulse spray mode could show the optimum consumption of $SCCO_2$ cooling rate that leads to an economic benefit and the overall manufacturing costs. Throughout this work, subsequent reduction of cutting temperature and cutting forces are the main focus of this study.

Experimental Setup

The AISI 1045 medium carbon steel was used as the working material with a diameter of 100 mm. It was turned on a Alpha 400 NC lathe machine with the capability of 6000 rpm maximum spindle speed. The experimental tests were carried out once for every parameters. Cemented carbide insert was used as a cutting tool with chip breaker and 14° of negative rake angle. For the cryogenic cooling delivery setup, a set of metering valve and flexible tubing was connected to the carbon dioxide (CO_2) chamber. The compressed gas flows via a nozzle that pointing to the cutting zone. In addition, a synthetic ester which reacts as a lubricant, mixed with the CO_2 gas in the mixing chamber. Meaning that, the lubricant was flew together with the CO_2 gas in a form of mist spray. The cutting parameters of the experiment have been considered and the presented in Table 1.

The cutting parameters such as input chamber pressure (P_c), cutting speed (V_c), feed rate (f_r) and depth of cut (d) were fixed to be constant. These experiments were conducted to collect the data and analyzing a relationship between different machining parameters through various setting of pulse spray modes which are cutting force, cutting temperature and tool life.

During the experimental tests, the cutting temperature was measured by using FLIR thermal infrared camera which was position at the length of approximately 30 cm to the cutting zone. The maximum cutting temperature was determined at the steady state area based from cutting force data evaluation. The maximum cutting temperature was determined by plotting a box measurement at the cutting zone as shown in Figure 1. Meanwhile, the cutting force was measured by using Kistler dynamometer where the data was processed via data acquisition card and displaying the results on a computer. The dynamometer was mounted on the bed of the lathe machine and connected to the multichannel charge amplifier, Kistler 5070 by R232 cable. The means of cutting force (F_c) reading was recorded in the z-axis direction at the steady state. Figure 2 shows the machining experimental setup for turning operation.

Nikon MM-60 tool maker microscope, installed with Image Pro 6.0 software was used to measure tool wear at the flank surface. Both flank wear and notch wear are the predominant wears that are measured. Further, the tool wear and tool life criteria was used ISO 3685 as the reference standard. The cutting tool is rejected and further machining was stopped based on or a combination of the following criteria of cemented carbide tool as shown in Table 2. The Mitutoyo Surface Roughness Tester (SJ-400) was utilized to measure the arithmetical mean deviation of the profile, R_a. The measurement procedure used ISO4288:1996 as the reference standard. The total measurement length and cut off length of 4 mm and 0.8 mm, respectively were utilized.

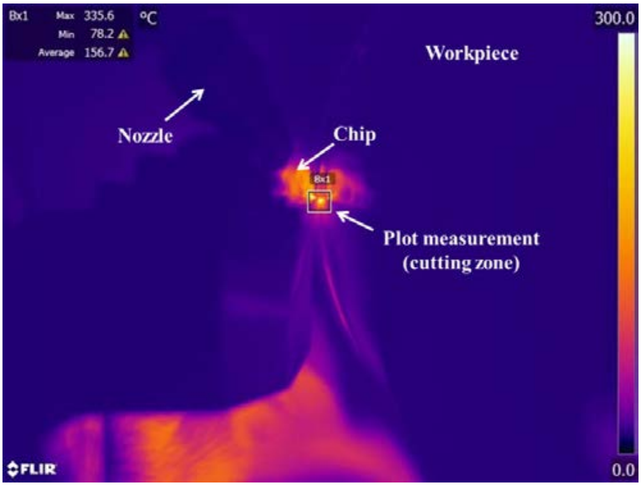


Figure 1: Generation of heat capture using thermal infrared camera.

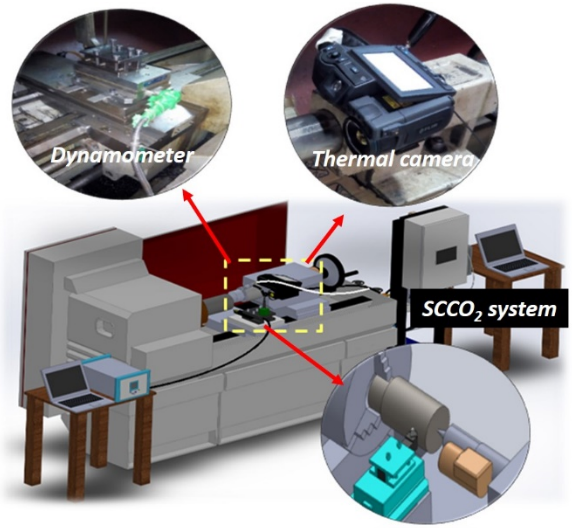


Figure 2: Machining experimental setup.

Table 1: Machining parameters.

Cutting parameter	Values
Cutting speed, V_c (m/min)	350
Feed rate, f_r (mm/rev)	0.08
Depth of cut, d (mm)	2
$SCCO_2$ parameter	**Values**
Input chamber pressure, P_c (MPa)	10.4
Pulse mode (Spray On : Spray Off) (centiseconds)	70:30, 50:50, 30:70
Nozzle distance (mm)	8
Nozzle diameter (mm)	1.8

Table 2: Tool wear criteria.

Type of wear	Value
Average flank wear, VB_B	$\geq$ 0.3 mm
Maximum flank wear, $VB_{B\,max}$	$\geq$ 0.6 mm
Maximum notch wear, VB_N	$\geq$ 0.6 mm
Catastrophic failure	-

Results and Discussion

Cutting force

Figure 3 presents the result of cutting forces under various spray modes at the constant input chamber, P_c of 10.4 MPa. It can be observed that continuous flow of CO_2 spraying, the cutting forces is slightly lower than the other controlled pulse spray modes. It shows a reduction of approximately 3.7%, 6.5% and 9.3% compared to the pulse spray modes of 70:30, 50:50 and 30:70, respectively. Among pulse spray modes, 30:70 recorded the highest cutting force, 5.5% higher than 70:30. Shorter Spray On time of 30:70 significantly reduces the gas-lubricant flow rate, hence increases the cutting force. In contrary, longer Spray On time of 70:30 recorded low cutting force value. Varying the pulse mode system is subjected to control the quantity of lubricant-gas flowing and penetrating to the cutting zone. Therefore, it affects to the lubricity on the metal sliding surfaces.

At shorter Spray On time, the friction at the tool-chip interface was consequently increased. The value of cutting force increases as the friction was increased. The increase in the coefficient of friction is attributed to the higher cutting force during the machining process [9]. It is also notable that the workpiece is experienced with the rapid changes of cutting temperature.

The workpiece surface was hardened due to the increment of workpiece temperature and undergo rapid cooling when the CO_2 gas was sprayed during the machining process. As a result, the hardness of workpiece material increases, hence boosting the cutting force value. It was also observed in other research that the $SCCO_2$ technique had significantly reduced the cutting force up to 14% when compared to MQL technique [6].

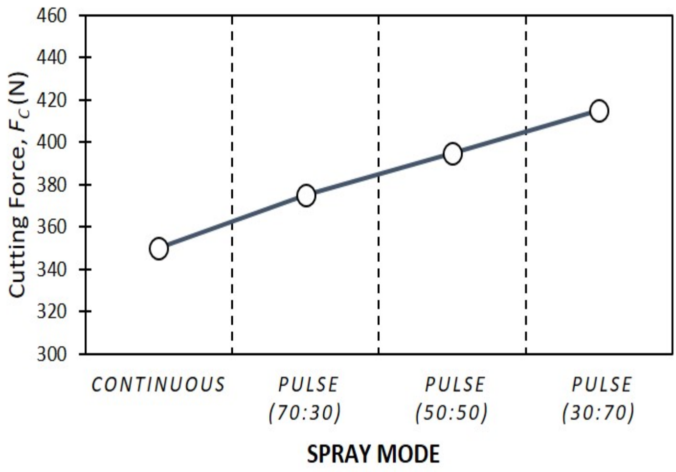


Figure 3: Cutting force under various pulse spray mode and fixed chamber pressure (P_c).

Cutting temperature

Cutting temperature is the primary factor that affects the cutting tool wear and promotes thermal damage to the machined surface. During machining process, the heat is generated at the primary, secondary and tertiary deformation zone. The generation of heat is due plastic deformation process and friction between the cutting tool and workpiece. These processes produce an energy and converted it into the heat.

Figure 4 shows the result of cutting temperature at various spraying modes. It can be observed that continuous spray mode, the cutting temperature is lower than the other controlled pulse spray modes. It shows a reduction of approximately 35%, 46% and 48% compared to the pulse spray modes of 70:30, 50:50 and 30:70, respectively. Notably, 30:70 recorded the highest cutting temperature, 9% higher than 70:30.

It was observed that, the shorter condition of pulse spray mode or shorter Spray On (30:70) explaining the smallest quantity of coolant flow rate than the other spray mode conditions. The longer time of Spray On mode means permitting more lubricant-gas flow rate. It can be suggested that, sufficient amount of lubricant-gas mixed in the cryogenic cooling system significantly reduces the damage impact between the tool surface and the workpiece. The longer the Spray On mode, significantly increases the flow rate of the lubricant-gas. This explained that the higher cooling capacity of the cutting fluid on lubricating and cooling the cutting zone. The higher quantity of lubricant-gas flow rate reduces the cutting temperature, thus improving the convection and heat transfer rate [4].

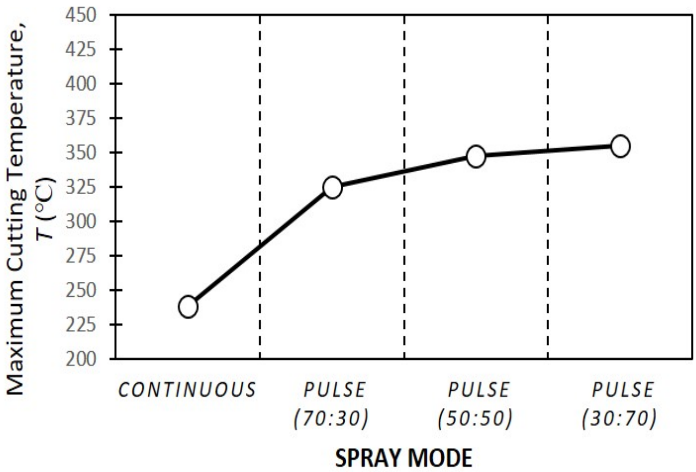
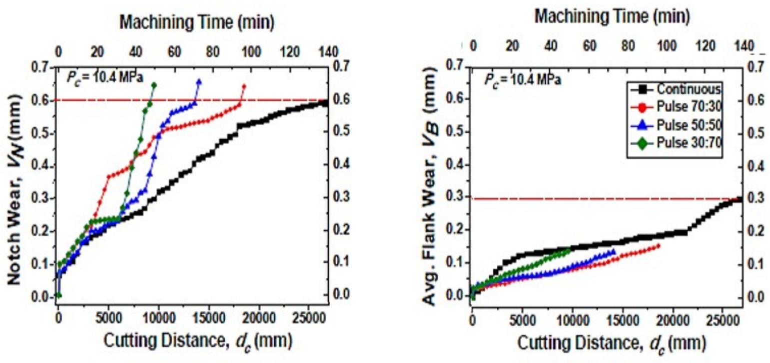


Figure 4: Cutting temperature under various pulse spray mode and fixed chamber pressure (P_c).

Tool life

Figure 5 shows the progression of tool wear, in terms of machining time and distance under the various types of the lubricant-gas conditions. Meanwhile, Figures 6 and 7 show the progression of cutting tool wear at the end of its life. It is noticeable in Figure 5 that the progression of tool wear was gradually increased with the decrease in the duration of Spray On. Most of the cutting tools suffered from flank wear ($VB_{B\ max}$) or notch wear (VB_N). The progression of cutting tool wear rate is related to the growth of cutting temperature and friction during the machining process. Interestingly, VB_N was shown as the dominant tool failure mode under all lubricant-gas condition.



(a) (b)

Figure 5: Result of (a) notch wear and (b) flank wear, under various pulse spray mode and fixed chamber pressure (P_c).

Continuous spray mode recorded the longest cutting tool life, with the machining distance and time of 26,650 mm and 133.25 minutes, respectively. It recorded a significant improvement of 192% when compared with the pulse mode of 30:70. This was attributed to the fact that more lubricant-gas was delivered to the machining zone, thus contributed to a superior lubricating and cooling efficiency. When comparing on the pulse mode conditions, it shows that 70:30 modes outperformed other modes in terms of cutting tool life. This phenomena can also be correlated with the result of cutting force and temperature. It can be assumed that, more quantity of lubricant-gas was supplied to the cutting zone, subsequently reduces the cutting force and temperature. As a result, the cutting tool wear rate reduces and significantly prolonging the cutting tool life.

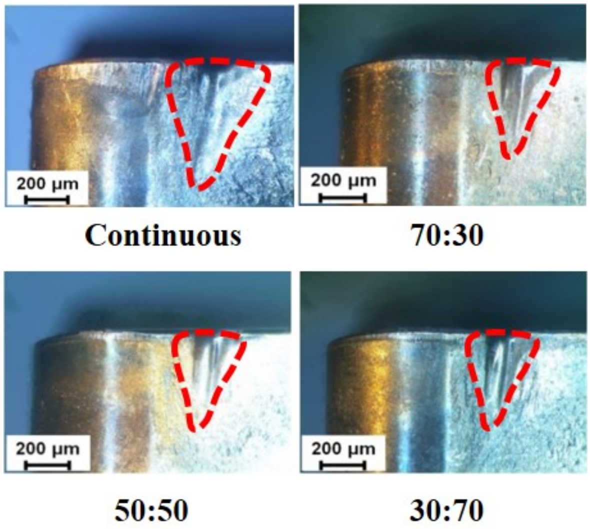


Figure 6: Notch wear at various conditions.

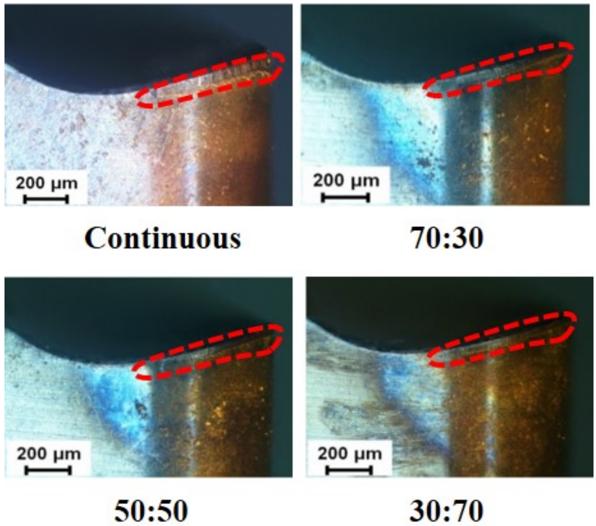


Figure 7: Flank wear at various conditions.

Surface Roughness

Figure 8 presents the result of surface roughness value under the various types of the lubricant-gas conditions. It can be observed that the continuous spray recorded the lowest value of 1.52 µm. It shows a reduction of approximately 7.2%, 3.3% and 1.3% compared to the pulse spray modes of 70:30, 50:50 and 30:70, respectively. Interestingly, at the pulse mode condition of 30:70, the smoother surface was obtained compared to other pulse mode conditions. Meaning that, better surface can be obtained at two conditions, continuous and pulse mode of 30:70. At continuous condition, the workpiece surface was cooled rapidly, hence contributed to the formation of brittle uncut surface during the machining process. As a result, better surface finish was obtained. Meanwhile, it can be assumed that near dry machining was performed under the 30:70 condition, whereby the lubricant-gas was supplied intermittently. Therefore, it contributed to higher generation of heat, subsequently softening the workpiece surface. It makes the cutting tool easily to cut the workpiece, thus improve the surface roughness value. It was reported that the value of surface roughness is lower by using $SCCO_2$ than MQL technique [5].

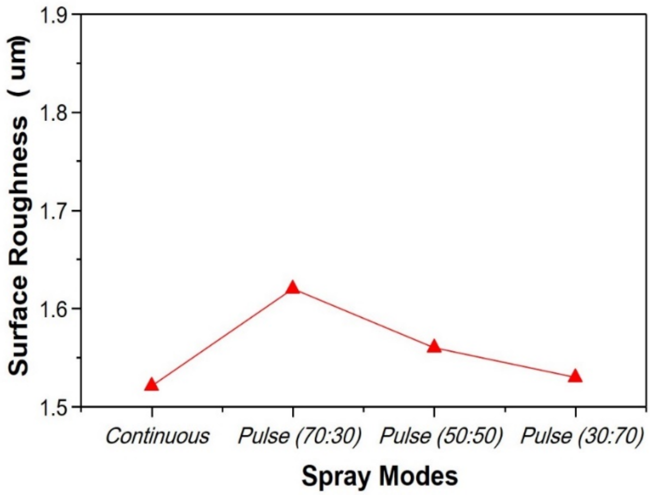


Figure 8: Surface roughness at various conditions.

Conclusions

At the end of this study, the effectiveness of SCCO2 cooling technique with different pulse mode conditions was successfully evaluated. From the value of cutting temperature, cutting force, tool wear and surface roughness, these conclusions were obtained.

i. The application of pulse mode in $SCCO_2$ cooling technique is suggested as a good solution for cutting lubricant consumption reduction. The longest Spray On mode of 70:30 at the input chamber pressure of 10.4 MPa depicts good comparable results to the continuous spray mode especially in reducing the cutting force, temperature and improving the tool life due to their good volumetric flow rate and cooling effect.
ii. The value of cutting force was drastically reduced when applying continuous spray mode. To reduce the consumption of lubricant-gas, 70:30 mode is applicable.
iii. Continuous spray mode significantly reduces the cutting temperature, thus prolonging the cutting tool life. However, spray mode of 30:70 exhibited very poor performance with a high cutting temperature.
iv. The surface quality obtained after the cutting processes with continuous spray mode indicates the lowest roughness value and comparable to the nearly dry machining technique shown by the shortest Spray On" mode of 30:70. However, all the other surface qualities are within the acceptable range of good surface finish below than 2μm.
v. The performance of $SCCO_2$ under continuous spray recorded the highest tool life when compare to other spray mode conditions. In order to meet the requirement of sustainable machining, whereby the minimization of waste becomes a major concern, then the application of 70:30 mode is recommended.

Acknowledgments

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