UTILIZATION THE MINIMUM QUANTITY OF LUBRIFICANT (MQL) WITH WATER FOR EXTERNAL CYLINDRICAL GRINDING PROCESS OF HARDENED STEEL

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Abstract. *To obtain parts with higher geometric precision and better surface finishing in manufacturing processes, particularly those where there is high heat generation as thegrinding, it becomes necessary to use cutting fluid. Using this element allows the lubrication in the contact area between the workpiece and tool surfaces and cooling, avoiding damage on the part surface, leading to better results. However, the use of cutting fluid causes a series of complications, especially in the environmental, economic and the health of the machine operators. Thus, intensified the search field based on reducing the use of cutting fluid. On this trend, this article analyzes the behavior of a recent method, so far applied only in machining processes with defined tool geometry, which consists of adding water in the technique of minimal quantity of lubricant (MQL). Three types of proportion in the air-oil mixture and waterwere assessed (1/1, 1/3 and 1/5). For a better evaluation of this method, the results were compared with two other methods of lubrication and cooling, conventional cooling and traditional MQL (oil-air). The cooling methods studied were evaluated based on the results of roughness, roundness errors and diametrical wear of grinding wheel. The results presented for the MQL with added water in proportion 1/5 lead to significant improvements with respect to traditional MQL and these results are similar to those obtained with abundant cooling for the results of roughness and roundness and with respect to the diametrical wear of grinding wheel, the results of MQL with added water in proportion 1 / 5 were better.*

Keywords*: grinding, MQL, MQL with water*

1. INTRODUCTION

According to Anderson *et al.* (2008), the grinding is a precise process where material is removed in part by the mechanical action of an abrasive grain of irregular size and shape, thereby producing machined surface. It is used as a finishing process, whose objective is to correct any mistakes from other stages and provide higher quality in terms of shape and surface integrity (Ren *et al*., 2009).

According Tawaloki *et al*. (2009), this process, however, is one of the operations that generate more complications in machining. Excessive wear of the cutting edges of abrasive grains substantially increases the contact surface, causing a high heat generation, which reportedly the work of Guo and Malkin (2003), will generate thermal deformation in machine and in workpiece, limiting the precision machining. Moreover, according to Anderson *et al*. (2008), there may be burning on the surface of the workpiece, microstructural changes with the appearance of residual stress and fatigue. Also, according to Desa and Bahadur (1999), if the material is very sensitive to residual stress and thermal expansion can cause cracks and distortions, affecting the surface integrity of the final product.

To minimize thermal damage during this operation, we use cutting fluid once removes the heat created by the interaction of the tool through the transfer of heat (Irani *et al*., 2005). He also has a lubricating effect which, according to Guo and Malkin (2003), reduces heat generation due to reduced friction between the workpiece and tool, thus reducing machining forces and residual stress. Moreover, according to Stanford *et al*. (2007), it has utility in the transportation of chips (cleaning), anti-corrosion protection of machine parts and pieces, and others.

However, alongside the technological advantages associated with the use of cutting fluids are the enormous dangers linked to these. According Sokovic and Mijanovic (2001), the fluid is harmful to operators of machines that can have direct contact such as breathing mist causing many health problems. Also, disposal is extremely harmful to the environment. There is also the problem of high cost, maintenance and disposal for businesses.

According to Silva *et al*. (2006), in order to minimize the problems mentioned, industries and universities are investing in research to reduce or even eliminate the use of cutting fluid, provided that no occurs the commitment of machining. For some machining processes, you can opt for their minimization, the minimum quantity of lubrication (MQL), or even the elimination, which is known for dry machining. However, according Obikawa *et al*. (2006), processes for which there is high heat generation, such as grinding, the better alternative is the use of MQL, which is a mixture of oil and compressed air, forming a mist that is applied in the cutting region, in place of conventional flood of cutting fluids.

Attanasio *et al*. (2006) affirms that the MQL technique emerges as a coherent alternative, since it combines the functionality of cooling with an extremely low consumption of fluids, up to 100 ml/h with pressure from 4.0 to 6.0 kgf/cm^2. According to the author, the MQL reduces environmental problems, the health of operators and those arising from high cost of machining. Furthermore, it makes no more the need for application of bactericides in reservoirs.

However, according to Brinksmeier *et al*. (1996), the major limitation of the technique of MQL is chilling, being hardly applied in situations where high cooling needs, such as grinding. In addition, Sahm and Schneider (1996) claim that since the MQL uses low fluid flow, a cleaning is not achieved efficiently using this technique, because instead of the chips are expelled, they mix the fluid and produce a paste of MQL oil with chips that adhere to the grinding wheel, clogging your pores, promoting greater roughness and diametrical wear of grinding wheel.

Aiming to improve the performance of the MQL technique in the grinding, as well as reduce the amount of cutting fluid in machining, reducing its negative effects, the purpose of this study was, therefore, add water to the MQL, minimizing the formation of paste of chips more oil, causing an increase in depth of cut due to reduced tool wear and, moreover, providing a higher quality of geometric shape and surface, in other words, betters values of roughness, as shown by Lee *et al*. (2002).

1.1. The cutting fluids in grinding

According to Pawlak *et al*. (2004), cutting fluids are applied in the machining of materials with the goal of reducing, by lubrication, tribological characteristics of the processes that are always present at the contact surface between the workpiece and tool and also reduce heat in the region of cutting through the cooling and lubrication.

Besides the cooling and lubrication, according to Stanford *et al*. (2007), the cutting fluids also promote anti-corrosion properties to the workpiece and machine tool. Moreover, according Tawaloki *et al*. (2007), transporting the chips generated by promoting the cleaning of the grinding wheel.

Due to the lubricating and cooling the use of cutting fluids implies the possibility of higher cutting speeds (greater savings), increase in tool life (greater productivity), and allows reduction of the roughness (best surface finishing), providing generally improving the efficiency of production (Sokovic and Mijanovic, 2001).

According to Anon (2003), however, the cutting fluids are made of toxic substances that are intended to ensure greater operating life to them. These include dispersants, anti-corrosion and biocides. Moreover, even according to the author, cutting fluids can be contaminated due to dust, poor quality water, fungus, bacteria and other fluids used in the operation. Thus, these fluids become noxious to humans.

These substances cause a lot of damage to the health of workers who may come into contact with such substances through direct contact with the skin, by inhaling mist from swallowing fluids or small particles and develop a series of problems such as dry skin, cracks and skin irritations, allergies, eye irritation, respiratory disorders and gastrointestinal disorders (Smith and Wood, 2006).

Regarding the economic aspect, according to Bartz (1995), cutting fluids entail expenses due to the effectuation of cleaning, maintenance and disposal. According to Diniz *et al*. (2003), costs related to the introduction and processing of fluids can reach double the cost of tools.

The use of cutting fluid also causes problems to the environment. According to Sadeghi *et al*. (2009), quality air is compromised by cutting fluids in operation producing fog, smoke and other particles. Moreover, according to Klocke *et al*. (2000), due mainly to leaks, losses, emissions, water tanks and wash their own disposal of cutting fluids, the fluids are also responsible for the contamination of soil and water.

According to Diniz *et al*. (2003), in consequences of the problems generated by the use of cutting fluid, much has been studied in order to avoid or minimize the use of cutting fluids in machining processes. We seek to accomplish this task without losing the gains that the use of these fluids brings, particularly with respect to tool life and quality workpiece.

1.2. The Minimum Quantity Lubricant (MQL)

According Obikawa *et al*. (2006), the minimum quantity of lubricant (MQL) is defined as a small amount of oil mixed with compressed air and directly applied in the cutting region. In this method the function of lubrication is ensured by the oil and cooled by compressed air.

According to Heisel *et al*. (1998), compared to the conventional method of lubrication and cooling, MQL can be understood as innumerous oil droplets dispersed in an air jet, where these droplets are carried in the air directly into the grinding zone, providing efficient lubrication, avoiding flooding of oil observed in conventional cooling. This last kind of cooling, conventional cooling, due to the use of additives, cannot directly enter the cutting area, and the MQL is more efficient in this aspect. Moreover, as the workpiece in MQL is not completely covered with fluid is more easily to be observed (Attanasio *et al*., 2006).

According to Heisel *et al*. (1994), besides these advantages, at the MQL method is used low fluid volume, in other words, instead of the order of liters are used thousandths of a liter, about 10 to a maximum of 100 ml / h at a pressure of 4.0 a 6.0 kgf/cm2.

According to Silverstein (2006), following the same reasoning, the fluid expended with MQL is less than using the conventional method since there is a reduction in the flow of oil around 27,000 times, while conventional methods of lubrication use 45 -50 liters of fluid per minute.

According to Dinesh *et al*. (2010), in addition to lower consumption, it is possible to reduce other parameters, making the minimum quantity of lubricant a more economical method.

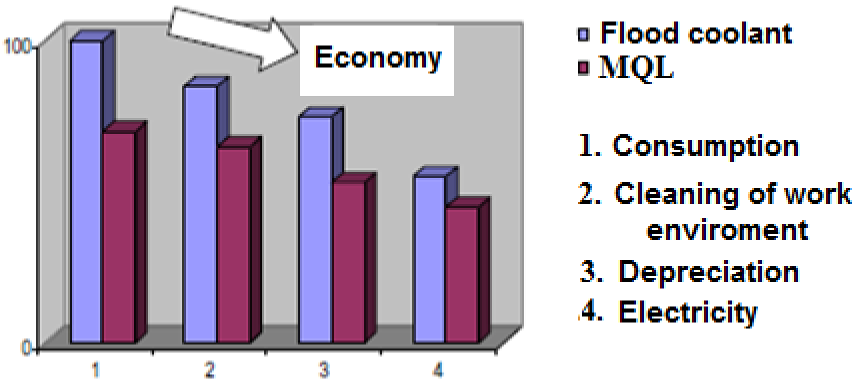

Figure 1 - Cost savings of the MQL compared to the cutting fluid in abundance (Dinesh *et al*., 2010 - modified).

According to Hafenbraedel and Malkinn (2001), although the MQL promote efficient lubrication, lower consumption, energy reduction and correction of specific energy to a level compared to cutting fluids (soluble oils) in situations not very severe machining, the roughness values are not achieved relatively good. Moreover, according Brinksmeier *et al*. (1996), a major challenge of the technique is minimum quantity lubrication in refrigeration and its application in problematic situations where you need high-cooled, as the grinding.

1.3. The Minimum Quantity Lubricant with added water

Itoigawa *et al*. (2006) developed a method that involves adding water to the MQL technique. This method has a large cooling ability because the water droplets, which play the roll of an oil carrier, also easily evaporate on the tool and work surfaces due to their size and chill the surfaces by their sensible and latent heat.

According to the author, the MQL system with water is more efficient than the traditional system of minimum amount of lubricant. Besides the reduction of machining forces, as well as reduced tool wear, the MQL with water show is also more efficient in the suppression of thermal expansion, making this technique more advantageous compared to traditional MQL.

Is important to point out, the results and conclusions obtained by Itoigawa *et al*. (2006) refer to the study of MQL with added water in defined geometry processes, as turning and milling. Regarding this recent technique, few studies have been published in the formal literature and none of them refers to the grinding process.

This fact, together with low applicability of the technique of MQL in grinding, motivated to perform this study, which sought to analyze the efficiency of this method and compare it with other more common application of cutting fluid, as the conventional method (abundance refrigerant) and traditional MQL.

2. MATERIALS AND METHODS

The experiments were carried out in a grinding machine equipped with numerical control.

The grinding wheel was used with vitrified CBN and dimensions of 350 mm outer diameter, 127 mm internal diameter, 20 mm wide and 5 mm thickness of abrasive material (SNB151Q12VR2).

The workpieces consist of steel rings SAE / AISI 4340, tempered and quenched (54 HRC hardness average), with an outer diameter of 54 mm, inner diameter of 30 mm and 4 mm.

The cutting fluid used in conventional method of cooling was soluble semi-synthetic oil with a concentration of 2.5%, which is applied in the discharge $2{,}83.10^{-4}$ m^3/s. As for the methods of MQL and MQL with added water was used to Rocol cleancut that can be diluted up to five parts water.

The equipment for implementing the minimum quantity of lubricant (MQL) is composed of the compressor, pressure regulator, flow meter and air nozzle. In this experiment, the air flow had a $6{,}0.10^{5}$ Pa pressure and flow of cutting fluid 2,7.10^{-8} m^3/s. The equipment used has a pulse supply system of oil and lets you regulate the flow of compressed air and lubricant separate ways. The compressed air flow was monitored with the aid of a flow meter calibrated the turbine at a pressure of 8,0.10^5 Pa.

Figure 2 shows the nozzle used for the MQL technique. This type nozzle minimizes turbulence of the air-oil and facilitates its penetration into the interface workpiece- grinding wheel.

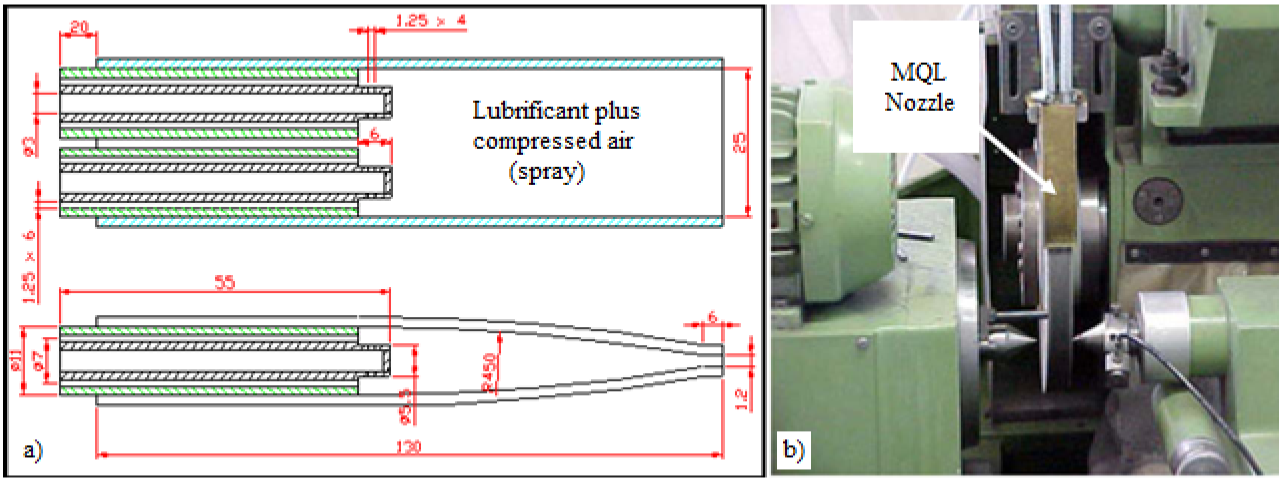

Figure 2. (a) Design of the nozzle (mm) used in MQL tests (b) Setup showing the location of the nozzle relative to the grinding wheel and workpiece.

We used a system for cleaning the cutting surface grinding wheel, having been found to form a paste (mixture of chips, oil and air), which consists of a mouthpiece through which passes air with air flow of 8, 0.10^{-3} m^3/s and pressure of 7.0 Pa. The cleaning nozzle was fixed at a distance of 1mm from the cut surface of the grinding wheel.

Figure 3 shows the design of the cleaning nozzle (a), its installation and positioning it in the rectifier (b).

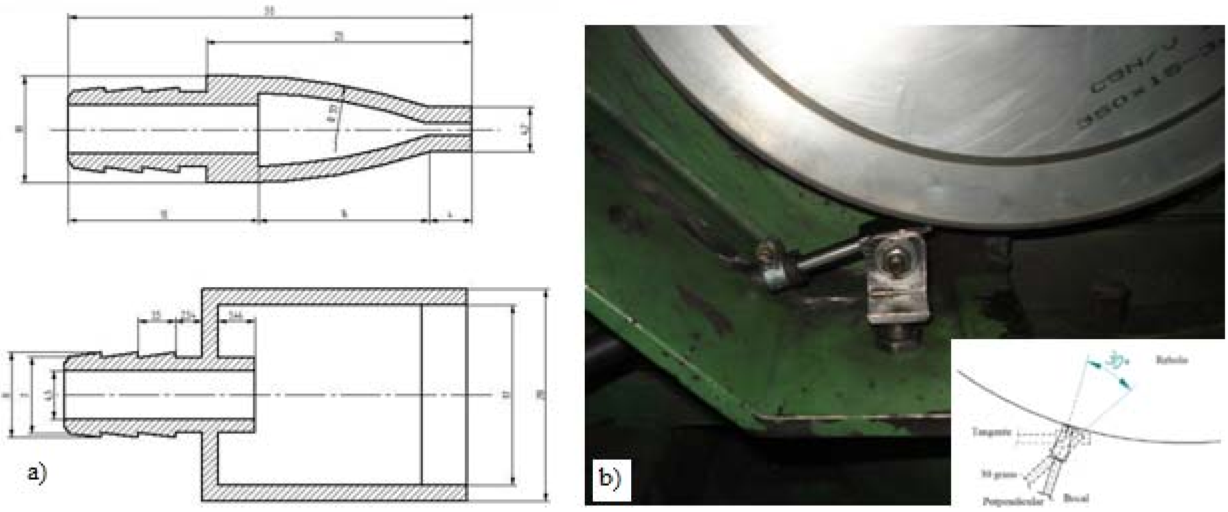

Figure 3. (a) Design of the nozzle cleaning, (b) Setup of the cleaning nozzle.

For each assay were rectified three workpieces. In addition to the different conditions of lubrication and cooling, the feed rate (v_f) of the grinding wheel was also an input variable, used in 3 levels: 0.25 mm/min, 0.5 mm/min and 0.75 mm/min.

The cutting speed (v_s) used was 30 m/s with spark-out time (ts) of to 8 seconds, grinding width of 4 mm, depth of dressing (ad) of 0.02 mm/pace, for 12 paces, to eliminate any imperfection left on the cut surface of the grinding wheel before the each assay. The speed dressing (v_d) was kept constant and equal to 0.0074 mm/min using a multipoint dresser fliese-type.

For each feed rate the assays were made with the conventional method of cooling (abundant/flood), the technique of MQL and MQL with adding water in proportions of 1/1, 1/3 and 1/5 part of oil per parts water.

The roughness measurement was performed using the parameter Ra. The roughness values presented in the results are averages of five readings at different positions for each of the three workpieces used for each condition of lubrication and cooling.

The measurement of wear of grinding wheel was made using a cylindrical workpiece of SAE / AISI 1020 for printing the cut surface of the grinding wheel. This measurement was possible due to not using the full width of the grinding wheel. As the grinding wheel had usable width of 15 mm and width of the workpiece is 4 mm, the wear caused a step in the diametrical grinding wheel. Thus, the step produced in the grinding wheel after the assay allowed the marking of wear on the cylindrical workpiece. The diametrical wear of grinding wheel was made by projection and profile measurement. After the assays, the roundness errors were measured in a roundness measurer (TAYROND 31C), where 5 measurements per each workpiece were made.

3. RESULTS AND DISCUSSION

In this section we present results for each grinding condition tested. As the trend between the methods of lubrication and cooling remained the same for all three types of feed rate, discussion of the results refer to the general trend discussed.

3.1. Roughness

Figure 4 shows the results for the average roughness Ra**Erro! Fonte de referência não encontrada.**.

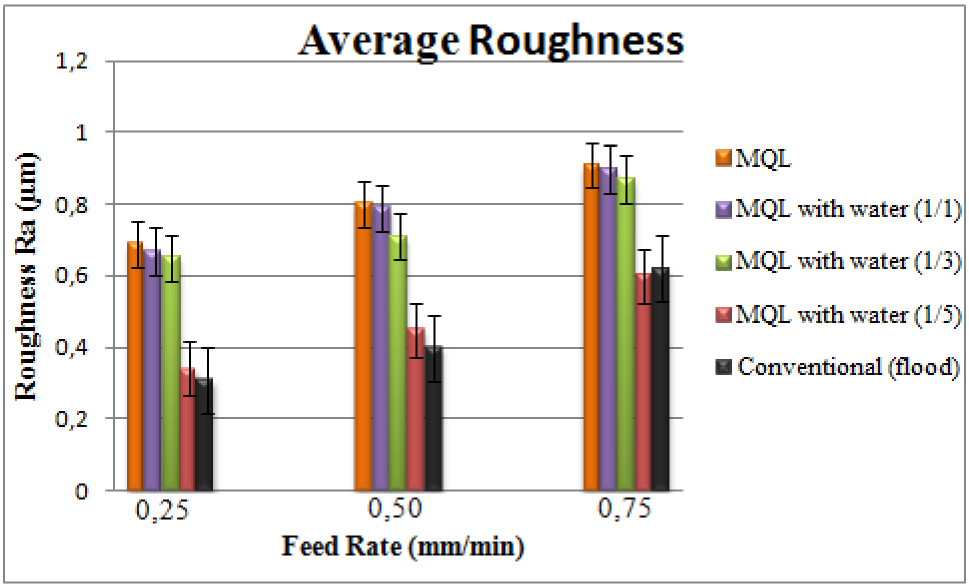

Figure 4. Results of roughness for different conditions of lubrication and cooling.

It is observed that with increasing addition of water in the composition of MQL, an improvement of the roughness. Among the ratios tested, was the best result of 1/5 (part of oil / parts water), reaching values close to or even lower (if the rate of 0.75 mm/min) to the conventional method of cooling that has the highest amount of water in the composition of cutting fluid.

The traditional method of MQL showed the worst results, because this method to observe the formation of a fluid paste with difficult removal chip, even compressed air at high speeds is difficult to pull. This paste with chip attached to the grinding wheel comes into contact with the workpiece, causing risks to the workpiece and, thus, increasing its roughness.

The addition of water in the MQL oil eases this problem, since it thins the oil, improving the removal of the chips in the cutting zone, reducing the risks in part generated by the chip and thereby providing better surface roughness values. Moreover, the greater the amount of water, the greater the cooling, according Itoigawa *et al*. (2006), it is important for accuracy dimensional geometry and the surface roughness. Therefore, there was an improvement of MQL with added water compared to traditional MQL.

With respect to the conventional method, the best results were obtained for this method because there is no the formation of the paste of chips with fluid that is formed in the MQL and MQL with added water and, thereby, clogging the pores of the grinding wheel with chips gets smaller. Besides the fact that the conventional method has a cooling effect much better than the MQL and MQL with water.

3.2. Roundness Errors

Figure 5 shows the values of deviations from roundness errors expressed in microns (μm).

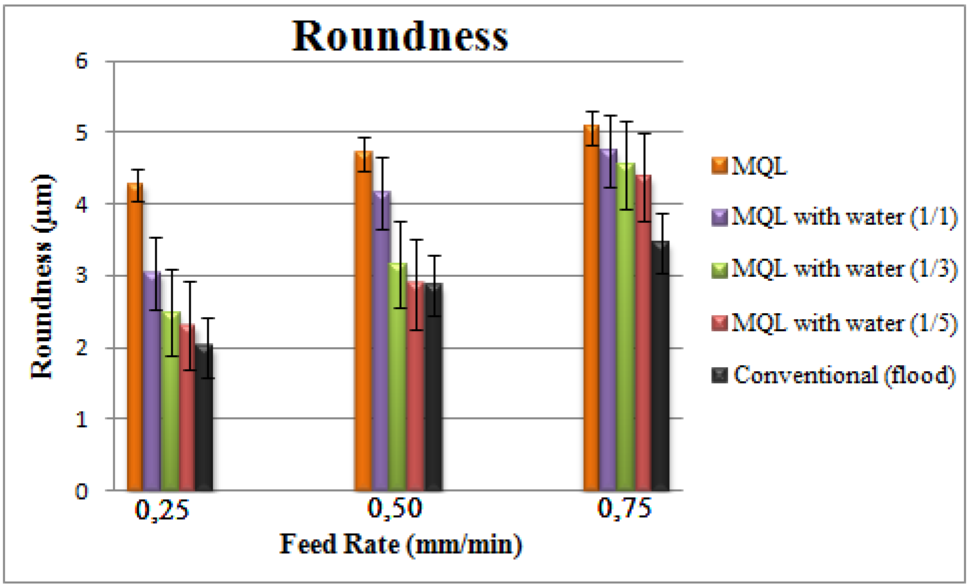

Figure 5. Results of roundness to the different conditions of lubrication and cooling.

It is observed that the trend of values of roundness was the same as that obtained for the values of roughness. The best values were obtained for the conventional method and the worst for the MQL (without water). The value of circularity has also decreases with increases in the proportion of water in the cutting fluid. Thus, the values of the MQL for roundness with added water at a ratio of 1/5 and the conventional method remained close.

The conventional method showed better values of roundness, it is the one with better cooling effect. Thus, there is less thermal expansion of parts, allowing for greater dimensional accuracy and geometrical.

Moreover, MQL and MQL with water had worse outcomes compared to conventional due to the formation of a paste of chip more oil that is formed with these methods. The presence of this paste increases the friction between chip and workpiece. Thus, there is higher heat generation, providing the biggest roundness errors.

As discussed in section 3.1, the increase in the proportion of water in MQL thins the MQL oil, softening the formation of paste of chips with fluid and, therefore, the clogging of pores of the grinding wheel by the chips, and improving the capacity of cooling the mixture. For these reasons increasing the proportion of water in MQL provided smaller values of roundness.

3.3. Diametral Wear of Grinding Wheel

Figure 6 shows the values of diametrical wear of grinding wheel.

At first, the results of the diametrical wear of grinding wheel seem to follow the same trend of the roughness and roundness, in other words, as it increases the proportion of water in the fluid you get betters values of wear of grinding wheel. This trend is indeed followed when we compared the MQL with the MQL with added water. However, the conventional method for lubrication and cooling, among the analyzed methods is the one with largest amount of water in fluid composition, the wear of grinding wheel is higher compared to other methods of lubrication and cooling analyzed.

First, according to Malkin (1989), the diametrical wear of grinding wheel is caused by deterioration of the high thermal and mechanical stress to which the grinding wheel is subjected. Therefore, the lower heat dissipation from the cutting area, the greater the loss of resistance of the binder, thus the greater the wear of grinding wheel. Therefore, by adding water to the MQL achieved a greater cooling effect and therefore a smaller diametrical wear of grinding wheel.

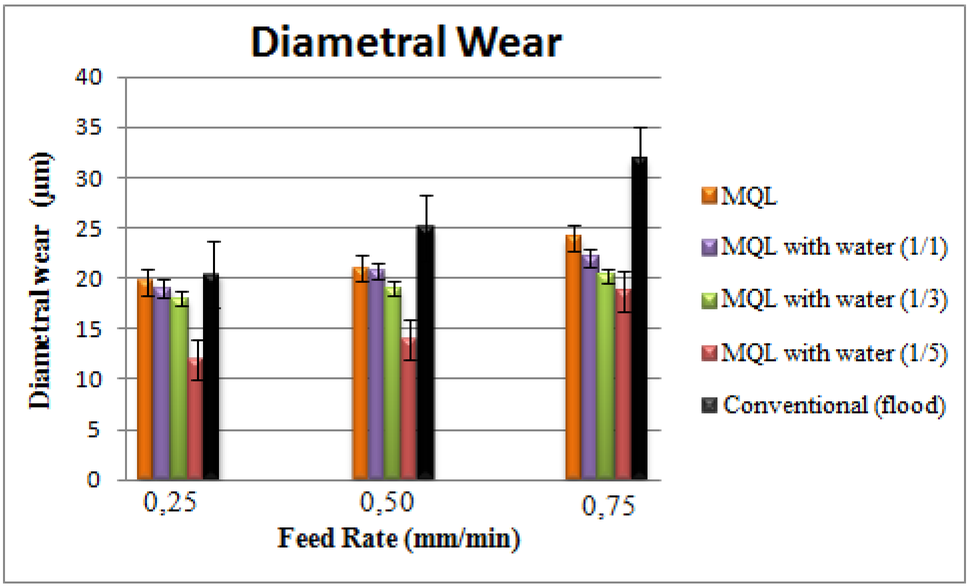

Figure 6. Results of diametrical wear of grinding wheels for different conditions of lubrication and coolant.

With respect to the conventional method, it is clear that the highest values of wear of grinding wheel are obtained for this type of lubrication and cooling. This can be explained since this method does not reach the cutting area as efficiently as the MQL and MQL with water. That's because these last two methods the fluid is injected at high pressure into the cutting zone. When using the conventional method of lubrication and cooling, the large flow of fluid creates turbulence when the fluid touches the workpiece and or the grinding wheel, hindering its penetration into the interface workpiece- grinding wheel. As its penetration into the interface is impaired, the fluid in abundance has cooling effect, because it removes heat from workpiece by conduction, since it is abundantly watered by the fluid, is effective to clean the pores of the grinding wheel, since it too is abundantly watered by the fluid, but its lubricating function is impaired. Then, the largest diametral wear of the grinding wheel obtained when using the conventional method of lubrication and cooling was caused by lack of lubrication of the interface workpiece- grinding wheel, which made the efforts made by the grains were larger, facilitating its removal.

To summarize: As it increased the water content in the MQL the diametral wear of grinding wheel decreased because, addition to the grinding wheel get cleaner, had better cooling of the contact area workpiece- grinding wheel. These two actions have overcome the decrease of lubrication caused by the addition of water to oil in MQL. Already when using conventional lubrication and cooling, despite the greater cleanliness of the grinding wheel and greater cooling of the workpiece (not necessarily greater cooling of the cutting area), the lack of lubrication of the interface workpiece- grinding wheel surpassed the other two actions and caused the more accelerated removal of grains of grinding wheel, generating its diametral wear.

4. CONCLUSIONS

Comparing the traditional method of MQL with the addition of water, the results indicate that the method of MQL with added water is more efficient than traditional MQL due to improvements made in part quality and less tool wear and the higher the proportion of water in oil, among the options considered (1/1, 1/3 and 1/5 part of oil / parts water), the better the results.

Comparing the methods of MQL (with added water and traditional) with the conventional method, it was noted that the last is worse for diametral wear of grinding wheel, once it is inserted into the cutting zone at a pressure less than the MQL.

However, in general, the conventional method of lubrication and cooling performs better than MQL and MQL technique with added water. However, the MQL with added water to the proportion of 1/5 part of oil / parts of water is technically feasible even when compared to the conventional method since the quality of workpieces for these methods were almost identical and the conventional method provides more diametral wear of grinding wheel. Its implementation, therefore, entail ecological and economic gains.

5. ACKNOWLEDGEMENTS

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