OPTIMIZATION OF COOLING IN EXTERNAL CYLINDRICAL PLUNGE GRINDING OF CERAMICS WITH DIAMOND WHEELS

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Abstract. *Due to the properties of high wear resistance and hardness, the advanced ceramics have been widely used in industrial applications, in the last two decades. The workpiece finishing process, generally made by grinding, which is still the most well-known operation, adds a large cost to the final product. In this context, companies are seeking to optimize the grinding process, by improvements such as the reduction of cutting fluid, meeting also the environmental requirements. Thus, this study aims to explore the technique of minimum quantity of lubrication in external cylindrical grinding of ceramics, with diamond grinding wheels. It was used two methods of cooling, conventional and MQL, with three feed rate in each case. It was used conventional and MQL nozzles, the last having a uniform jet flow in output. The variables analyzed were acustic emission, G-ratio, scanning electron microscopy (SEM) analysis, roughness and circularity errors. With the results, it was concluded that the conventional cooling provided the best results, comparing to the MQL. However, with MQL it was obtained satisfactory results that may be sufficient in several cases of grinding. Considering the difficulty to disposing the cutting fluid due to the large environmental impact, difficulty that tends to increase in coming years, MQL comes as a strong trend in cooling method for machining processes.*

Keywords*: External plunge grinding, MQL, advanced ceramics, environmental concern.*

1. INTRODUCTION

Bustamante and Bressiani (2000) reported the importance of the Brazilian ceramics industry for the country, stating that this segment accounts for approximately 1% of Gross Domestic Product (GDP). Despite the attractive characteristics of hardness and wear resistance, even nowadays the piece finishing process (almost always done by the grinding process), aggregates a high cost to the final product. Grinding is practically the only viable finishing process of ceramics after sintering that obtains high surface quality and geometric precision. Irani (2005) apud Uhlmann (1998) reported that in the manufacture of ceramics, the finish cost, mainly due to grinding, is responsible for 50% of the total manufacturing cost.

Not different from the mechanical industry, ceramic grinding is accomplished using cutting fluids. Its function is to provide lubrication, reducing the tool-workpiece friction, cooling (dissipating heat generated by friction), removal of chips and protection against corrosion. However, due to the current concern about environmental hazards, cutting fluids have gained special attention due to its high contamination potential. There are, nowadays, laws monitoring its use and disposal in any industrial machining sector. Thus, the minimum quantity of lubricant technique comes as a new alternative for companies seeking a solution to the problem of cutting fluids in machining processes.

In MQL technique, it is a minimum quantity of lubricant (from 10 to 100 ml/h) mixed with a jet of compressed air. The function of lubrication is provided by the oil and the cooling is mainly provided by the compressed air.

This project evaluated the minimum quantity of lubricant (MQL) used in the external cylindrical grinding of advanced ceramics using diamond wheels, as well as the performance of the abrasive tools through results seeking the process optimization.

2. OBJECTIVE

The main objective of the present study is to evaluate the technique of minimum quantity of lubrication (comparing to conventional cooling) in the external cylindrical grinding of advanced ceramics, using a diamond wheel, analyzing output variables such as roughness, acoustic emission, G-ratio, circularity errors and scanning electron microscopy (SEM) analysis.

3. ADVANCED CERAMICS

Mamalis et al. (2002) reported that ceramics in mechanical engineering applications have gained headway due to three very favorable characteristics, concerning heat dissipation, wear and corrosion resistances. Modern advanced engines and gas-turbines contain several parts which must work durably and reliably at a temperature of 2000°C. The extraordinary wear resistance is very beneficial for bearings, packing (sealing) elements and ball-end operations.

Ramesh et al. (2001) cites that ceramics are usually divided into two main groups, i.e. oxide and non-oxide ceramics. The atoms, bonding arrangement and crystal structure govern the properties of such materials. Ceramic crystals have low symmetrical structure compared to the highly symmetrical metallic structure. Crystals are formed with covalent bond, ionic bond and a combination of both. The ratio of covalent to ionic varies from 4:6 (Al_2O_3 and oxide ceramics) to 9:1 (SiC and non-oxide ceramics). Differences in atomic bonds are responsible for divergences in hardness and Young’s modulus. Covalent bonded ceramics are typically hard, strong and have high melting temperatures. However, ceramics are brittle and cannot withstand large internal strains, induced by thermal expansion or thermal transients.

4. CERAMIC GRINDING

Ramesh et al. (2001) mention that, during the process of sintering, there is an unavoidable "shrinking" of material. Therefore, it is needed a process of manufacturing to achieve the form and accuracy required for the component.

Mamalis et. al. (2000) explain that material removal mechanism, in the case of ceramic grinding, differs considerably from classical grinding theory. In the latter, in so-called ductile-type grinding, the chip removal is accomplished by elasto-plastic changes. In the brittle-type grinding of ceramics, the removed material removal is carried out by crack formation, separation, and spalling of the material. The crack formation mechanism is illustrated in Fig. 1.

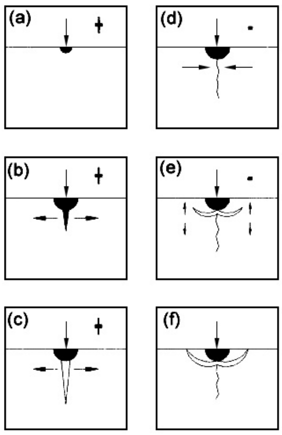

Figure 1. Stages of crack formation under point indentation (Malking and Hwang, 1996)

The six characteristic phases of crack formation can be seen in the same figure. Initially, a plastic zone of small diameter is developed near the surface - Fig. 1(*a*)- , whereas subsequently, owing to the developed tensile stress field, a small longitudinal crack initiates - Fig. 1(*b*) - and propagates as the indentation proceeds and increases in size - Fig. 1(*c*).

A decrease of load results in reducing the size and/or closing the longitudinal crack, owing to the compressive stresses prevailing, as it can be seen in Fig. 1(*d*). Subsequent decrease of load results in the formation of transverse cracks, owing to lateral tensions (Fig. 1(*e*)). After unloading, in virtue of the tensile residual stress field developed, the size of lateral cracks increases, leading to possible separation and/or spalling of the materials in the form of chips - see Fig. 1(*f*).

Malkin & Hwang (1996) reported that metal removal mechanism with spall formation may be the governing chip formation mechanism in the precision grinding of ceramics; the particular effect on a precision ground ceramic is indicated in Fig. 2:

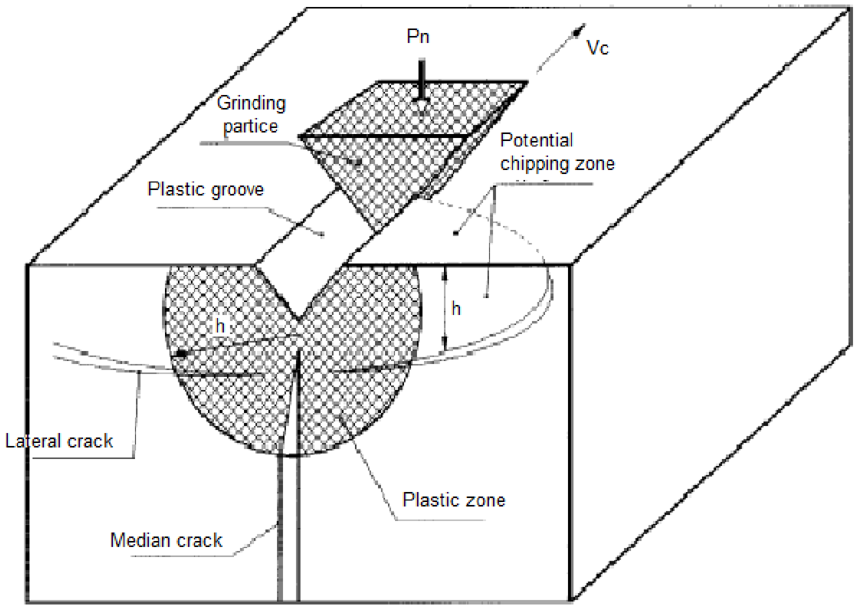

Figure 2. Plastic zone and crack formation due to scratching by an abrasive grain. (Malkin and Hwang, 1996)

It can be noted, also, that, when grinding ceramics, it must be taken into account that the real depth of cut is larger than the assumed, because the movement of the grains causes additional splintering, leading to a larger depth of cut (Fig. 3).

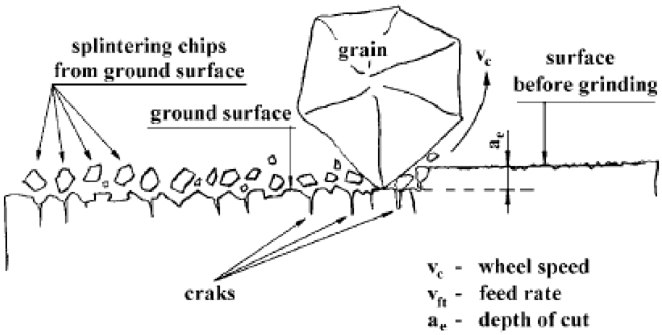

Figure 3. Model of chip formation.

The main task in grinding ceramics is to define the conditions under which they can be ground economically with minimal crack formation.

5. EQUIVALENT THICKNESS OF CUT (h_{eq})

The paper of Peters and Decneut (1975) apud Oliveira (1988) cites that the thickness of cut removed by the grinding wheel in a single rotation is called the equivalent thickness of cut (h_{eq}), which is a parameter that allows to quantify process condition. It is still defined as the ratio between the specific rate of material removal (Q'_w) and the cutting speed (V_s). Thus, Graf (2004) in their study states that equivalent thickness of cut in the external cylindrical grinding process can be represented by Eq. 1.

$$h_{eq} = \frac{Q'_w}{V_s} = \frac{\pi.d_w.V_f}{60.1000.V_s} \tag{1}$$

where d_w is the piece diameter, and V_f is the feed rate.

Malkin (1989) reported that equivalent thickness of cut is directly related to the performance of the grinding process, depending on involved variables such as cutting forces, roughness, tool life, etc. Diniz et al. (2000) stated that an increase in h_{eq} reflects in increasing cutting forces, roughness values and decreasing the grinding wheel life. Thus, it must be sought to always use the wheels whose matrix bond support high speed in order avoid these deleterious effects.

6. THE TECNICHE OF MINIMUM QUANTITY OF LUBRICATION (MQL)

According to the work of Obikawa et al. (2006), in MQL cutting, a small amount of biodegradable oil, mixed with compressed air in order to form an oil mist, is applied to the cutting zone instead of the flood supply of water-miscible or water-immiscible cutting fluids.

The MQL setup is shown in Fig. 4:

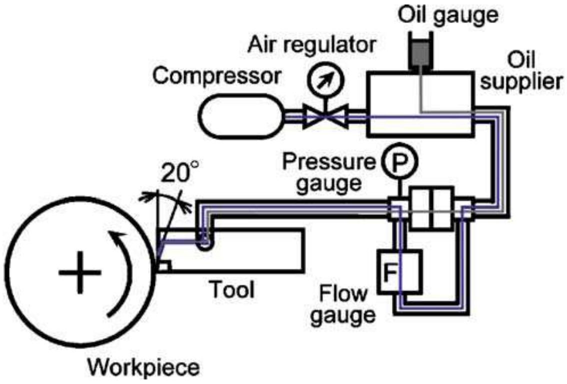

Figure 4. The minimum quantity lubrication system (Obikawa et. al, 2006)

Klocke & Einsenblätter (1997) and Young et al. (1997) report the many advantages of using MQL instead of conventional cooling. Among them, the main is the reduction of grinding power and specific energy, in addition with the improved surface quality and less wear of the grinding wheel. For the MQL fluids in grinding surfaces, the best results are provided with ester oil, as it suggests good lubrication performance.

Heisel et. al. (1998) report an advantage of the minimum quantity of lubricant, which is the absence of residual stresses caused by large temperature gradients, especially important for the cutting of brittle materials.

Attanasio (2006) cites several advantages from applying this method. The mist and vapor, harmful to the health of the worker, are reduced and the needful mixture dosage is very easy to be controlled. Other benefits are the lack of need in cleaning the final piece and the ability to visualize the process, since the grinding zone is not flooded by the cutting fluid, as in the conventional cooling technique.

Young et al. (1997) also cite a minimum quantity of lubrication as an alternative for a cleaner process and less hazardous to the environment.

According to Attanasio (2006), the main limitation of the MQL method is its inability to efficiently cool the cutting surface. This means it is not able to provide substantial advantages, if it is applied in an operation where cooling is strictly needful, like in grinding. In these cases, it is very important to define correctly the conditions that allow the MQL technique to be applied with real benefits.

7. MATERIALS AND METHODS

In this section are described all the equipment and materials used in the tests, as well as description of procedures and plans for experimentation.

The experiments were performed in a SULMECÂNICA, 515 H RUAP CNC cylindrical grinder equipped with computerized numerical control (CNC).

Workpieces were commercial alumina cylinders, composed by 96% aluminum oxide and 4% bond oxides as SiO_2, CaO and MgO. The apparent density of this material was 3.7 g/cm³.

It was used a resinous bond diamond grinding wheel, with 350mm (outside diameter) x 15mm (width) x 5mm (layer), internal diameter 127mm, alloy hardness N, concentration 50 and grain size of 126 mm (D 107 N 115 C50) made by Nikkon Cutting Tools Ltda.

The cutting fluid was an emulsion of 5% water in ROCOL 4847 Ultracut 370 semi-synthetic oil. Also in its composition were: anti-corrosion, biocides, fungicides, among others substances.

The equipment used to control the MQL was Accu-lube device provided by ITW Chemical Products Ltd, which uses a pulsating oil supply system and allows the air and lubricant flow rates to be adjusted separately.

The measurement of acoustic emissions was made using a Sensis DM12 system, with a fixed sensor positioned at the tailstock near the grinder counter-peak.

Circularity was measured on a specific machine to control geometrical tolerances Taylor Hobson Talyrond 31c.

The surface roughness was obtained through a Surtronic^{3+} profilometer, with a cut-off length of 0.8 mm.

Analysis of microstructure was performed by scanning electron microscopy (SEM).

The grinding wheel wear was measured by printing the profile of the grinding wheel in a 1010 steel workpiece, properly prepared for this purpose, and then, with a TESA Comparator Gauge the measurement of wear could be detected.

For the tests were established the following machining conditions: deep speed (V_f) of 1 mm/min, wheel peripheral speed of 30 m/s, depth of cut of 0.1 mm, 5 seconds of spark out, flow rate of cutting fluid in conventional cooling of 22 l/min, the flow rate of fluid in MQL of 100 ml/h, air pressure of 8 bar, and the outlet air velocity was 30 m/s in the nozzle, being 13 tested workpieces for each condition.

The wheel speed was 30 m/s due to unitary rate between the wheel speed and the flow rate, in the case of MQL, which guaranteeing a maximum efficiency system.

The three feed rate chosen were: 0.75, 1.00 and 1.25 mm/min.

Thus, according to Eq. (1), the three equivalent thicknesses, known by h_{eq1}, h_{eq2} and h_{eq3} were respectively 0.0707, 0.094 and 0.118mm.

8. RESULTS AND DISCUSSION

8.1. Acoustic Emission

The results of RMS acoustic emission are expressed in volts (V) and presented according to the number of finished pieces, for each system of lubrication-cooling and equivalent thickness of cut. Its influence is shown in Fig. 5.

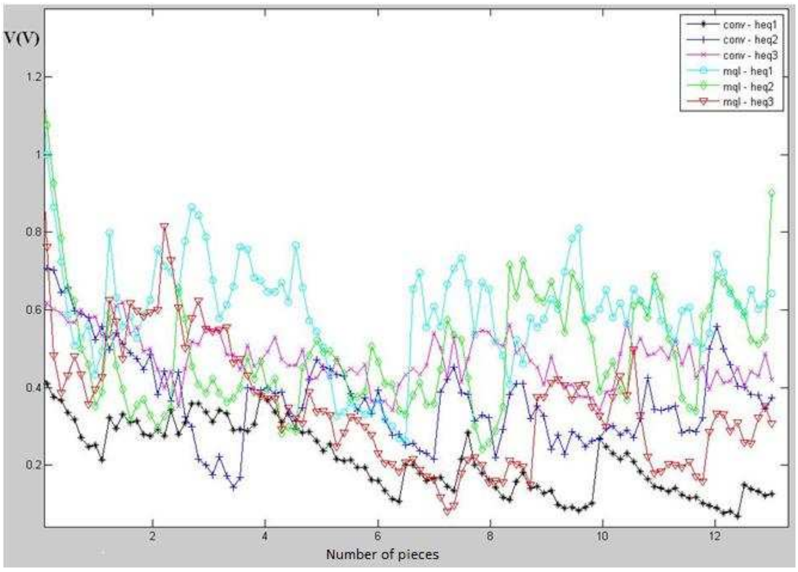

Figure 5. Variation of acoustic emission results for each condition tested.

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The comparison between the conditions of machining with MQL and conventional techniques indicate no significant differences in relation to acoustic emissions. It can be seen also that the condition which presented the lowest results as a whole, was the test with conventional cooling using h_{eq1} (smaller equivalent thickness of cut), and the higher ones were provided by MQL technique with h_{eq1}.

A possible explanation for these phenomena is the small influence of the equivalent thickness of cut in the MQL, caused by other significant variables in the process, such as thermal dissipation of the cutting zone. Since this lubrication method dissipates less heat zone, the removal of heat occurs mainly by the thermal conduction of the grinding wheel, which is constant for all tests. As the equivalent thickness of cut is determined by feed rate, the higher thickness of cut has a greater contact area between workpiece and wheel, which causes greater heat conduction. It can be noted that this type of conclusion can emerge just because the workpiece has reduced thickness in relation to the wheel. For thicker workpieces, the thermal conduction can get to a limit where it cannot be considerable in the grinding process anymore.

8.2. G Ratio

This item presents the G-Ratio for each equivalent thickness of cut and condition of lubricating-cooling. It was calculated by measuring the wear of the grinding wheel using the volume of worn material. The wheel wear could be measured due to the use of its partial width. The grinding wheel width was 15 mm, whereas the ceramic was 4 mm.

Fig. 6 shows the values of the G-Ratio, illustrating the influences of equivalent thickness of cut and type of lubricating-cooling.

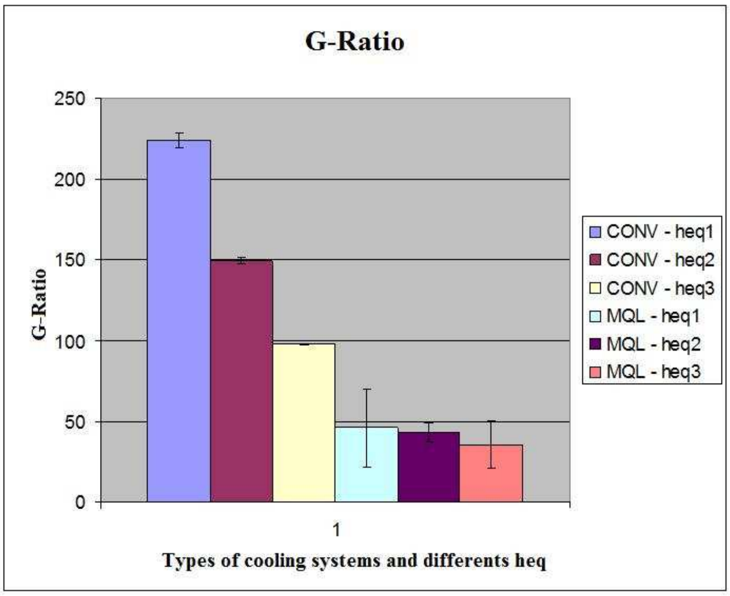

Figure 6. Variation of G Ratio for each condition tested

Through the analysis of Fig. 6, it can be noticed that the higher values for the G-Ratio were provided by the conventional cooling. One possible reason for these results is the lower heat dissipation in the cutting region, caused by the MQL, which provokes a loss of bond resistance, consequently increasing the wheel wear.

It can be stated that in conventional cooling system, the equivalent thickness of cut is a factor which can greatly influence the grinding wheel wear, as well as the G-Ratio. Analyzing the graph, it can be seen that the greater the equivalent thickness of cut, the greater the wear, consequently, the lower the G-Ratio.

For the MQL technique, the equivalent thickness of the cut could not effectively influence on the G-Ratio. This can be explained by other factors that probably prevailed in the wheel wear, for example, lower heat dissipation in the cutting zone, which made the influence of equivalent thickness of cut in the wear of the grinding wheel almost negligible.

8.3. Scanning electron microscopy (SEM)

The surface quality of the machined part is of great importance. Superficial damages of a material may significantly affect the piece, causing changes in wear resistance, nucleation and propagation of cracks, and reduction of the fatigue limit.

The SEM is a powerful technique for microstructural assessment, which can analyze the state of machined surfaces.

Figure 7 represents the results for the scanning electron microscopy (SEM) obtained for each condition of lubricating-cooling system and equivalent thickness of cut, using a 1000 times zoom.

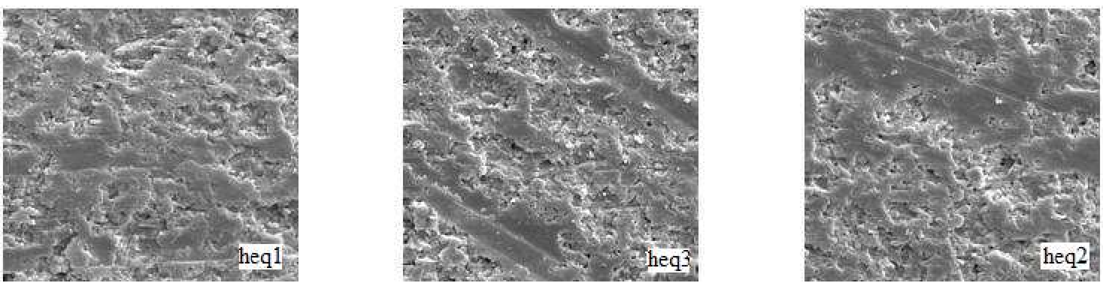

Figure 7. SEM for conventional cooling with h_{eq1}, h_{eq2} and h_{eq3}.

Analyzing the Fig. 7, it can be seen that in conventional cooling system, the occurred a fragile mode of material removal. The tendency to ductile mode removal increases as the equivalent thickness of cut increase, providing an improvement in the finishing of the workpiece.

Figure 8 represents the results for the scanning electron microscopy (SEM) obtained for the conditions of lubrication with the MQL technique, with each equivalent thickness of the cut, zoomed in 1000 times.

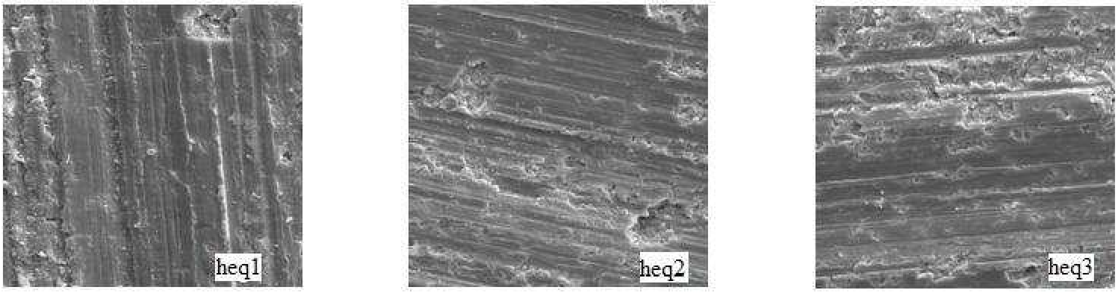

Figure 8. SEM for MQL cooling with h_{eq1}, h_{eq2} and h_{eq3}.

It can be observed that the predominant mode of material removal using the MQL technique was the ductile, which provides optimal conditions for surface finish along with material strength, due to the reduction of micro-fractures, agents of stress concentrators. Visualizing the images, it can be also seen that, the lower the equivalent thickness of cut, the more ductile is the process of removing material.

The better characterization of the surface of the piece with MQL cooling may be explained by the greater power of the lubricating oil used in the MQL, in comparison to the emulsion used in conventional cooling.

8.4. Circularity errors

The results for the circularity errors were obtained for all tests, and for each it was built an evolution of 5 workpieces (for example, pieces 1, 4, 7, 10, 13).

The graph of Fig. 9 shows the evolution of the circularity errors, for all conditions used in this experiment.

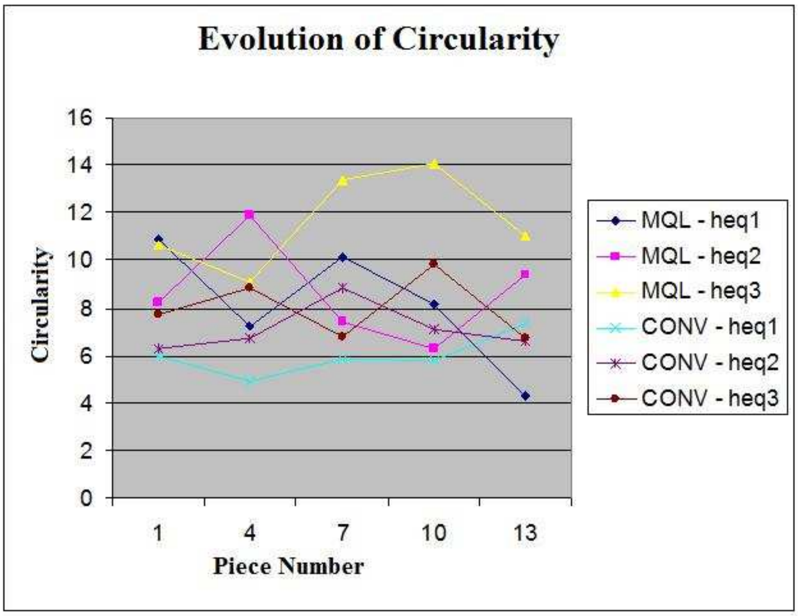

Figure 9. Variation of circularity errors for each condition

Looking at the figure 9, it can be noted that only for the more severe condition of MQL lubrication, the circularity errors have dramatically increased.

Analyzing the obtained results as a whole, it can be also observed that for the less severe conditions, the cooling with MQL did not differ significantly.

8.4. Surface Roughness

Figure 10 shows a graph with the results for the average roughness Ra, comparing the conditions of conventional and MQL lubricating-cooling. The roughness values shown are an average of 5 roughness measurements at different positions for each condition, along with their standard deviations.

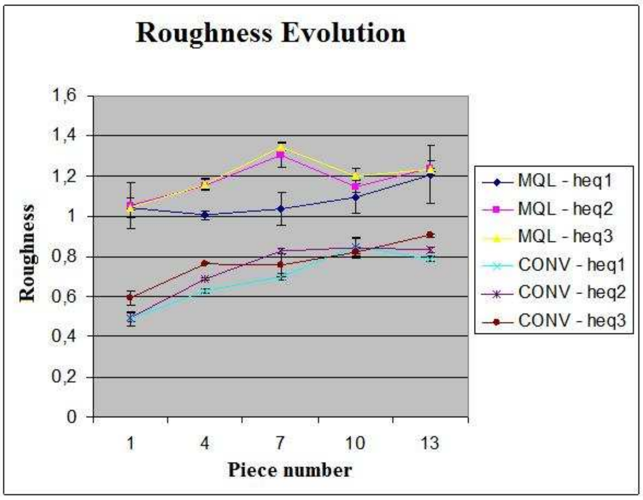

Figure 10. Surface roughness results for each condition tested.

Analyzing the results, it can be observed in general that the roughness values were lower for the conventional lubricating-cooling technique, possibly due to the better removal of chips in the cutting zone provided by the conventional cooling. In the case of MQL, that was a grout formed by fluid and material with prejudiced the chip removal, even with the compressed air at high speeds, thus harming considerably the roughness values.

The lower roughness values for the use of MQL is observed when using the lowest values of h_{eq}, proving that smaller thicknesses of cut allow also smaller values of roughness, in virtue of the lower material removal rate and greater lubrication achieved.

The roughness is mainly influenced by the conditions of lubrication. The emulsion type of cutting fluid presents the characteristics of defective lubrication yet providing satisfactory cooling, which thus affects the roughness.

9. CONCLUSION

Analyzing the data obtained in the tests, it can be stated that:

For the technique of the MQL, the condition which presented the best results was the less equivalent thickness of cut, h_{eq1} (feed rate of 0.75 mm/min).

With respect to the roughness, conventional lubricating-cooling showed lower values then the MQL technique, but the values obtained mainly with the h_{eq1}, (deep speed of 0.75 mm / min) for the MQL were satisfactory.

Looking at the surface integrity, with scanning electron microscopy (SEM), it was observed that the MQL technique showed better results in relation with conventional cooling.

On the circularity, there were no significant differences between the lubricating-cooling methods, using h_{eq1} and h_{eq2} (feed rate of 0.75 and 1.00 mm/min).

In relation to the wheel wear, the technique of MQL caused considerable increase compared with the conventional cooling. Consequently, the G-Ratio was relatively inferior to the one obtained with conventional cooling.

Thus, the general analysis of the results indicates that the MQL technique was proved to be a viable alternative to replace the conventional method, only with the restriction where the roughness of workpiece needed is not less than 1.2. In addition, an estimate for the cost should be done for each case to enabling the use of MQL. There is a cost increase due to the abrasive material (grinding wheel), however, that can be offset by the lack need for maintenance and disposal of cutting fluid, which today is a considerable cost in a process, due to the current standards for preserving the environment.

10. ACKNOWLEDGEMENTS

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