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Wheel wear and workpiece surface analyses after grinding hardened steel with minimum quantity lubrication technique assisted with wheel cleaning jet (MQL-AWCJ)

Environmentally Friendly Fluids

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Abstract: *Minimum Quantity Lubrication (MQL) technique has been consolidated in the machining processes as an alternative to conventional technique because of its cleaner production characteristics. However, for grinding process some problems exist when using the MQL technique, such as the wheel clogging phenomenon which impairs the process efficiency. This is mainly caused by an inefficient chip removal from the cutting zone that results to the formation of sludge composed of oil and chips that clogs the pores of the wheel. An alternative to overcome this problem can be the use wheel cleaning system during grinding. In order to explore the potential of the MQL technique in grinding, this paper evaluated the wheel wear and workpiece material surface after plunge grinding a hardened steel with the MQL technique assisted with the wheel cleaning jet under various cutting conditions. Grinding tests were also performed with the traditional MQL technique and with the conventional coolant technique (flood coolant) for comparisons. The results showed that the MQL-AWCJ technique outperformed other techniques tested, thereby justifying it as a technically viable method for grinding operation.*

Keywords: *Cylindrical Grinding, Food coolant, MQL technique, Wheel Cleaning jet, Wheel Wear, Surface Roughness.*

1. INTRODUCTION

Dry grinding is not recommended due to the heat generated during the process in the cutting zone, which is difficult to be dissipated by the grinding wheel, chip and the environment. Most of the heat generated goes to the workpiece and can lead to thermal damages (Dudzinski *et al.,* 2004). Typical examples of thermal damages in grinding operations are burning, microstructural changes and tensile residual stresses on the workpiece material, thereby compromising its functionality. The large amount of energy dissipated as heat is one of the limiting factors of the grinding process (Badger and Torrance, 2000). However, the proper selection of cooling-lubrication technique can be a solution to prevent occurrence of thermal damages in grinding, especially with conventional abrasive grinding wheel. The lubricating action of the cutting fluid which minimizes heat generation by reducing friction and the cooling actions usually dissipates the greater part of the heat during grinding.

In addition to the lubrication and cooling properties, the cutting fluids in grinding have the function of cleaning the chips from the cutting zone. This helps in the maintenance of the wheel pores (Malkin and Guo, 2008). Despite of the benefits of cutting fluids, their application in large amounts has been questioned by environmentalists and researchers, mainly because of the damage they can cause to human health and the environment. They also require special care to handle them from the storage stage till the disposal, in order not harm the ecosystem (Byers, 2006).

In this context, the use of ever smaller amounts of cutting fluids is of great importance, as long as it does not hinder the machining performance (Novaski and Dörr, 1999). According to Soković and Mijanović (2001), it is necessary to replace the traditional cooling-lubrication techniques in order to obtain manufacturing conditions that leads to minimum environmental impact and are both technically and economically coherent. The 1990s witnessed the introduction of alternatives techniques of cooling-lubrication. A typical example is the Minimum Quantity of Lubrication (MQL).

The MQL technique uses a mixture of compressed air (coolant) and oil (lubricant) that are mixed and expelled through an orifice. This technique has been used as an alternative for the conventional technique for more than 20 years in other machining processes with a defined geometry tool, such as in turning. However it has presented limitations in the grinding process. The limitations, according to Sahm and Schneider (1996), are associated with the formation, on the grinding wheel cutting surface, of a "sludge", which consists of oil and chips generated during the operation. As a result, clogging of the grinding wheel pores usually occurs, and the traditional MQL technique is not efficient in promoting the cleaning of the grinding wheel. The clogging of the grinding wheel makes it impossible to accommodate the chips generated during the process and ends up deteriorating the surface finish.

In order to overcome this limitation, Oliveira *et al.* (2012) performed a study in the grinding process of ABNT 4340 (54 ± 2 HRc), with CBN grinding wheel, using a system of compressed air jet directed to the grinding wheel to promote the cleaning of its cutting surface. They reported that the auxiliary cleaning system improved the process overall performance and the nozzle positioned at an angle of 30 degrees presented better results.

The use of the auxiliary cleaning jet together with the MQL cooling-lubrication technique makes the application of low amount of lubricant in the grinding process promising and enables studies of applications of biodegradable fluids, which can also be diluted in water. Grinding with MQL technique can be considered, under the ecological aspect, a better alternative. However, if part of that amount of oil is replaced with water, the process becomes even more environmentally efficient. Belentani et al., (2014) carried out grinding experiments using the MQL technique with additions of water in the oil in various proportions on AISI 4340 steel with CBN grinding wheel and found that the best results were obtained for the ratio of 1:5.

Thus, in order to explore the benefits that the use of an auxiliary wheel cleaning jet (AWCJ) can offer, the current work employed the AWCJ with the aluminum oxide grinding wheel. The cutting fluid was applied via the conventional cooling-lubrication technique (flood) and the MQL technique. For the later the experiments were performed with and without the cleaning jet for comparisons.

2. METHODOLOGY

The grinding tests were performed on a CNC external cylindrical grinding machine. The operation used was the external plunge grinding, with a cutting speed (vs) of 30 m/s and a sparkout time of 7.5 s. The stopping criterion of each test was the volume of material removed of 1743.53 mm^3 through 50 cycles of machining with 1 mm withdrawal per cycle. The grinding wheel used was the conventional aluminum oxide (38A 150 L 6 V) with dimensions: 350 mm of external diameter, 127 mm of internal diameter and 25.4 mm of width. Quenched and tempered AISI 4340 steel workpieces (58 ± 2 HRc) in the form of rings with dimensions of 58 mm external diameter, 30 mm internal diameter and 4 mm thickness were used. The dressing operation of the grinding wheel was performed in the interval of the tests with a diamond conglomerate dresser (15 mm x 8 mm x 10 mm), to ensure that each test was performed in the same dressing region. A dressing depth of 0.020 mm and a speed of approximately 200 mm/min were employed.

Three-different cooling-lubrication techniques were evaluated: conventional (flood), using ME-1 fluid (1:39), the traditional MQL (MQL) and the MQL technique with auxiliary wheel cleaning jet (MQL-AWCJ). The cutting fluid applied by both MQL techniques was the LB1100 fluid. The flood cooling technique was used at a flow rate of 17 l/min with a pressure of 0.4 MPa while for both MQL techniques flow rates of 150 ml/h (oil) and 162 l/min (compressed air) and pressure of 0.6 MPa were used. The air and lubricant flow rates were controlled separately by the MQL system. The auxiliary wheel cleaning jet consisted of an air compressor, pressure gauge and a nozzle, which was fixed 1 mm from the grinding wheel cutting surface at an angle of 30 ° to the radius of the grinding wheel. The air was applied at a pressure of 0.8 MPa and flow rate of 480 l/min.

Three radial feed rates were tested (0.25 mm/min, 0.50 mm/min and 0.75 mm/min), thus resulting in 9 different cutting conditions. Each test was replicated twice in order to obtain a greater statistical reliability of the results, thus totaling 27 tests. The output parameters analyzed were the grinding wheel wear and the surface roughness (Ra and Rq).

The surface roughness (both parameters) was evaluated in three equidistant positions for each workpiece using the Taylor Hobson's Surtronic3 + rugosimeter with a cut-off of 0.25 mm and a measuring length of 1.25 mm.

The grinding wheel wear was measured using the grinding wheel profile printing method. In this method, cylindrical piece of AISI 1020 steel, with a diameter of 35 mm and a length of 120 mm is used as workpiece that is ground with the worn grinding wheel under a pre-determined volume of material. After grinding, then the differences between the worn and not worn regions of the grinding wheel that were printed to the piece are measured. To perform such a measurement, the Surtronic3 + rugosimeter and Taylor Hobson software TalyMap were used.

3. RESULTS AND DISCUSSIONS

In this section, the results and their discussions will be presented for each grinding condition used and for each analyzed output variable (wheel wear and surface roughness). The flood coolant (traditional technique) was used as reference in the discussion because it is a technique already consolidated and widely applied in the industries.

Grinding wheel wear

Figure 1 shows the radial wear values measured on the aluminum oxide grinding wheel after grinding under the three lubrication-cooling conditions as function of the three radial feed rates (v_f). It can be seen that the grinding wheel wear increased with the radial feed rate for all the cooling-lubrication techniques employed, as expected, due to the fact that increasing the feed rate increases the grinding wheel motion against the workpiece, resulting in a greater equivalent chip thickness (heq) (Choi et al., 2008).

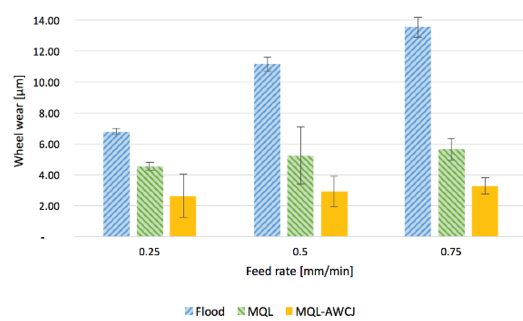

Figure 1 – Wheel wear after grinding with various cooling-lubrication techniques and different feed rates.

Figure 1 also shows that the grinding wheel wear was lower after grinding with the MQL relative to conventional coolant flow. This occurs because of the improved lubrication provided by the MQL technique. The superior capability of the spraying the mixture of oil and air is able to break the air barrier that is formed around the rotating grinding wheel during grinding (Belentani et al., 2014). This cannot be possible with the use of the flood technique due to the lower fluid pressures used.

Comparing the results between MQL-AWCJ and the conventional coolant techniques, wheel wear was about 76% lower after grinding with the MQL-AWCJ technique under 0.75 mm/min feed rate. This can be attributed to the presence of the air jet that promoted an efficient cleaning of the wheel pores, therefore avoiding premature wear of the abrasive grits and, consequently, maintaining grit sharpness for longer periods (Oliveira et al., 2012).

Surface roughness

Figures 2a and 2b show the surface roughness values, Ra and Rq, respectively, recorded after grinding with various feed rates and cooling-lubrication techniques. It can be seen that the plots for both parameters are very similar. The surface roughness values (both parameters) increased with increasing feed rate, irrespective the cooling-lubrication technique employed due to the increase of the equivalent chip thickness (heq) (Choi et al., 2008). The roughness also increased with the higher shear forces produced by the faster wheel advancement resulting to vibrations which adversely affects the surface finish (Sohal et al., 2014).

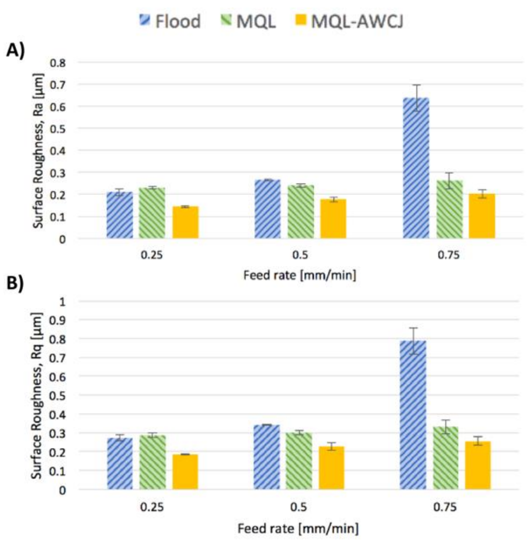

Figure 2 – Surface roughness versus the feed rate in different cooling-lubrication techniques after grinding with aluminum oxide grinding wheel: a) Ra parameter and b) Rq parameter.

Figure 2 also shows that although the Ra and Rq values were below 0.4 μm for all the conditions tested, with exception of the condition in which the conventional coolant technique and the highest feed rate was employed, the MQL technique outperformed flood technique after machining under the most severe cutting conditions. This can be attributed to the better lubrication of the oil in the MQL technique that reduces friction among abrasive grits, chips and workpiece surface, thereby resulting in better surface finish. Compared to the results after machining with the MQL-AWCJ technique, they were lower than those obtained for the other techniques, irrespective the roughness parameter evaluated. Like for the wheel wear results, the presence of the additional air jet that promoted an efficient cleaning of the wheel pores, preventing the wheel clogging phenomenon and improving the surface finish (Oliveira et al., 2012). Also, when a grinding wheel is periodically cleaned during operation, it can constantly accommodate the chips being generated, thereby enhancing the surface finish of the workpiece (Oliveira et al., 2012).

4. CONCLUSIONS

The following conclusions can be drawn this study:

- The grinding wheel wear increased with the radial feed rate and was lower when using the MQL-AWCJ technique, followed by the MQL technique, and finally the flood technique while the oil of the traditional MQL system provided better lubrication at the wheel-workpiece interface, the presence of the wheel cleaning jet prevented the wheel pores clogging phenomenon and premature wear of the abrasive grits.
- The surface roughness (Ra and Rq parameters) exhibited similar behaviour: they increased with increasing feed rate for all the cooling-lubrication techniques employed. The MQL-AWCJ technique outperformed the other cooling-lubrication techniques tested for these parameters.
- The MQL-AWCJ technique proved to be a viable alternative to the traditional cooling-lubrication technique. This in addition to environmental benefits also improved overall process performance under the conditions investigated in this study.

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