ANALYSIS OF THE VIABILITY OF THE MINIMUM QUANTITY OF LUBRICANT (MQL) TECHNIQUE IN SURFACE GRINDING OF STEEL

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Abstract: This research aimed to analyze the viability of the minimum quantity of lubricant (MQL) technique towards different methods of lubrirefrigeration in tangential grinding of steel, considering process quality, wheel life and the viability of using cutting fluids. The proposal methods were the conventional (abundant fluid flow), the minimum quantity of lubricant (MQL) and the optimized method proposed by Webster (rounded nozzles). This analysis was done in equal machining conditions through the assessment of grinding variables such as grinding force, roughness, G ratio (volume of removed material/volume of wheel wear), and micro-hardness. The results show the possibility of improvement of the grinding process. Besides there is the oportunity for production of high quality workpieces with lower costs. The MQL technique showed efficiency in lower depths of cut. The optimized method of Webster applies the fluid in a rational way, without waste a great amount of fluid. Hence, the results show that industry can rationalize and optimize the application of cutting fluids, avoiding inappropriate disposal, inadequate use and consequently environment pollution.

Keywords: Grinding , Cutting Fluids, MQL, Optimization.

1. INTRODUCTION

Grinding is a very complex machining process, with many characteristic parameters influencing each other (Chen et al., 1998). The characteristic of grinding is the removal of material by the contact between a tool containing abrasive grains (grinding wheel) and the workpiece surface. Each grain of the grinding wheel topographic structure removes a small quantity of material, providing the work surface with a better finishing (Malkin, 1989).

According to Hassui and Diniz (2003), grinding is the ideal process for a workpiece which needs a good surface and dimensional and geometric quality. Due to these requirements, the process is usually one of the last steps in the machining chain. When the workpiece reaches the grinding stage, it already has high aggregated value from the previous procedures. This makes a possible failure during the finishing process with consequent rejection very expensive and undesirable.

Process industries are seeking for higher production, cost reduction, flexibility, better dimensional and/or surface quality. This is becoming more and more important to these industries in order to keep, or even increase their market shares in global economy (Irani et al., 2005). Grinding is a finishing process, characterized by obtaining results such as precise dimensional tolerance and high superficial quality. However, a limiting factor in this process is the excessive heat generation on the cutting interface. This excessive heat can cause thermal damage to the workpiece, undesirable in a finishing process. Thus, to minimize heat generation, fluids are used to cool and lubricate the cutting zone (Kopac and Krajnik, 2006).

In grinding processes, the function of cutting fluids is to remove the excessive heat generated during the cutting operation, lubricate the region where it happens, remove the excess of chips formed, keep the cutting tool (grinding wheel) clean, and minimize corrosion on the material involved (Tawakoli et al., 2007).

Nevertheless, cutting fluids are dangerous substances for the environment. Their disposal is considerably expensive and involves hard procedures. Besides, those substances can cause several diseases after prolonged exposures, such as dermatitis, problems in the respiratory and digestive system, and sometimes even cancer (Tawakoli et al., 2007).

As shown, cutting fluids play an important role in the productive process, and their use results, most of the times, in a longer life cycle of the tool and in better quality of the machined workpiece. However, their use brings along a few issues, such as difficulties and high cost with recycling and disposal, environmental pollution and chronic diseases for people exposed. Because of this, a lot of research has been done in order to avoid or minimize cutting fluids use in grinding processes, but without losing the benefits these fluids bring, mainly related to the tool life cycle and the workpiece quality (Ebbrell, et al. 2000).

This paper seeks to analyze lubrication-cooling alternative methods to the conventional method, making it possible to use cutting fluids more rationally, without any loss concerning the quality parameters. These methods are, mainly, the minimum quantity of lubrificant (MQL), and a fluid application optimized method, proposed by Webster (1999), which uses a rounded nozzle. Through experimentation and analysis of obtained data, the purpose is to verify if the MQL technique can be considered as an alternative to fluid application in grinding, keeping the standards for dimensional and surface quality, characteristic of this process. Besides, it is proposed to analyze whether the optimized method proposed by Webster (1999) can be an alternative to the conventional method of application in terms of cutting fluid usage.

In this research the grinding wheel peripheral speed and the workpiece speed were chosen as constant, and the depth of cut varied in 0,02mm, 0,05mm and 0,08mm. This choice was made in order to simulate three different conditions of grinding: a smooth one (0,02mm), which could be a finishing condition; a severe one (0,08mm); and an intermediate one (0,05mm). Hence, the adopted values can summarize the conditions of grinding in industries. These values were reached in trials experiments. Besides that, the grinding machine used allows a better control of the depth of cut than the other parameters.

2. MATERIALS AND METHODS

The equipment set consists of a tangent plane grinding machine SULMECÂNICA, model 1055E; a vitrified super abrasive grinding wheel CBN, whose dimensions are: 350 mm external diameter, 127 mm internal diameter, 20 mm wide, with 5 mm thick abrasive material, code SNB151Q12VR2; workpiece made of steel 4340 ABNT (Brazilian Association for Technical Standards), tempered and quenched (54 HRc average hardness), rectangular shape, 100x200x10 mm dimensions. The dressing operation was kept constant, using a multigranular fliese-type dresser that did not influence the output variables of the process.

The cutting fluid utilized in the conventional and optimized method by Webster (1999) was a semi-synthetic soluble oil, diluted 1:20, that is, one part of the fluid was diluted in 20 parts of water, providing a concentration of 5% of fluid in the emulsion, as recommended by the manufacturer. In the conventional method, this fluid is plentifully applied on the workpiece/tool contact interface, in a flow rate of approximately 27,5 l/min. In the optimized method, a pump makes it possible to apply the fluid at a speed of 32m/s, the same speed as the grinding wheel. In this case, the pressure used was about 8 bars, and flow rate is the same as the one used in the conventional method (27,5 l/min).

The MQL technique consists of atomizing small quantities of fluid in a compressed air line. The MQL system is composed of: compressor, pressure regulator, air flow meter, dosing device and nozzle. The MQL equipment set allows a fine adjustment of lubricant/air volume separately, by means of a needle type register. The cutting fluid used was biodegradable vegetal oil with additives for extreme pressure, severe operations and antioxidants. In this experiment, the air flow was pressured nearly 8 bars, and cutting fluid rate was 100 ml/h.

The method proposed by Webster (1999) requires a special nozzle with rounded surfaces, which can reduce turbulence flow of the cutting fluid. This nozzle was produced as like as the author indicates in his paper. This method also requires a pump, in order to apply the fluid to speed at the cutting zone.

With the equipment ready, preliminary experiments were carried out, to define grinding parameters. Keeping the workpiece speed at 0,0033m/s and the grinding wheel peripheral speed at 32m/s, both constant, the depth of cut was varied in 0,02mm, 0,05mm and 0,08mm.

The stop criterion was the specific volume of the material removed, adopted 5000 mm^3/mm. Since there were three different depths of cut, the interval to obtain the specific volume was different in each situation.

The tangential cutting force was measured through the determination of electric power consumed by the engine of the grinder spindle, using an electronic module and a board of data gathering, manipulated by a data gathering program, based on the software LabView, of National Instruments®.

Roughness data were obtained measuring R_a, parameter with a roughness meter Taylor Hobson, model Surtronic *3*+, at each 1000 mm^3/mm of removed material.

The grinding wheel wear measurement was made using specimen made of steel 1045 ABNT for impress the wheel. The impression made was measured by a coordinate measuring machine of Tesa Company, model Micro-Hite 3D Direct Computer Control (DCC).

Micro-hardness Vickers was also determined. To obtain this measure, a BUEHLER micro-hardness meter model 1600-6300 was used.

For each depth of cut, three different lubrication-cooling methods were tested, the conventional, the MQL and the Webster method application with rounded nozzles (optimized). For each method, the experiments were repeated three times. Thus, a total of 27 experiments were carried out.

3. RESULTS AND DISCUSSIONS

In this topic, the gathered data was analyzed. It is important to remember that the grinding wheel peripheral speed and the workpiece speed were kept constant, only the depth of the cut varied in 0,02mm, 0,05mm and 0,08mm.

3.1 Tangential Cutting Force

Figure 3.1 shows the tangential cutting force behavior along the experiment for the three depths of cut experimented. We can observe that in the MQL technique at 0.02 and 0.05 mm depth of cut the cutting force is smaller than that observed in the conventional and optimized methods. This can be explained by the fact that the MQL under those conditions allows a more effective lubrication in the cutting zone, overcoming the air barrier generated by the grinding wheel through its movement. This way, the strength spent on the friction between the workpiece and the tool is minimized. Similar condition is observed in the optimized method, whose behavior is quite similar to the MQL method.

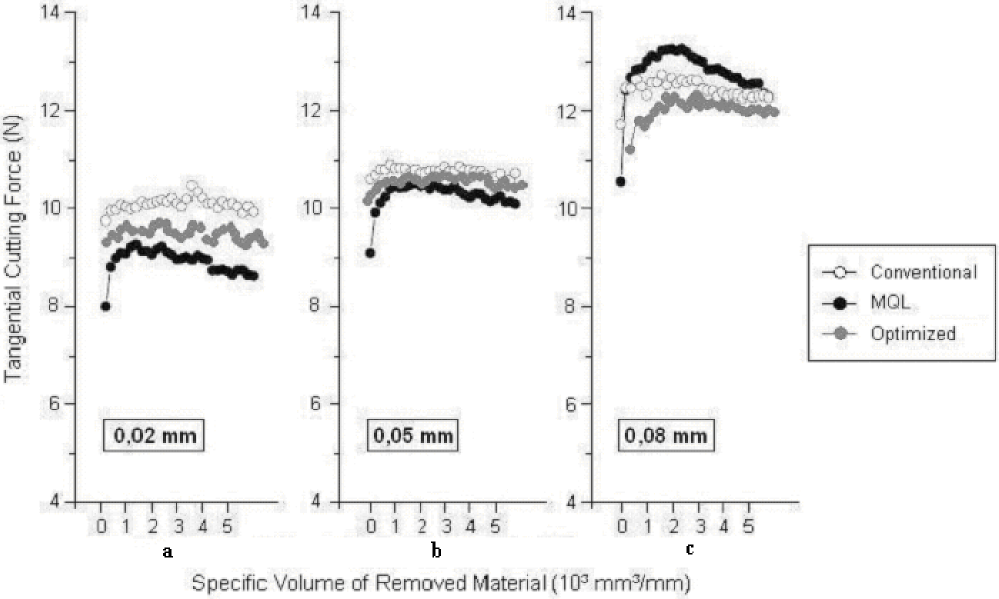

Figure 3.1 – Tangent cutting force data – a) 0,02mm; b) 0,05mm; c) 0,08mm.

At 0.08 mm depth of cut, the force observed in the MQL is the biggest. That grinding condition is the rudest among the ones analyzed, which can be confirmed by an increase in the cutting force. The fact that the forces in the MQL are greater refers to the difficulties with efficient lubrication of the process. Under these more severe conditions of cutting, a high stress is present. Besides the inefficient lubrication, the cutting zone cooling by the air flow is not able to minimize the excessive heat generation. In this case, the optimized method seems to be more efficient, because it allows better penetration in the cutting region and the removal of the excessive heat that is generated.

The optimized method showed good results due to its capability of cooling the cutting zone. This capability relies in the way the cutting fluid is applied. The high speed enables the fluid to penetrate the cutting zone, passing through the air barrier generated by the grinding wheel. The behavior of this method throughout the increasing of the depth of cut is constant. The conventional method presents higher values, although its behavior is constant too. These higher values are caused by the air barrier of the wheel, which the abundant flow of cutting fluid cannot surpass efficiently.

It is possible to conclude that increasing the depth of cut, the average values of tangential cutting force tend to increase. This is a consistent presumption, since an increase in the depth of cut produces a bigger contact area between the grinding wheel and the workpiece, and although the number of grains in contact is also bigger, the strength to remove a bigger volume of material is increasing, which consequently produces higher cutting forces.

Observing the cutting force behavior, which varies along the experiment, it is possible to notice its inconstancy. It is due to the CBN super-abrasive grains friability. Along the process, the grains are worn out, losing their cutting edges, becoming flatter. This produces a bigger force of cut, due to the decreasing of their cutting capacity and to the increasing of the drag process. Those worn out grains are released from the matrix, renewing the cutting edges. CBN grinding wheels have this capacity of self-sharpening, which strengthens their quality characteristic.

3.2 Roughness

It is important to analyze the roughness variable because the surface finishing affects the fatigue resistance of the workpiece significantly when they are under strength. A workpiece roughness is still linked to lubrication and depends mainly on the size of the abrasive grain present in the grinding wheel, on the dressing conditions and material removal rate (Malkin, 1989).

Thus, due to the importance of roughness on ground workpiece, the average roughness (R_a) was measured. In Figure 3.2 roughness values are given in micrometers, resulting from the arithmetic mean of all experiments with the same depth of cut.

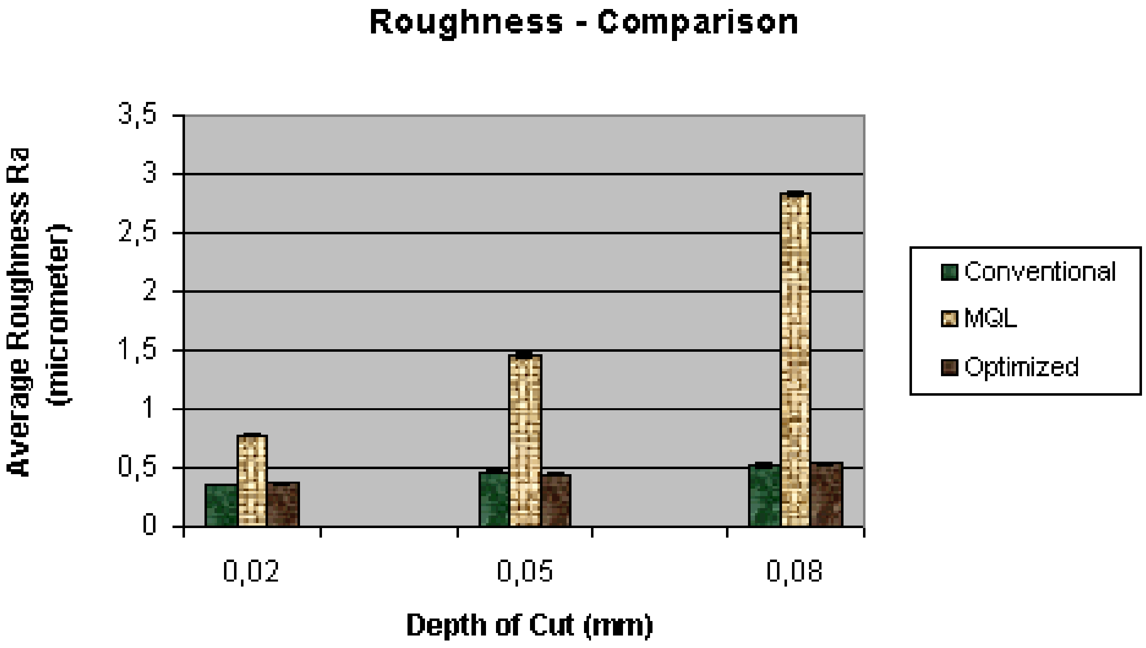

Figure 3.2: Comparison of roughness among the methods tested.

Fig. 3.2 shows that all roughness data gathered in the conventional and optimized lubrication-cooling methods were bellow the ones obtained in the MQL method. At 0.08mm depth of cut, roughness data in MQL are almost six times bigger than the other values.

According to Malkin (1989) the acceptable range for average roughness in a grinding process is 0.2 to 1.6µ*m*. Therefore, all values obtained with the conventional and optimized methods are within the tolerance range, being quite satisfactory. The values are very similar to these methods, so it is possible to conclude that both methods removes chips away and guarantee the characteristic surface quality of the grinding process.

In the MQL, however, roughness data obtained at 0.08mm depth of cut are out of the considered range, which disqualifies the process concerning its surface quality. At the best condition, 0.02 mm, the values produced by the MQL are higher than the ones produced by the other two methods. Nevertheless, the MQL is a considerable alternative, even for finishing. For 0,05mm, the MQL method is in the limit of the considered range, which means the surface quality has not been kept. In this case and for 0,08mm depth of cut, the MQL technique can be disqualified.

The reasons of those variations can be explained. The conventional and optimized methods allow the removal of the chips in the cutting zone, improving the lubrication in the region and minimize the friction between the tool and the workpiece. The MQL method, being inefficient in these tasks, makes the chips stay in the cutting zone, and the bigger the chip, more difficulty is to remove it, and worse surface quality, which can be corroborated by the high values of roughness. The air flow is efficient removing the chips produced with a 0.02mm depth of cut. However, its efficiency decreases with the increase of the depth of cut, fact confirmed by the 0,05mm depth of cut value.

Although MQL requires a lower cutting force, the roughness of the workpiece is higher. The explanation to this fact consists in the grinding wheel topography. The CBN wheel allows the thin chips produced in the MQL methods, resulting in lower forces and medium roughness. However, the increase in the depth of cut increases chip size, which makes more difficulty to settle the chips in the wheel porosity, which results in deplorable surface quality.

3.3. Grinding wheel wear and G Ratio

Grinding wheel wear is an extremely important variable in grinding process, since the bigger the wear, the shorter the grinding wheel life cycle. Figure 3.3 presents the diametric wear of the grinding wheel at each depth of cut for the three types of lubrication-cooling considered.

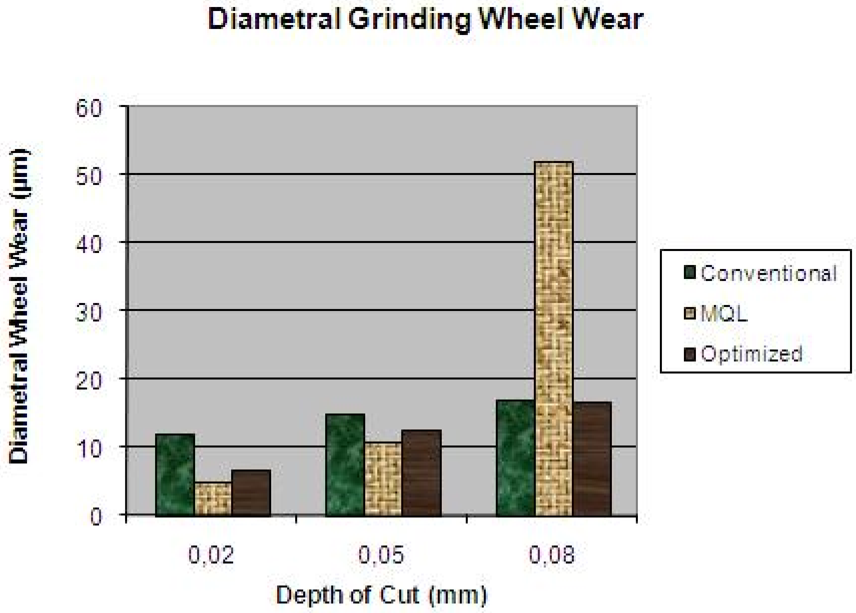

Figure 3.3: Grinding wheel wear comparison.

Fig. 3.3 illustrate that the diametric wear of the grinding wheel using the MQL technique was smaller at 0.02 e 0.05mm depths of cut, whereas at 0.08mm, the value obtained using MQL was much bigger than the one obtained with the two other methods. These behaviors can also be observed with the cutting force data, since the bigger the strength on the grinding wheel, the bigger the cut forces needed and, consequently, higher the wear of the tool is.

Undoubtedly, the more the lubrication-cooling fluid penetrates in the cutting zone less wear is produced by the friction between the tool and the chips and better is the removal of the generated heat. The porosity of the grinding wheel should be considered, since it is responsible for the accommodation of the chip produced, improving the access of the fluid to the cutting zone, with consequent improvement in lubrication, minimizing the wear by friction.

The grinding wheel used is a CBN grinding wheel with vitrified bond. This kind of bond is less susceptible to erosive wear by chips, presenting a greater retention force of the bond on the abrasive grain and, consequently, minimizing the diametric loss of the grinding wheel.

In the MQL at low depths of cut, parts of the chips mixed with the oil atomized lodge in the grinding wheel pores, allowing a portion of the lubricant to reach the cut zone better, decreasing the wear by friction. This also allows the air flow to remove part of the heat produced, improving the cooling of the place. So, even with this lodging condition producing a higher roughness on the machined surface, it contributes to a smaller wear of the tool.

However, when the generated chip becomes bigger, as when increasing the depth of cut, the pores are not able to accommodate this bigger chip, and the air flow is not efficient to remove it from the cutting zone. Then, the chips damage the cutting and increase the abrasive strength of the tool on the workpiece, decreasing the lubrication capacity in the cutting zone, causing damage on the surface and more diametric wear on the grinding wheel.

The optimized method also presents satisfactory results, showing much more efficiency than the conventional method. The high speed of the fluid application makes the removal of chips and excessive heat easier in the cutting zone than the abundant fluid flow. It justify why the optimized method showed better results, guarantying a longer wheel life.

The G Ratio is the ratio between the quantity of removed material per quantity of worn material. This relation was obtained from the grinding wheel wear data.

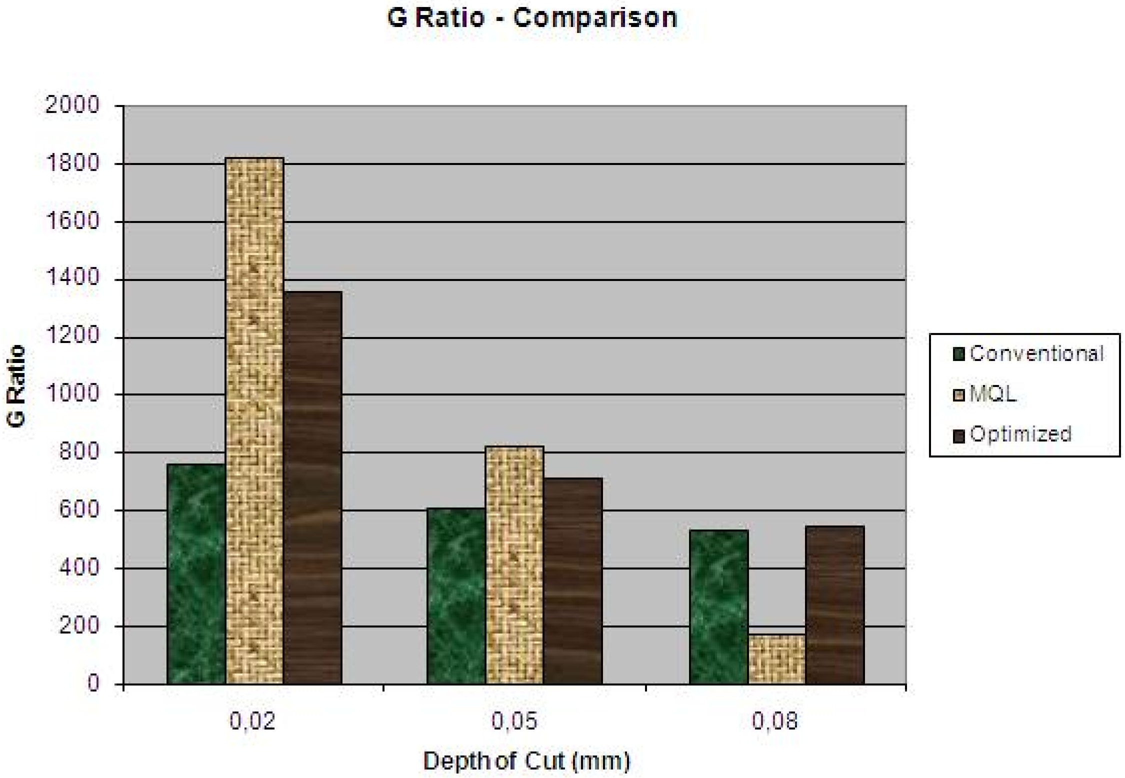

Figure 3.4 - G Ratio comparison among lubrication-cooling methods analyzed.

Figure 3.4 shows that the MQL is a good alternative for low depths of cut. The optimized method needs to be highlighted, since it shows that the fluid application in high speed is more efficient than the excessive fluid application in the conventional method. As the depth of cut increases, G ratio values decrease, due to the increase of tool wear. For medium values, the MQL and the optimized method were the best. In this condition, however, the MQL presents high values for roughness, which damages the process.

For high depths of cut, the MQL showed to be ineffective in its functions. In this condition, the performances of the conventional and optimized methods are similar, because the high quantity of heat is difficult to be removed, even with the fluid being applied at high speed.

3.4 Micro-hardness

Micro-hardness in the ground workpieces was also analyzed. This kind of analysis is made in deeper regions of the surface. After analyzing the gathered data, the graph in Fig. 3.5 was produced. This graph also shows the reference value adopted, which is the micro-hardness of the workpieces before grinding.

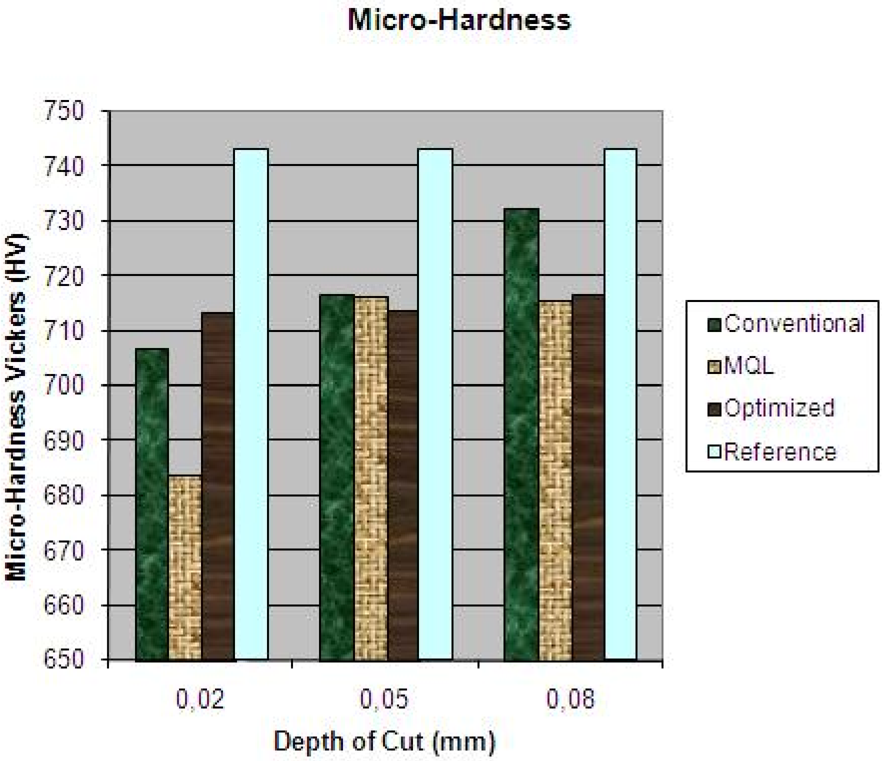

Figure 3.5 - Vickers micro-hardness in the ground workpieces.

Micro-hardness obtained in the workpieces shows that in all machining conditions and using the three methods of lubrication-cooling there is a loss in surface micro-hardness. This loss is associated with capacity of heat dissipation and cooling speed of the specimens. Such factors are determinant to define the granular structure obtained.

Analyzing firstly the data gathered with 0.02mm depth of cut, the loss obtained using the conventional method is smaller than the one using the MQL, but higher than the one with the optimized method. This is consistent with the fact that the MQL produces much more heat during cutting, while the excessive fluid and directed fluid jet of the conventional and optimized methods, respectively, remove more heat from the cutting zone. The ground workpieces under conventional lubrication-cooling lost around 5% of their surface micro-hardness, compared to the reference. The ones ground by the optimized method lost around 4%, whereas by MQL, approximately 8%.

At 0.05mm depth of cut, the differences between the fluid application methods are very small, showing a very similar behavior, which makes impossible any conclusion about micro-hardness tendency in the workpieces. On the other hand, there is a loss around 4%, compared to a non-ground workpiece.

At 0.08mm depth of cut, the values obtained by the MQL method are much lower than the ones obtained by the conventional and optimized methods. This can be explained by the fact that the MQL in this condition produces too much heat during the cutting process, consequently damaging the workpiece (with high roughness values) and the tool (with enormous wear). In this grinding condition, micro-hardness loss of the ground workpiece by MQL was around 4% and approximately 1.5% by the conventional method. The optimized method was not very efficient to remove heat at high depths of cut, presenting a behavior similar to MQL and inferior to the conventional method.

Another interesting fact can be observed in Fig. 3.5. The micro-hardness loss in the most severe condition was smaller than the one obtained in the mildest condition. One of the reasons is that the mildest experiment took as many as three times longer than the most severe. Therefore, there was more exposure of the surface to constantly generated heat, although this generated heat was present in smaller values. Another explanation concerns to the performance of the CBN grinding wheel, developed for more severe work conditions, which allows better results under heavier machining conditions.

To sum up, it is possible to conclude that the heat generated during the grinding process causes a reduction of the workpiece hardness, independently of the lubrication-cooling method utilized.

4. CONCLUSIONS

From data gathered with the experiments using three different methods of lubrication-cooling – conventional, optimized (proposed by Webster (1999)) and MQL – it is possible to conclude that, for plane grinding of tempered and quenched steel ABNT 4340 (Brazilian Association for Technical Standards), varying the depth of cut, and keeping other grinding parameters constant, that:

- The tangent cutting force presented the smallest results in the MQL for 0.02 and 0.05mm depth of cut, whereas for 0.08 mm in this method this variable suffers a big increase, being superior do the value obtained in the other two methods.
- The roughness of grinded workpieces by conventional and optimized methods was always smaller than the ones present in the MQL method; roughness of workpieces grinded by MQL is still in the acceptable range, however, for medium and high depths of cut, the roughness is on the limit or exceeds the values considered as acceptable. Under these conditions, the MQL produces low quality surfaces.
- The grinding wheel wear was smaller in the MQL than in the other two methods. The optimized method is to be highlighted for presenting good performance at low and medium depths, whereas the conventional method is to be highlighted for higher values.
- The workpieces micro-hardness shows that in the three methods there was hardness loss due to the heat generated during the cutting process.

The MQL technique in grinding is viable only when the removal of material is not severe. This way, it is possible to use MQL without considerable surface quality loss and with production gain, due to the longer life cycle of the grinding wheel. However, surface quality is impaired, producing surfaces with more roughness. For more removal of material, the MQL shows it is not an efficient lubrication-cooling method, damaging the workpiece finishing, wearing too much the tool and the machine.

The optimized method is to be highlighted for low and medium depth of cut values. It produces excellent surface finishing and small wear of the tool. It shows that the application of cutting fluid with high speed is efficient in removing chips and the excessive heat from the grinding zone. For higher depths of cut, the conventional method is better indicated, although the resulting parameters are not satisfactory.

The choice of the method depends on several parameters. As long as equipment is available, the MQL is a very effective method for low removals. The optimized method proposed by Webster (1999) is a good alternative to the conventional method, because it makes the fluid application better and more dynamic, and allows a longer life cycle for the grinding tool.

This analysis was made varying the depth of cut and keeping other grinding parameters constant. A proposal for further researches is to vary other parameters, in order to attend industries demand, and analyze whether the cooling methods are efficient in maintaining process quality.

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