Performance Evaluation of Sustainable Coolant Techniques on Burnishing Process

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Abstract. Cryogenic coolant in machining is very significant effects on the surface quality. Flood coolant in existing finishing processes and lubricant techniques give the less effectiveness performance to machine tool, temperature and surface integrity. Cryogenic coolant significantly affects the mechanical properties of material by changing the microstructure under heat treatment. Dry condition trust force higher cryogenic condition was more effective in order to decrease the thrust force compared with dry and MQL conditions. Parameters to be evaluate are burnishing force, surface roughness and temperature using burnishing process with diameter 12mm of tool radius 1mm and 2mm. The application of cryogenic condition in burnishing process reduces the amount of thrust force against dry condition and MQL conditions. Cryogenic condition recorded the lowest average thrust reduction compared to dry and MQL, respectively. The reduction of thrust force reduces the force of kinetic friction at the tool and workpiece interfaces.

Keywords: sustainable, coolant technique, burnishing, performance

1. Introduction

Burnishing process is one of popular topic in recent advanced manufacturing studies. It is involved between input and output parameters. To be competitiveness, performing and continuous improvement in machining processes are really needed. Machining processes should be more efficient to deal with high quality product, cost saving in productions, and an environmentally friendly. El-Khabeery and El-Axir [1] studied on the effect of roller-burnishing on the surface roughness, surface micro-hardness and residual stress of Aluminium Alloy 6061-T6. Experimental work successfully on a lathe activity to establish the effect of burnishing speed, depth of penetration, burnishing time and the initial hardness. Shiou and Chen [2] studied the ball burnishing surface finish process on the surface plastic injection mold using machining center. The parameters experiment such as ball material, burnishing speed, burnishing force, and feed, were selected as the factors of Taguchi’s design of experiment (DOE) to proof the optimal burnishing parameters that have an influence on surface roughness. Revankar et al. [3] investigated the internal machined and burnished by an internal ball burnishing tool. The experimental work to establish the effect of burnishing parameters such as burnishing speed, feed rate, depth of penetration and number of passes. The improvement on surface micro hardness in aluminium alloy (Ti–6Al–4V) is very significant.

Korzynski [4] studied the eccentric ball burnishing or eccentric burnishing. It’s very easy method to hold oil or coolant pockets in slide bearing sleeve surfaces. It can be applied on lathe machines with a
very simple, and easy. Further research or experiment should determine an optimum pattern of post machining to encountered tribological kinematic pairs in eccentric burnishing. Electrical Discharge Machining (EDM) with ball burnishing, Yan et al. [5] investigated and studies of improving surface integrity with combining the process of electrical discharge machining (EDM) and ball burnishing using the Taguchi method. Three values of parameter, such as material removal rate, surface roughness, and improvement ratio of surface roughness are selected. The results indicate that the combined process effectively improves the surface roughness, micro pores and cracks.

The new hybrid method of burnishing process is laser assisted ball burnishing, Tian et al. [6] was proposed to studies and investigated experimentally. The workpiece surface layer is temporarily and locally softened by a controllable laser beam, and then immediately processed by a conventional burnishing tool. From these experiments it’s found that LAB can produce much good surface finish, surface hardness, and similar compressive residual stress compared to conventional burnishing process. Preve [7] studied about Low plasticity burnishing (LPB). Since LPB processing was tested in a machining process the cost effective and practically and improving the structural integrity of aging aircraft (alloy substitution). Sasahara et al. [8] in their experiment work focus on to develop frictional stir burnishing and to prove and reduce the number of machining processes.

Generally, burnishing process operates under dry condition, means not using any lubricant. As mentioned by Supekar et al. [9] cryogenic machining controls the detrimental effect of thermal softening on the machined workpiece, thus increases the hardness throughout the burnished layer depth. Conventional flood cooling technique carries away some heat but liquid nitrogen in cryogenic cooling is much more superior to dissipating the heat. Cryogenic burnishing is the most effective method of increasing surface hardness due to the strong cooling effect of liquid nitrogen. Conventionally, flood coolant is a popular technique but contributes to the substandard impacts to the environment, health, and economy. Alternatively, was introduced and exhibited outstanding performance, which secured the environmental issues and human health for the next generation in green manufacturing. The main objective of these technique is to minimize or the used of fooled coolant. These alternative is based on the cryogenic assisted concept. This cooling technique consists on applying cryogenic gases just on the contact zone to reduce temperature. Cryogenic cooling is considered as a clean, safe and environmental friendly technology. Liquid nitrogen (LN2) and carbon dioxide (CO2) are the most used cryogenic fluids. Normally by comparing cryogenic cooling with dry and minimum quantity lubrications (MQL).

Minimum quantity lubrication (MQL) technique is a misting with a very small quantity of lubricant, the flow rate of 50 to 500 ml/hour, in an air flow directed towards the contact zone. The external supply system is sprayed the lubricant using one or more nozzles. The quantities of coolant used in MQL around 3-4 lower than the amount of used in flood cooling. Rahim et al. [10] reported that MQL is “near-dry machining” or “spatter lubrication”. MQL is consider the latest technique of delivering fluids to the point of contact zone.

High production machining is having high strength and heat resistant materials; it is associated with the generation of a large amount of heat. From this issue, the common cooling techniques such as dry condition and flood coolant give the less effectiveness performance to machine tool, generation of heat and surface integrity. Therefore, in this study is to evaluate the burnishing performance by comparing different cooling techniques in term of burnishing force, temperature and surface roughness.

2. Experimental setup
In this study, the workpiece made from carbon steel (SS400) was undergoing burnishing process by using Frictional Stir Burnishing process as shown in Figure 1. The process was performed on the computer numerical control (CNC) vertical machining center. The workpiece was mounted on the piezoelectric force sensor dynamometer (Kistler Dynamometer 9254) as shown in Figure 2. Signals from the dynamometer were transferred and translated by using multichannel amplifier 5070A. Cylindrical tungsten carbide tool (grade K10) with a diameter and corner radius of 12 mm and 1 mm respectively, was attached to the burnishing tool holder. Spring with a stiffness value of 157 N/m was
installed in the tool shank assembly and its preload can be controlled in the tool shank. The burnishing tool moves and rotates on the workpiece surface. The setup of experimental and burnishing process parameter as shown in Figure 2, Table 1 and Table 2. A K-type thermocouple (Nickel-Chromium) and FLIR thermal imager camera were used to measure the workpiece and tool surface temperature, respectively.

Starting from the edge of the workpiece, the thermocouple wire was embedded into the hole at locations 36.8 mm and 85.8 mm. The distance of endpoint thermocouple and the top surface of workpiece approximately 0.03 mm as shown in Figure 3. Conductive epoxy and silver substance were used to further increase the sensitivity and accuracy of the thermocouple. All the eight-channel amplifier triggered and recorded the electric signal from the thermocouple wire and subsequently transferred into the DEWESOFT software for acquiring the data.

The surface roughness of the workpiece after burnishing process was measured using surface roughness tester (Mitutoyo SJ-400), according to JIS1994. The arithmetical average roughness, Ra value was measured at three sections on the burnished surface. The cut-off length, \( \lambda_c \) and evaluation length, \( l_n \) was set at 0.8mm and 4 mm, respectively. Various cooling techniques such as dry, MQL, and supercritical carbon dioxide (SCCO\(_2\)) + MQL.

![Figure 1. Frictional Stir Burnishing (FSB)](image-url)
Figure 2. Experimental set up for burnishing process

Figure 3. Endpoint thermocouple and the top surface.

Table 1. Burnishing parameters.

| Parameters                        | Value(s)                   |
|-----------------------------------|----------------------------|
| Spindle speed, (rpm)              | 10,000                     |
| Indentation force (N)             | 750                        |
| Number of tool passes             | 1                          |
| Feed rate (mm/min)                | 200                        |
| Burnishing tool material          | Carbide (Grade K10)        |
| Burnishing tool diameter (mm)     | 16                         |
| Corner radius of tool (mm)        | 1                          |
| Cooling Techniques                | Dry, MQL, SCCO₂ + MQL      |
| Workpiece material                | Carbon steel (SS400)       |
Table 2. Coolant parameters

| Cooling technique | Parameters       | Value(s)             |
|-------------------|------------------|----------------------|
| MQL               | Input pressure (MPa) | 0.4                  |
|                   | Nozzle distance (mm) | 8                    |
|                   | Nozzle angle (º)    | 45                   |
|                   | Lubricant type      | Synthetic Ester      |
|                   | Lubricant flow rate (1/hr) | 0.16              |
| SCCO$_2$ + MQL    | Input pressure (MPa) | 10.4                 |
|                   | Nozzle distance (mm) | 8                    |
|                   | Nozzle angle (º)    | 45                   |
|                   | Lubricant type      | Synthetic Ester      |
|                   | Lubricant flow rate (1/hr) | 2.61              |

3. Result and discussion

3.1. Thrust force

Figure 4 shows the result of average thrust force under various cooling techniques. It was observed that, the highest average thrust force was produced under dry burnishing condition. At this condition, it was recorded 2.9% and 6.5% higher than under MQL and SCCO$_2$ + MQL condition, respectively. Dry condition induces high friction during burnishing process thus increase the thrust force. Due to the higher friction and higher thrust force, it contributes to the higher energy consumption to the burnishing operation T. Mulyana et al. [11].

It was found that SCCO$_2$ + MQL condition was more effective in order to decrease the thrust force compared with dry and MQL conditions. The application of SCCO$_2$ + MQL condition in burnishing process reduces the amount of thrust force 6.1% and 3.4% against dry condition and MQL conditions, respectively. High input chamber pressure of 10.4 MPa used in this condition causes high lubricant flow rate and high cooling rate. The increased lubricant flow rate supplied the higher quantity of the lubricant penetrated towards the burnishing region, thus reduces the thrust force and energy. The mixing of SCCO$_2$ with MQL has observed as a high potential to become a sustainable coolant due to reducing the energy consumption.

Figure 4. Average thrust force under various cooling techniques
3.2. Surface roughness

Figure 5 shows the results of the average surface roughness, measured on the top of burnished surface under various cooling techniques. It was observed that the trend of result is similar to the result of average thrust force. It was found that SCCO$_2$ + MQL condition recorded the smoothest surface roughness when compared to other cooling conditions. It recorded a reduction of approximately 56.2% and 52.4% compared to dry and MQL conditions, respectively. The correlation between the value of thrust force and surface roughness can be expressed visually. The higher value of average thrust force tends to produce rougher burnished surface on the workpiece. Therefore, it was depicted that under SCCO$_2$ + MQL condition, the effectiveness of burnishing process is obvious in order to obtain smoother burnished surface. This is due to lubrication and cooling rate, thus reduced the thrust force and friction at the tool-workpiece interfaces. Zhang and Liu [12] found that burnishing effect induced by the roller ball in dry condition.

![Figure 5. Result of surface roughness under various cooling techniques](image-url)
Figure 6. Workpiece temperature under various cooling techniques

3.3. Temperature
Figures 6 and 7 show the result of the maximum workpiece and maximum tool surface temperature under various cooling techniques. It was found that the SCCO$_2$ + MQL condition recorded the lowest maximum temperature for both workpiece and tool surface compared with other conditions. For example, temperature at location 2 recorded 68.2% and 64.5% reduction against dry condition and MQL conditions, respectively. At the same condition and same location, it was found that maximum tool surface temperature was reduced 23% and 12.2% when compared to dry and MQL conditions. As mentioned, SCCO$_2$ + MQL condition shows higher cooling rate and higher lubricant flow rate compared to other conditions. It removes the heat efficiently due to the better cooling rate, thus lower the burnishing temperature. Furthermore, with higher lubricant flow rate can lubricate the tool-workpiece interfaces, significantly reduces the friction of burnishing process and the generation of heat. As reported by Rahim et al. [13], the temperature was much lower related to the sequence of energy dissipation in a cooling effect and lubricating effect within coolants. The high amount of small particles of lubricant from the SCCO$_2$ + MQL condition quickly reduced the friction between tool-workpiece interfaces hence reduce the heat generation.
4. Conclusion
This study is to evaluate the burnishing performance by comparing with various cooling techniques such as dry, MQL, and SCCO$_2$ + MQL conditions in term of thrust force, temperature and surface roughness. The major conclusion can be summarized as follows:

1. SCCO$_2$ + MQL condition recorded the lowest average thrust force which is 6.5% and 2.9% of reduction compared to dry and MQL, respectively. The reduction of thrust force reduces the force of kinetic friction at the tool and workpiece interfaces.

2. The SCCO$_2$ + MQL condition has improved its surface quality by 56.2% when compared with dry condition and 52.4% compared to MQL conditions.

3. The maximum temperature for both workpiece and tool surface under the SCCO$_2$ + MQL were reduced by 68.2% and 23% when compared to dry and MQL conditions, respectively. The reduction of temperature is due to the high cooling rate and high lubricant flow of SCCO$_2$ + MQL.

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