Effect of Burnishing Tool Diameter and Coolant Strategies on Burnishing Performance

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Abstract. A burnishing process is employed to improve the surface integrity of the component, especially for aerospace, medical, and nuclear industries. It requires proper cooling and lubricating techniques, usually flood cooling technique. However, this technique is harmful to the working environment. Therefore, this study introduces the application of minimal quantity lubrication (MQL) and cryogenic cooling using CO2 gas. Two burnishing tools made from carbide with a diameter of 10 mm and 16 mm were used to burnish a SS400 carbon steel. Dry burnishing condition is employed and its performance is compared with MQL and supercritical CO2+MQL (SCCO2) conditions. The result shows that the SCCO2+MQL outperformed dry and MQL in terms of burnishing force, temperature and surface roughness.

1. Introduction
The service life of a component is depends on its surface properties, thus effort to improve manufacturing processes are needed. For this reason, substantial consideration on post-machining operations is essential. Normally, conventional machining processes such as milling and turning produce irregular surfaces. Therefore, the finishing processes such as grinding, lapping, polishing and honing commonly being selected to improve the surface finish [1]. However, these methods are subjected to chip removal process and may cause surface abrasion and out-of-tolerance. New technique of surface finishing operation such as burnishing process was introduced to confine the anomalies and improves other surface properties such as surface hardness and surface roughness.

Surface modification process such as burnishing produces a smooth surface finish by the rotation of a burnishing tool. This process does not comprise the removal of chip from the workpiece. In this method, a large contact force is applied on the workpiece surface by a fine roller burnishing or a ball burnishing. This contact causes plastic deformation of surface irregularities. The high burnishing force, surpassing the yield strength, causes roughness peaks to flow toward the valleys, coat the texture of the rough surface, resulting in smoother surfaces [2]. As a result, peaks and depth of the valleys were reduced, thereby improving the surface roughness. In other case, burnishing process can becomes as a cold working process, due to the fact that the workpiece surface suffered to severe stress. If the value of
stress exceeds the yield strength, it promotes an occurrence of plastic flow from the surface irregularities into the valleys. As a consequence, surface roughness and residual stress were improved.

Low & Wong [3] stated that the surface roughness decreased slightly at low burnishing force on the polymer, due to incomplete deformation. However, as the burnishing force increases to 124 N, the surface roughness tends to be increased. As this force increased, the penetration of the burnishing ball on the workpiece surface became deeper, consequently increases the amount of asperities being deformed. Hassan & Al-Bsharat, [1] was conducted the experiment on burnishing force using different tool diameter. They reported that as the indentation force increases the 15 mm ball outperformed 10 mm ball in terms of its surface integrity. This is due to the increase of indentation pressure subjected by the high diameter of burnishing ball. At this condition, it enhancing the process of plastic deformation and improving the compressive residual stresses. Burnishing tools size and material significantly affects the surface finish of the burnished workpiece. The material of the tool should has higher hardness and toughness than the workpiece material. Takada & Sasahara [4] studied the friction stir burnishing process using four levels of burnishing tools tip radius and investigated their effect on surface roughness, hardness and residual stress of 0.45% C steel shaft. They summarized that the surface roughness is increased under the condition of a smaller tool tip radius. Meanwhile, the thickness of the hardened layer is increased as the tool tip radius was decreased. The residual stress on the processed surface was turned to compressive when a smaller tip radius tool was used, and tensile when using larger tip radius.

Burnishing process creates high heat due to the friction, thus diminish the burnishing tool shape. It causes dimensional deviation in the workpiece, premature failure of the tools and impairs the surface integrity of the product. Generally, these problems are controlled by using existing lubricant technique which is conventional lubricant such as flood lubricant. This method is not only ineffective to surface integrity, but also spoil the working environment by producing harmful working environment. Alternatively, minimal quantity lubrication (MQL) [5,6] and cryogenic cooling [7,8] during the machining and burnishing process. Therefore, this study is to evaluate the burnishing performance by comparing various cooling techniques and burnishing tool diameter in term of burnishing force, temperature and surface roughness.

2. Experimental Setup
Grade SS400 carbon steel was used as a workpiece material for burnishing process. The Frictional Stir Burnishing (FSB) tool assembly in figure 1 consists of a burnishing tool made from tungsten carbide grade K10. It is cylindrical shape with 1mm corner radius and is attached at the end of the tool top. A spring with value of stiffness 157 N/mm is inserted into the tool shank, and the spring preload can be controlled. The FSB tool is then mounted into the spindle of vertical machining center (MAZAK Nexus
410-A). It rotates and moves on the workpiece surface as shown in figure 2. The number of tool pass on the workpiece surface was set to one time for each condition. The workpiece was attached on the piezoelectric force sensor dynamometer (Kistler Dynamometer 9254). A multi-channel amplifier 5070 A was transferred and translate the signals that received from the dynamometer. The overall experimental setup and burnishing conditions are shown in figure 2 and table 1, respectively. The position of nozzle for MQL and SC CO₂ + MQL conditions is shown in figure 3. Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

Two types of temperature measurement, namely a FLIR thermal imager camera and an embedded thermocouple, were used to measure the temperature generation during the burnishing process. The thermal imager camera was used to record the temperature surrounding of the tool tip along the burnishing process. Meanwhile, K-Type thermocouple wire (Nickel-Chromium) was used to measure the temperature at the designated location during burnishing process. The wire was embedded into the hole at 36.75 mm and 85.75 mm starting from the edge of workpiece and fixed into place with the help of epoxy and silver substance as shown in figure 4. The silver substance was applied to further increase the sensitivity and accuracy within the thermocouple. The end point of thermocouple was placed as closed
as possible toward the workpiece surface approximately at 0.03 mm as shown in figure 4. The thermocouple wires were connected to the eight channels amplifier to trigger and record the electric signal. The DEWESOFT software was used to analyze the data that transferred from amplifier.

Surface roughness of workpiece was measured by using surface roughness tester (Mitutoyo SJ-400). Standard used is JIS1994 as a reference for this measurement. The position of measurement was divided into three sections as shown in the figure 5, in which the arithmetical average roughness, $Ra$ value was obtained and averaged. The cut-off length, $\lambda_c$ was set at 0.8mm and the evaluation length, $l_n$ is 4 mm according to DIN EN ISO 4288. The conditions for both MQL and SCCO$_2$ + MQL are shown in table 2.

Table 1. Burnishing process parameters.

| Parameters                              | Value(s)        |
|-----------------------------------------|-----------------|
| Spindle speed, $N$ (rpm)                | 10,000          |
| Indentation force, $F$ (N)              | 750             |
| No. of tool passes                      | 1               |
| Feed rate, $f_r$ (mm/min)               | 200             |
| Burnishing tool material                | Carbide (Grade K10) |
| Burnishing tool diameter, $d$ (mm)      | 10 and 16       |
| Cooling Techniques                      | Dry, MQL, SCCO$_2$ + MQL |
| Work piece material                     | Carbon steel (SS400) |

Table 2. MQL and SCCO$_2$+MQL parameters.

| Cooling technique | Parameter                  | Levels      |
|-------------------|----------------------------|-------------|
| MQL               | Input pressure, $P$ (MPa)  | 0.4         |
|                   | Nozzle distance, $N_d$ (mm)| 8           |
|                   | Lubricant type             | Synthetic Ester |
|                   | Lubricant flow rate, $Q$ (1/hr) | 0.16   |
| SCCO$_2$ + MQL    | Input chamber pressure, $P_c$ (MPa) | 10.4       |
|                   | Nozzle distance, $N_d$ (mm) | 8           |
|                   | Lubricant type             | Synthetic Ester |
|                   | Lubricant flow rate, $Q$ (1/hr) | 2.61       |

3. Result and discussion

3.1. Burnishing force

Figure 6 shows the results of average thrust force under various coolant-lubricant conditions and different burnishing tool diameter. The results showed that, dry burnishing cutting condition recorded the highest thrust force, compared to the other conditions. The thrust force value under the dry condition was 4% higher than that of MQL condition. This led to a higher value of friction during burnishing, thus increasing the cutting force. Generally, energy consumption in the burnishing operation was related with
friction and cutting force. Hence, it was more important to achieve a lower cutting force to enhance burnishing quality and reduce the production cost.

It was showed that, SCCO$_2$ + MQL is much more effective than dry and MQL conditions. For burnishing tool diameter of 10 mm, the cutting force for SCCO$_2$ + MQL was reduced by 5% relative to the MQL and 8.6% relative to the dry condition. The mixture of cryogenic gas and lubricant, which provides lubricating and cooling effect prone to reduce the burnishing force. The higher lubricant flow rate contributed to the higher quantity of lubricant being supplied towards the machining region. The application of lubricant reduced the friction coefficient between the tool and the workpiece [9,10]. As the lubricant was continuously supplied and penetrating towards the machining region, the reduced friction thus caused within the machining interface resulted in enhanced tool ability to withstand the extreme force and pressure during machining [8]. However, the lubricant diminished faster due to the amount of heat and extreme friction developed.

Meanwhile, for the result of different diameter of burnishing tool, 10 mm diameter showed the higher thrust force, compared to the 16 mm diameter. It was recorded that the diameter of 16 mm showed a reduction of thrust force by 33.7%, 34% and 40% against diameter of 10 mm in dry condition, MQL and SCCO$_2$ + MQL. This is according to the concept of pressure which is the pressure is inversely proportional to the area. The smaller diameter of burnishing tool which is has a small area of contact produced a higher pressure loading with a constant indentation force.

3.2. Burnishing temperature
Figure 7 (a) shows the graph of maximum workpiece temperature against various cooling techniques, measured by using thermocouple. It was observed at $d = 10$ mm and location 2, the SCCO$_2$ + MQL recorded the lowest maximum workpiece temperature compared to MQL and dry conditions. This condition recorded 34% and 35% of reduction in maximum workpiece temperature against MQL and dry respectively. Meanwhile, figure 7 (b) depicts the result of maximum tool surface temperature against various cooling techniques. It shows that the lowest maximum tool surface temperature was observed at SCCO$_2$ + MQL. It was found that by using SCCO$_2$ + MQL on burnishing process, the percentage of reduction against MQL and dry condition are 4.7% and 40%, respectively when using $d = 10$ mm. As noticed, SCCO$_2$ + MQL has a higher cooling rate and a higher lubricant flow compared with others cooling technique. As a consequence, the burnishing temperature and friction can be reduced. Burnishing tool of $d = 10$ mm recorded a higher temperature of workpiece and tool surface at all coolant conditions, due to the higher average thrust force. At this condition, force of kinetic friction tends to increase, hence accelerate generation of temperature.

![Figure 6. Result of burnishing force.](image-url)
Figure 7. Result of burnishing temperature.

Figure 8. Result of surface roughness.

3.3. Surface roughness

Figure 8 shows the surface roughness of the workpiece after the burnishing process. From the observation, dry condition recorded the highest surface roughness compared to other cooling techniques. At dry condition, the burnishing tool of 10 mm diameter recorded 10% higher than MQL condition. Meanwhile, SCCO₂+MQL exhibits 48.5% and 43% of reduction relative to the dry condition and MQL, respectively. Moreover, the burnishing tool of 16 mm diameter recorded lower surface roughness value than 10 mm diameter. It depicts a decrement of 48.5%, 67.5% and 61.4% of surface roughness against 10 mm diameter under dry condition, MQL and SCCO₂+MQL, respectively.

The observation shows that the trend of surface roughness results is similar to the trend of cutting force. Both cutting force and surface roughness results were correlated, where the higher cutting force produces higher surface roughness value, which means rough surface is produced compare to the lower cutting force. As the cutting force is increased, the penetration of burnishing tool on the workpiece becomes deeper. At this condition, the amount of roughness or asperities of workpiece being deformed become higher and it increased the surface roughness of workpiece [3]. Another factor that contributes to the higher surface roughness is diameter of burnishing tool itself. Smaller diameter of burnishing tool produces smaller contact area on the workpiece, thus produces deeper depth of indentation. Therefore, stirred volume on the workpiece surface becomes larger when small diameter of burnishing tool is
applied. As reported by [4] that the value of surface roughness increases with a smaller tool tip radius. In addition, the application of lubricant under MQL and SCCO$_2$+MQL conditions has improved the machinability of materials and reduce the force thus the better surface roughness can be obtained.

4. Conclusions
The application of various cooling strategies were successfully evaluated. It was found that SCCO$_2$+MQL condition is shown to play a significant role that reduces the thrust force and temperature, which subsequently improves the surface roughness. In addition, larger diameter of burnishing tool of 16 mm outperformed 10 mm in terms of the aforementioned responses.

5. References

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