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Utilization of Minimum Quantity Lubrication (MQL) with Water in CBN Grinding of Steel

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The use of cutting fluids is fundamental to machining processes, mainly when it comes to high heat generation, which is the case of grinding. Thus, lubrication and cooling provided by cutting fluids improve the final quality of the workpiece. However, cutting fluid usage provide some drawbacks concerning environmental, costs and health issues. Therefore, new methods for application and optimization of cutting fluids are being researched aiming to reduce the amount of fluid used, as well as the minimization of cutting fluid hazards. The present study analyzes the behavior of a recently proposed optimization method, up to now only tested in turning, which consists of adding water to minimum quantity lubrication (MQL). Three different proportions were tested in this study: 1/1, 1/3 and 1/5 parts of oil per parts of water. The following output variables were evaluated: surface roughness, roundness errors, grinding power and diametric wheel wear. Also, optical microscopy and microhardness measurements were conducted, in order to detect burns and surface alterations. The obtained results were also compared to conventional (flood coolant) cooling-lubrication and traditional MQL (without water). MQL with water (1/5) presented better results of surface roughness and roundness errors, when compared to traditional MQL, and the results are very close to when using flood coolant. For grinding power and wheel wear, the results for MQL with water (1/5) were the best among the tested conditions.

Keywords: *grinding, minimum quantity lubrication (MQL), cutting fluid optimization, MQL with water*

1. Introduction

Grinding is an abrasive machining process, in which material removal occurs through the interaction of abrasive grains and workpiece[1]. Differently from other processes using tools with defined geometry (such as turning and milling), abrasive grains have irregular and randomly distributed cutting edges in a macroscopic view. However, in a scale much lower than the workpiece surface roughness, the grains also have regular geometry. Grinding is a finishing process used in manufacturing of high quality parts, which require high surface integrity and tight tolerances[2].

Grinding is one of the most complex machining operations due to the stochastic nature of its cutting mechanics. The excessive wear of cutting edges increases substantially the contact area, thus increasing heat generation[3]. The higher amount of heat will cause thermal distortions on both machine tool and workpiece, limiting the attainable workpiece accuracy. These thermal damages are one of the most limiting factors in grinding[4].

The occurrence of thermal damages can be minimized by lubricants such as cutting fluids[5], which remove the heat generated in the cutting zone. Heat generated from friction between workpiece and tool is also decreased, since cutting fluids act as both lubricants and coolants, contributing to reduce cutting forces and residual stresses[6].

Besides their fundamental importance to grinding, some components of cutting fluids, such as bactericides and fungicides, react with other substances, leaving them hazardous to human health[7]. Along with cost issues, environmental concerns related to the use of cutting fluids must be also taken into account, since they are being in discussion nowadays, due to the deleterious effects caused by pollution and waste disposal[8].

Aiming to minimize the aforementioned problems, industries and universities are seeking to reduce and even eliminate cutting fluids from machining processes. Until now, it was concluded that, for processes using tools with defined geometry, minimum quantity lubrication (MQL) and dry machining were viable alternatives, both in terms of costs and final results. However, for processes with high heat generation, such as grinding, MQL still stands as the most effective alternative, since dry grinding is not so effective in terms of heat removal[9].

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In order to reduce further the amount of oil used in cutting fluids, the present work aims to study the feasibility of a new cooling-lubrication method for grinding, consisting of water addition to traditional MQL technique, which conventionally uses only oil. Its uniqueness comes from the application in grinding of an already successful optimization of MQL technique, and the results proved beneficial to the process.

1.1. *The use of cutting fluids*

According to the definition, cutting fluids are liquids or gases applied around the workpiece/tool interface, in order to facilitate the cutting process[10]. The two most important considerations when working with grinding wheels are cooling and lubrication, due to high heat generation, which harms surface quality and cause dimensional and geometric non-conformities on the workpieces[11,12].

For that, the use of cutting fluids in grinding is crucial. Besides cooling and lubrication, cutting fluids are also responsible for corrosion protection for the machine tool and the workpiece[11]. Secondary functions are removal of machined chips from the cutting zone and wheel cleaning[13]. Cutting fluids increase tool service life, resulting in higher productivity and the ability of using higher cutting speeds, thus reducing surface roughness.

However, the use of cutting fluid has some drawbacks mainly concerning health hazards, since the worker is sometimes exposed to direct skin contact or inhalation of cutting fluid vapors. Skin damages and inflammation, respiratory and gastrointestinal disturbs can be developed by exposure to cutting fluids[6,14].

Cutting fluids can also contaminate soil, water and air, due to leaking, wastes, cleaning water and fluid disposal. Problems related to costs were also cited, such as: acquisition, treatment, maintenance and disposal[15]. Costs related to installation and proper fluid treatment can reach two times the costs involving tool acquisition[16]. Also, conventional cutting fluid application systems are relatively inefficient in grinding, particularly under severe machining conditions[17].

Due to the problems arising by the usage of cutting fluids, many works have been conducted in order to minimize or avoid the amount of fluid used. In doing so, no losses concerning surface quality and tool service life can be tolerated[16].

1.2. *Minimum quantity lubrication (MQL)*

When trying the minimization of cutting fluid, MQL arises as a viable alternative, since it uses only a very small flow rate of oil (100 mL/h, at a pressure of 4.0 to 6.0 kgf/cm^2). Among other advantages, the application of bactericides in the reservoir can be avoided, since there is no fluid circulation, but evaporation in the environment[18].

MQL consists of a spray of oil droplets in a compressed air jet, aimed directly to the cutting zone, very differently from the conventional flood coolant application, which covers the cutting zone with fluid. Lubrication is mainly assured by oil, and cooling is assured mainly by the compressed air flow[19].

Some advantages of minimum quantity lubrication, when compared to flood coolant (conventional cooling-lubrication) are: higher lubricating capacity, reduction of grinding power, grinding specific energy and wheel wear. Also, the costs related to workpiece cleaning are minimized, and the operation of cutting is more visible to the operator, since cutting fluid does not cover the workpiece[18].

However, one of the disadvantages is that MQL does not promote cooling as efficient as when using flood coolant[20]. This drawback, along with the higher heat transferred to the workpiece during machining, compared to the use of defined geometry tools (since abrasive grains have a negative rake angle, increasing friction at the interface and deformation of the chip), leave traditional MQL insufficient to abrasive processes, when cooling is necessary.

Many studies analyzed the various effects of MQL in grinding, and all of them states that the increase of temperature promotes higher surface roughness, thermal distortions, roundness errors and wheel wear, thus harming tolerance control and overall precision[21,22]. Recently a study was done about the use of compressed air jet for wheel cleaning, when applying MQL in grinding with CBN wheel. The results showed that an air jet incidence angle of 30º turns its penetration in the cutting zone more efficient, providing a better cleaning of the wheel, improving surface roughness, roundness errors and wheel wear, when compared to traditional MQL (without cleaning)[23]. Reduction of fluid flow associated with better results indicate that this improvement of cooling-lubrication conditions in grinding may reduce environment and health hazards, contributing to a cleaner, faster, and more cost-effective manufacturing process.

1.3. *Minimum quantity lubrication with addition of water*

Even after the advent of minimum quantity lubrication, the search for alternative methods in cutting fluid application remains intensely active. So, studies concerning the minimization of fluid (and its deleterious drawbacks) are still in discussion among researchers and industry.

As a consequence, researchers improved the traditional MQL adding water to it. Water has a higher cooling capacity than oil (two times the specific heat of pure oil), but its lubricating capacity is much lower. This method, therefore, presents higher cooling capacity than traditional MQL, due to water additions. The resultant water droplets sprayed are covered by a thin layer of oil, which may evaporate on the workpiece surface, thus promoting cooling. However, lubrication is harmed, when compared to traditional MQL (without water)[24].

The application of water in MQL grinding was studied recently[25]. In that study, a green cooling method for grinding, which is defined as minimum quantity oil–water lubrication cooling (oil–water MQL) was proposed to deal with the thermal damage during grinding of hardened AISI 52100 steel under different cooling-lubrication conditions (wet, dry, pure oil MQL and oil–water MQL). The grinding performance was investigated and compared in terms of grinding force, temperature, and workpiece surface integrity. Compared with dry grinding, surface finish and quality of

MQL grinding were significantly better due to lubrication and cooling of water and/or oil. However, MQL could not provide better lubrication and cooling in comparison to wet grinding. Even so, MQL could be considered as a future alternative to wet grinding because the former is a more economic and more environmentally friendly technique. The study of oil–water MQL grinding showed that it could significantly reduce grinding temperature and thickness of the heat affected layer compared with pure oil MQL grinding, which indicated better cooling. Pure oil MQL grinding in comparison to oil–water MQL grinding reduced tangential force and surface roughness due to better lubrication around the workpiece, chip, and grinding wheel.

Based on recent works, MQL with water proved itself more efficient than traditional MQL. Besides reducing tool wear, water additions were also responsible for suppressing thermal distortions, improving precision and final quality[26]. Previous research tested MQL with additions of water in turning, a process which behaves distinctly from grinding. This fact motivated the present study, which aimed to analyze the viability of MQL with water additions in CBN grinding, when compared to conventional (flood coolant) cooling-lubrication and traditional MQL (without water).

2. Material and Methods

The tests were carried out in a RUAP 515 H-CNC cylindrical grinder manufactured by SulMecânica. A vitrified bond CBN wheel was used, with the following dimensions: 350 mm external diameter, 127 mm internal diameter, 20 mm width and 5 mm abrasive thickness (specification SNB151Q12VR2).

Workpieces of SAE/AISI 4340 quenched and annealed steel rings were used (54 HRc), with 54 mm external diameter, 30 mm internal diameter and 4 mm thickness. A semi-synthetic soluble oil was applied in conventional (flood coolant) method, with concentration of 2.5%, at a flow rate of 2.83×10^{-4} m³/s. Its composition has already anticorrosives, biocides, fungicides, alkalizers, anti-foam, non-ionic tensoactives, alkanolamides and others. For MQL and MQL with water, vegetable oil in the proportions of: 1:1, 1:3 and 1:5 parts of oil per parts of water (Figure 1) was used.

The device for application of MQL is composed of air compressor, pressure regulator, flow rate meter and nozzle. In this experiment, the air pressure was 6.0×10^5 Pa, and the fluid flow rate was 2.7×10^{-8} m³/s. This device provides oil and allows control of oil/air flow rates individually. The air flow rate was monitored using a turbine-type meter, calibrated to a pressure of 8.0×10^5 Pa. Figure 2 presents the nozzle for MQL application[8]. This design aims to minimize

Figure 1. Cutting fluid dilution for MQL with water. From left to right: pure oil, 1:1, 1:3 and 1:5 parts of oil/parts of water.

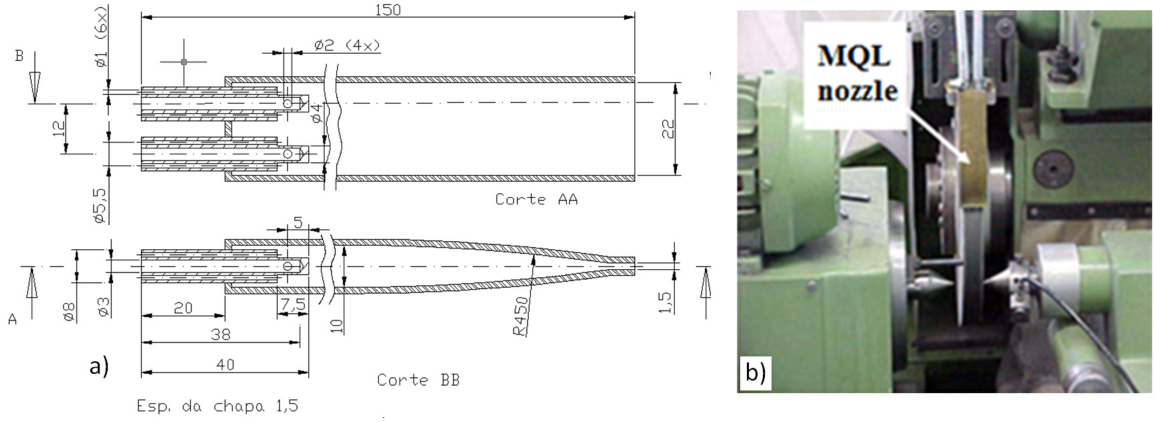

Figure 2. (a) MQL nozzle design (dimensions in mm); (b) Nozzle placement in relation to the wheel[24].

turbulence of the air-oil mixture, enhancing penetration at the wheel/workpiece interface.

A wheel cleaning system using compressed air (at a flow rate of 8.0×10^{-3} m^3/s and pressure of 7.0 bar) was also used[23]. The nozzle was placed at 1 mm in relation to the wheel cutting surface. Figure 3 presents the wheel cleaning nozzle design (a) and positioning (b).

For each test, three workpieces were ground. Besides the distinct cooling-lubrication conditions, three feed rate (v_f) values were used: 0.25, 0.5 and 0.75 mm/min. The other machining parameters were: 30 m/s cutting speed (v_s), 8 seconds sparkout time (t_s), 4 mm grinding width, 0.02 mm depth of dressing (a_d) for 12 passes, in order to remove any imperfections from the wheel surface caused by previous grinding operation. Dressing speed (v_d) was kept constant and equal to 7.4 mm/s, using a conglomerate-type dresser. For each feed rate, tests were conducted using the conventional (flood coolant) cooling-lubrication technique, MQL and MQL with water additions (1:1, 1:3 and 1:5 parts of oil/parts of water).

Surface roughness measurements were done using the arithmetic mean value (Ra). The presented results are averages of 5 readings in different positions along the perimeter for each of the three workpieces used in each condition. A Taylor Hobson Talyrond 31c was used to measure roundness errors values, and five readings were also performed in different positions of the workpiece.

The assessment of diametric wheel wear was indirectly, by "printing" the worn wheel profile on a SAE/AISI 1020 steel cylinder. This measurement was possible, since the wheel width (15 mm) was not completely worn in each test (workpiece width: 4 mm). Thus, a wear profile could be detected and measured. Diametric wheel wear values were obtained using a surface roughness meter, along with specific profiling software that measured the difference between the diameters in the piece. For that, five measurements were conducted in each workpiece.

Cutting power was determined through measurements of the consumed power from the wheel spindle. An electronic circuit was designed and built in order to convert the voltage and current values from the motor to compatible voltage signals, which then were sent to a data acquisition board and processed by a specific routine in National Instruments LabVIEW 7.1.

Optical microscopy was conducted by Olympus BX51 microscope, while Mitutoyo HM-200 performed microhardness measurements. For both measurements, five workpieces of each condition were analyzed.

3. Results and Discussion

3.1. *Surface roughness*

Figure 4 presents the obtained results for surface roughness (R_a).

It can be observed that increasing water parts in traditional MQL improved surface roughness. Among all the proportions tested, 1:5 parts of oil/parts of water provided the best results, reaching values close to (and even lower than, for 0.75 mm/min feed rate) conventional cooling-lubrication, which uses a greater amount of water in its composition.

Traditional MQL provided the worst results, since a grout was formed by the mixture of machined chips and oil, and could be detected after the tests. Even high-velocity compressed air jets are not able to remove it properly from the cutting zone. This grout scratches the workpiece surface, increasing surface roughness.

The addition of water minimizes this problem, since the overall viscosity is reduced, improving chip removal from the cutting zone, minimizing scratching and reducing surface roughness. Besides, for greater amounts of water, cooling becomes more efficient. Cooling is fundamental for dimensional and geometric accuracy, and also for satisfactory surface roughness values[24]. This explains the better results obtained for MQL with water additions, when compared to traditional MQL.

When it comes to conventional (flood coolant) cooling-lubrication, the best results were obtained, since no grout is formed and then, wheel loading (lodging of chips in the

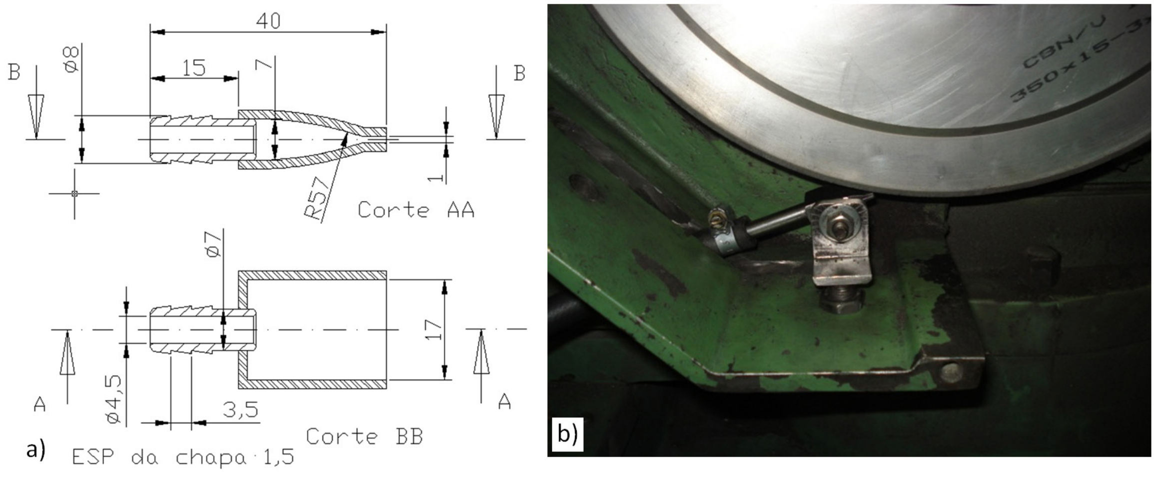

Figure 3. (a) Wheel cleaning nozzle design; (b) nozzle positioning (30° in relation to normal angle).

wheel pores) is minimized (Figure 5). Also, conventional cooling-lubrication possesses a higher cooling capacity than MQL and MQL with water. Figure 5 illustrates the most (traditional MQL) and less severe (MQL with 1:5 parts of oil/parts of water) conditions concerning wheel clogging. The shiny spots can indicate machined chips which were lodged in the wheel pores.

3.2. *Roundness errors*

Figure 6 presents the roundness error values for each condition tested.

It can be observed that roundness errors presented the same tendency as the results for surface roughness. The lowest values were obtained for conventional (flood coolant) cooling-lubrication, and the highest for traditional MQL. The results for roundness errors were improved with the increase of water, close to the values for conventional cooling-lubrication, for MQL with water (1:5).

Flood coolant application provided the best roundness results, due to better cooling capacity. With that, thermal distortions are minimized, allowing for better dimensional and geometric accuracies. Besides, for MQL and MQL with water, results worse than conventional cooling-lubrication were obtained, due to the aforementioned grout formation (mixture of MQL oil and chips), which lodges in the wheel pores. The presence of this grout increases friction between wheel and workpiece. With that, heat generation is increased, and roundness is worsened.

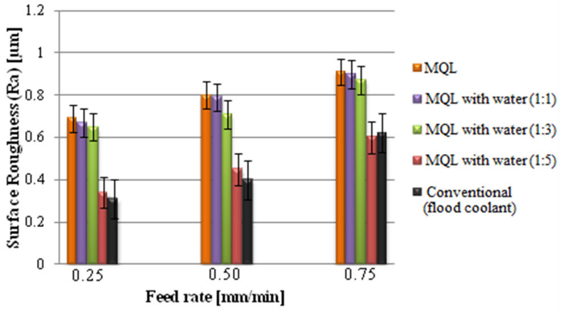

Figure 4. Surface roughness results for each cooling-lubrication condition.

As discussed previously, the increase of water reduces cutting fluid viscosity, minimizing grout formation and, consequently, wheel loading, besides improving cooling capacity. In relation to that, the increase of water parts provided lower values for roundness errors.

3.3. *Diametric wheel wear*

Figure 7 presents the results for diametric wheel wear, for each cooling-lubrication conditions tested.

The behavior of previous results (surface roughness and roundness errors) is, *a priori*, followed here. With the addition of water in MQL, diametric wheel wear decreases. This happens exactly when MQL is compared to MQL with water. However, for conventional cooling-lubrication, despite presenting the highest amount of water among all the conditions tested, the highest values of diametric wheel wear were obtained.

Diametric wheel wear is caused mainly by thermal degradation and high mechanical stresses to which the wheel is subject[27]. Therefore, for lower heat dissipation, higher will be bond strength losses, consequently increasing wheel wear. For that, water additions in MQL provided higher cooling capacity and thus, reduced wear.

In relation to conventional cooling-lubrication, higher wheel wear values are obtained. That can be explained, since this method does not provide efficient penetration of the cutting fluid, such as MQL (with or without water), which uses pressurized jets straightly directed to the cutting zone. For conventional cooling-lubrication, high flow rate disperses when the fluid contacts the wheel/workpiece interface, harming efficient penetration. Therefore, the abundant flow is responsible for wheel cleaning and cooling the flooded workpiece, since it removes heat by conduction and convection. Lubrication, however, is harmed. Thus, higher wheel wear for conventional cooling-lubrication can be explained by the lack of lubrication capacity at the cutting zone, which increased stresses on the abrasive grains, facilitating their removal.

As water parts increased in MQL, wheel wear was reduced due to better wheel cleaning (Figure 5) and more

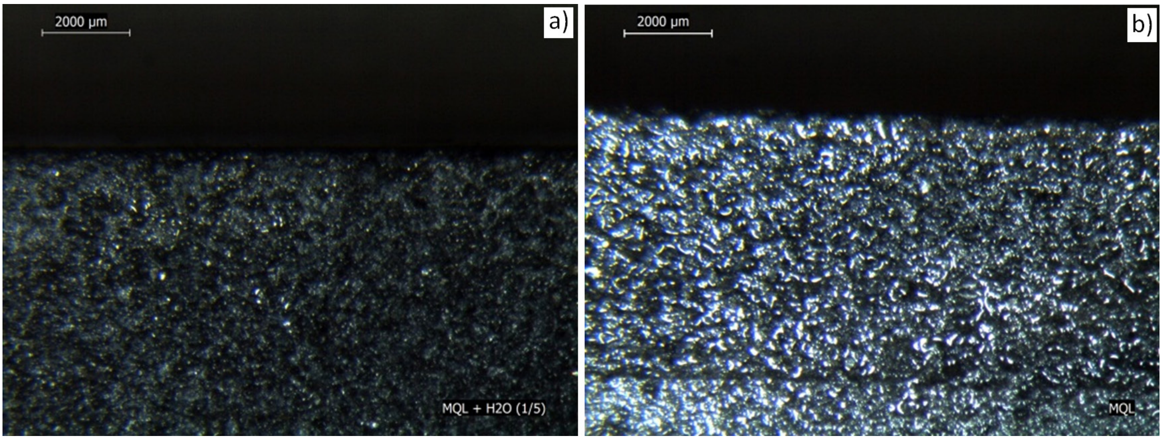

Figure 5. Wheel clogging for a) MQL with water at the proportion of 1:5 parts of oil per parts of water b) traditional MQL (without cleaning).

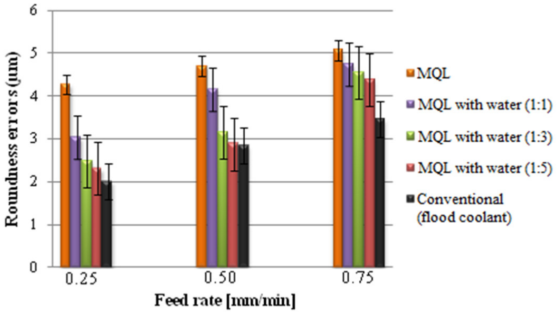

Figure 6. Roundness errors results for each cooling-lubrication condition.

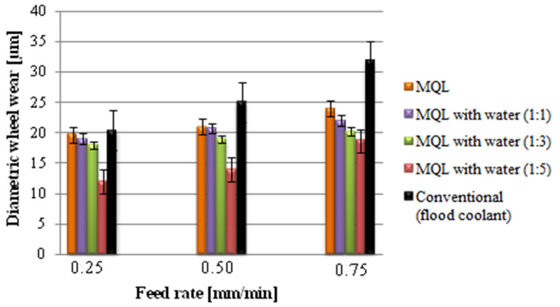

Figure 7. Diametric wheel wear results for each cooling-lubrication condition.

efficient cooling at the wheel/workpiece interface. These two phenomena overcame the lubrication losses caused by adding water to the cutting fluid. When conventional (flood coolant) cooling-lubrication was used, despite promoting higher cleaning and cooling (not necessarily more efficient), the deficiency in lubrication of the cutting interface overcame cleaning and cooling, causing accelerated grain removal from the wheel, thus increasing wear. It must be noted that cooling and lubrication are not independent phenomena, as the cutting fluids are responsible for both.

3.4. *Grinding power*

Figure 8 presents the results for grinding power, for each cooling-lubrication condition tested.

It can be observed that, among the cooling-lubrication methods tested, MQL provided lower grinding power values. This can be explained by the fact that MQL is able in disrupting the air barrier formed around the rotating wheel. Compressed air is thus capable of penetrating directly in the cutting zone, promoting efficient lubrication. Additions of water in traditional MQL were responsible for increasing grinding power, since lubrication is impaired (when it comes to MQL) due to the lower amount of oil, which increased cutting forces and power. For more parts of water per parts of oil, higher were the grinding power values.

Conventional (flood coolant) cooling-lubrication method presented relatively higher results for grinding power when compared with MQL (with and without water). The high amount of unpressurized fluid flow is responsible for the inefficient penetration in the cutting zone. Therefore, the grinding wheel is subject to higher stresses, since a greater resistance must be overcome at the interface between grain and workpiece, which increased power. Also, it must be noted that conventional cooling-lubrication is the most efficient in wheel cleaning. These results prove that the lack of lubrication is more harmful, when it comes to consumed power, than friction between lodged chips and workpiece. In other words, when it comes to grinding power, friction in the cutting surface is less deleterious than cutting and scratching promoted by the abrasive grains and lodged chips, respectively, when lubricated by MQL oil.

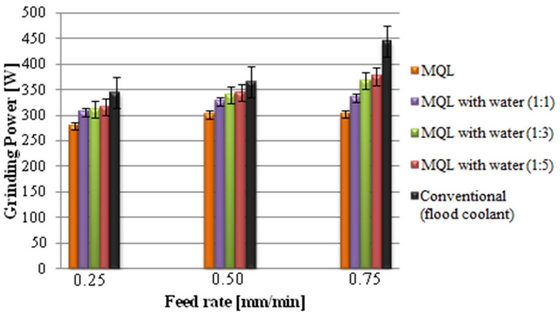

Figure 8. Grinding power results for each cooling-lubrication condition.

3.5. *Optical microscopy and microhardness measurements*

Initially, microhardness measurements were conducted for non-ground workpieces and conventional (flood coolant) cooling-lubrication condition. The first stands as a reference for the workpiece surface, and the latter stands as a reference of comparison with the MQL methods (with and without water) tested.

No surface burn areas (distinct phases) or subsurface alterations were detected. The average microhardness value for non-ground workpieces was 711.79 HK, while for conventional cooling-lubrication it was 693.1 HK. It can be observed that the values are close, which indicates that workpiece surface integrity was maintained.

Among the MQL methods tested, only extreme situations were analyzed, i.e., traditional MQL as the more severe condition, and MQL 1:5 parts of oil/parts of water as the less severe. Figure 9 presents the microscopy results for traditional MQL (without water).

It can be noted that traditional MQL was more severe to the workpiece surface, since it clearly presented a white burn. Microhardness measurements corroborate with this result, since a value of 849.1 HK was obtained, much higher than the reference values. During grinding of hardened steels, surface burns promote hardness increase, which is caused by quenching, consequence of reaustenitizing followed by formation of non-annealed martensite[20,24]. White burns are very deleterious to the workpiece integrity, since the hardened surface becomes extremely brittle, and high tensile residual stresses are present, which can cause crack nucleation and growth, reducing considerably wear and fatigue resistances[20].

Figure 10 presents the microscopy results for MQL with 1:5 parts of oil/parts of water.

Analyzing the figure above, it can be noticed that no surface burns were present. The average microhardness value was 745.8 HK, much lower than 849.1 HK from traditional MQL (without water). This can be observed since the higher amount of water provided more cooling and chip removal, reducing the number of particles in contact with the workpiece, minimizing thus strain hardening.

However, in relation to non-ground workpieces (711.79 HK) and conventional (flood coolant) cooling-lubrication condition (693.1 HK), workpiece surface suffered more damages, since the lack of wheel cleaning increased loading, due to lower chip removal, which is responsible for scratching and damaging the surface. Therefore, it can be observed that increasing water parts in MQL, in terms of surface quality and microhardness, corroborates with the best finishing results, since no surface burns could be detected and the overall integrity could be maintained.

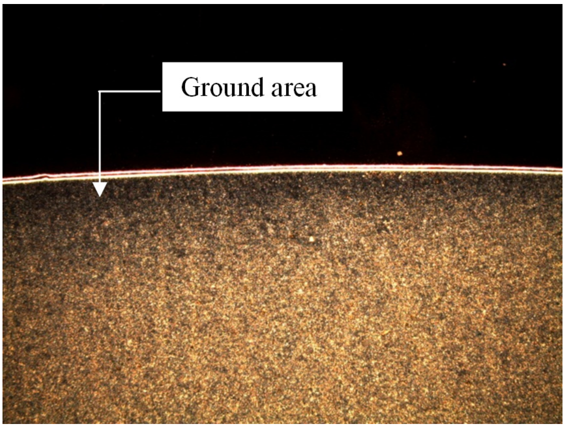

Figure 9. Optical microscopy for the traditional MQL condition (10× magnification).

4. Conclusions

Based on the results obtained, it can be concluded that, for CBN grinding of steels using MQL with water additions, compared to conventional (flood coolant) cooling-lubrication and traditional MQL (without water):

- When MQL (with or without water) is used, a wheel loading grout is formed by the mixture of oil and chips, being responsible for scratching the workpiece and worsening both surface roughness and roundness precision. With the increase of water parts, less grout is formed and better results can be obtained. Also, when using MQL, wheel wear was lower than for conventional cooling-lubrication, since the latter does not provide efficient lubrication at the workpiece/wheel interface, due to lack of pressurized flow, which disrupts the air barrier around the rotating wheel and penetrates efficiently at the cutting zone;
- By increasing the proportion of water in MQL, higher was the required grinding power, since the lower lubricating capacity caused higher friction. Conventional cooling-lubrication, on the other hand, provided the highest grinding power values among all methods tested, since it is not as efficient as MQL in disrupting the air barrier around the rotating wheel, due to the low pressure at which it is applied. Thus, higher the lubricating capacity of the cutting fluid, lower will be the consumed grinding power;
- MQL with addition of water is more efficient than traditional MQL (without water) due to the improvements observed in both finishing quality (surface roughness and roundness errors) and lower tool wear;
- When using MQL with water, for higher additions of water (1:5 parts of oil/parts of water), better results can be obtained;

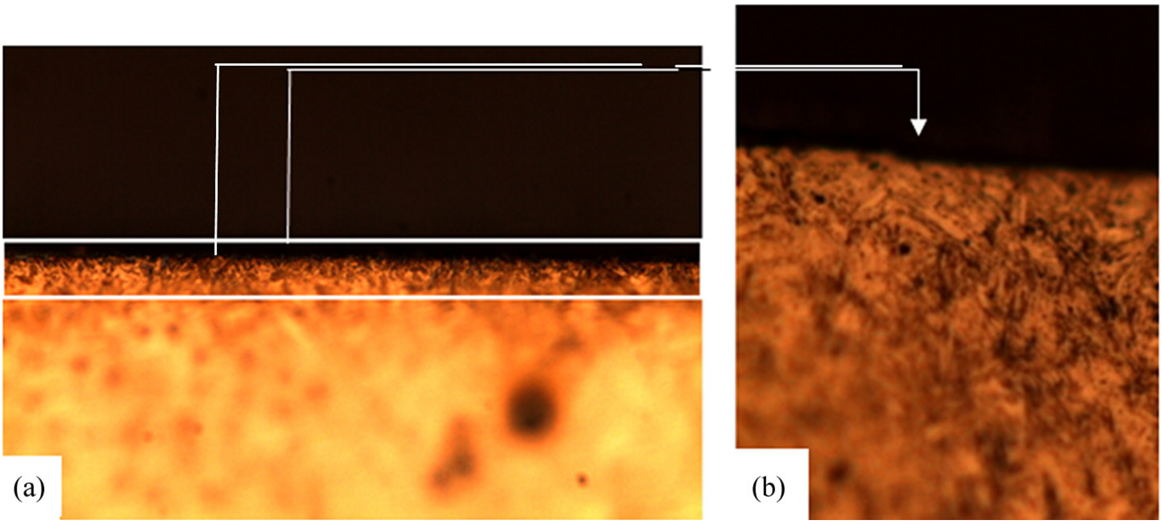

Figure 10. a) Microscopy for MQL with 1:5 parts of oil/ parts of water (10× magnification); b) Detail of the ground surface (500x magnfication).

- Conventional cooling-lubrication provided, in a general way, more satisfactory results than MQL (with or without water), except when wheel wear is taken into account;
- MQL with 1:5 parts of oil/parts of water is technically viable, even when compared to conventional (flood coolant) cooling-lubrication, since similar workpiece quality could be obtained for both methods, and the latter provided higher wheel wear and grinding power. The implementation of MQL plus water can be responsible, thus, for economic and environmental gains in grinding.

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