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Utilization of Teflon and Aluminum Oxide for Wheel Cleaning in Minimum Quantity Lubrication (MQL) Grinding

Bianca Gomes Barros, Tiago da Silva, Rubens Chinali Canarim,

Paulo Roberto de Aguiar, Eduardo Carlos Bianchi*

Bauru School of Engineering, Universidade Estadual Paulista – UNESP,
Av. Luiz Edmundo Carrijo Coube, 14-01, CP 473, CEP 17033-360, Bauru, SP, Brazil

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Researches concerning cooling-lubrication optimization in grinding have been conducted to contribute to a more sustainable process. An alternative to flood coolant is minimum quantity lubrication (MQL), which spray oil droplets in a compressed air jet. However, problems related to wheel cleaning were reported, due to wheel loading by a mixture of chips and oil, resulting in worsening of surface quality. This work aims to evaluate the viability of Teflon and aluminum oxide for wheel cleaning, compared to MQL without cleaning and MQL with cleaning by compressed air, through the following output variables: surface roughness, roundness, wheel wear, grinding power and acoustic emission. Vickers microhardness measurements and optical microscopy were also carried out. The results showed that both materials were efficient in cleaning the wheel, compared to MQL without cleaning, but not as satisfactory as compressed air. Much work is to be done in order to select the right material for wheel cleaning.

Keywords: *grinding, CBN grinding wheel, wheel cleaning, minimum quantity lubrication (MQL)*

1. Introduction

Grinding is an abrasive machining process used mainly when high dimensional quality and surface finishing are required. Material removal occurs by the mechanical action of an abrasive grain, with irregular shape and size distribution[1].

Due to its intrinsic characteristics, the countless cutting edges of the grains require a great amount of specific energy (energy per unit volume of removed material). This energy is thus converted to heat, and the high temperatures generated are one of the main causes of workpiece damages during grinding[2]. This heat can thermally damage the parts, compromising their surface integrity by the occurrence of cracks, thermal distortions, high residual stresses and dimensional non-conformities[3].

Therefore, the main concern of the process is related to deleterious effects, to which high temperatures can give rise to both workpiece and tool. Therefore, the use of cutting fluids is indispensable to heat removal, generated mainly due to friction and plastic deformation, which results from the interaction between grain and workpiece[4].

According to Pawlak et al.[5], cutting fluids are applied in machining processes to improve, through lubrication, the tribological phenomena (friction, wear) are always present in the contact zone, and through cooling, cool the generated heat. In this way, the use of cutting fluids makes possible to use higher cutting speeds, and also to increase the process efficiency[6].

Cutting fluids assure the dimensional and surface qualities by cooling and lubricating the workpiece/tool interface. Besides that, grinding without cutting fluids (dry grinding) can damage both workpiece and wheel, due to wheel clogging by machined chips[7].

Nevertheless, cutting fluids must be used in a right and conscious manner, since they can harm workers and environment. However, conventional cooling-lubrication (flood coolant) is responsible for a high aggregated cost in grinding, since it needs adequate selection, maintenance and disposal.

On that basis, many alternatives are being sought in order to reduce cutting fluids usage, as the minimum quantity lubrication (MQL), since dry grinding did not prove itself feasible due to the excessive heat generation[8,9].

The minimum quantity lubrication method uses a spray of oil droplets in a compressed air jet, where oil is responsible for lubrication, and air for cooling. However, this conventional MQL setup did not present satisfactory results concerning wheel cleaning, since a grout is formed by the mixture of oil and machined chips, which lodges in the wheel pores, thus loading the wheel and increasing surface roughness and wheel wear.

These shortcomings associated to MQL are described on the work by Sahm and Schneider[10]. In order to minimize its effects, the present study aims to use a Teflon block and an abrasive rod in contact to the wheel to promote cleaning of its pores, during MQL grinding. In doing so, it was expected to obtain a higher efficiency of this cooling-lubrication method, since it is a suitable and environmentally friendly alternative when compared to flood coolant application.

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*e-mail: bianchi@feb.unesp.br

2. Theoretical Background

2.1. *Grinding*

Grinding is an abrasive machining process, where material removal occurs by the interaction of abrasive grains with the workpiece. Differently from other processes, which use tools with defined geometry, the grains have irregular cutting edges[11].

The grinding process is used mainly during the last steps in manufacturing chain, where high surface quality and narrow dimensional tolerances are required, which makes it an expensive process. Moreover, the high temperatures generated are a common problem in grinding. Thus, cutting fluids are used to minimize thermal damages to the workpieces.

2.2. *Minimum quantity lubrication (MQL) and the wheel clogging phenomenon*

MQL consists of a spray of oil droplets in a compressed air jet, directed straightly to the cutting zone[12]. Minimum quantity lubrication can minimize many shortcomings of high cutting fluid consumption, like increased costs and environmental and health hazards[13]. Also, the workpiece comes out practically clean, and the visual monitoring of the grinding operation becomes viable, since it is not covered by fluid.

Therefore, MQL presents itself as a trend when it comes to cooling-lubrication methods applied in machining[14]. However, the great drawback of minimum quantity lubrication is related to cooling capability, thus impairing its application when high cooling rates are necessary, such as in grinding[15].

When energy in contact between tool and workpiece generates an increase in temperature, metallic particles are more prone to lodge in the wheel pores[16]. Therefore, a further increase in temperature will take place, thermally damaging the workpiece surface with burn, besides impairing surface finishing and increasing wheel wear.

For lower specific grinding energies, damages are less prone to occur[17]. The wheel clogging phenomenon can be explained as following: when machined chips are not completely removed from the cutting zone by the cutting fluid, they lodge in the wheel pores, impairing cooling-lubrication and, also, wheel cleaning. These lodged chips decrease grinding efficiency, since the cutting capacity is hindered, and material removal occurs mainly by plastic deformation. Thus, increasing the process energy, the generated heat in the cutting zone will also be higher[18].

Specific alloys of poor machinability easily load the wheels, when chips lodge in the pores between abrasive grains. With high removal rates, wheel loading is more likely to occur; however, some wheels are more prone to load than others. Two ways to avoid clogging are: using open structure wheel, which can increase the probability of bond fracture; or redress the wheel, which increases the total process costs. An alternative is to use wheel cleaning by cutting fluid[19].

Figure 1 presents a micrograph of a loaded wheel surface (100x).

Figure 1. Wheel surface with lodged chips.

2.3. *Minimum quantity lubrication with wheel cleaning*

The minimum quantity lubrication technique presents certain limitations in relation to chip removal from the cutting zone, which causes wheel loading. A grout formed by the mixture of chips and MQL oil adheres to the wheel surface, and the centrifugal force is not high enough to properly remove this material. The chips thus scratch the workpiece and increase both surface roughness and wheel wear.

In this way, aiming to improve MQL in relation to wheel cleaning, i.e., grout removal, wheel cleaning systems were tested and compared on this study: the application of a compressed air, a Teflon block and an aluminum oxide rod were.

3. Objectives

The present work aims to test the minimum quantity lubrication technique in grinding, with wheel cleaning by a Teflon block and an abrasive rod, comparing the obtained results to the additional compressed air jet (angle of incidence: 30°, which provided the best results, based on previous results by the authors), to MQL without cleaning and to flood coolant (conventional cooling-lubrication).

Also, the intention is to optimize the application of minimum quantity lubrication, in a way that the obtained results are comparable to flood coolant, especially in severe machining conditions, thus increasing the viability of MQL in industries.

4. Material and Methods

4.1. *Material*

The experiments were conducted in a SulMecânica RUAP 515-H CNC cylindrical grinding machine. The dimensions of a vitrified CBN wheel with the designation B91R300V23A were: 350 mm external diameter, 127 mm internal diameter, 15 mm width and 5 mm abrasive thickness.

The specimens were AISI 4340 steel rings, quenched and tempered (54 HRc average), with the following dimensions: 54 mm external diameter, 30 mm internal diameter and 4 mm thickness, The cutting fluid used in conventional flood coolant application was Quimatic ME-I semi-synthetic soluble oil, with 2.5% concentration, applied at a flow rate of 17 L/min. This fluid contains in its composition anticorrosives, biocides, fungicides, alcalizers, anti-foam, non ionic tensoactives and alkanolamides.

The MQL application system was Accu-lube 79053D, manufactured by ITW Chemical Products Ltd. In the experiments, the air pressure was 6.0×10^5 Pa, and the fluid flow rate was 2.7×10^{-8} m^3/s. This equipment uses a pulsating system for oil supply, which allows the separate regulation of oil and air pressures.

The compressed air wheel cleaning system is composed of: compressor, flow and pressure meters, flow distributor and application nozzles. The air flow rate was 480 L/min, and the pressure for each nozzle was 7.0×10^5 Pa. The air flow meter was Siemens Sitrans-P.

The block/rod cleaning system is composed of: alumina rod (rectangular, 60 mm × 25 mm, 80 mesh), commercial Teflon (rectangular, 60 mm × 25 mm), Festo pneumatic double acting cylinder (with 32 mm diameter 150 mm stroke), C2 50AAF STECK electric contactor, 100A 200V three-phase cut-out, STECK S2D20 100 A temporizer to control the time in which the blocks remained in contact with the wheel, metallic 20MT TDTD NPN 18mm barrier sensor, 110/220 VAC PA-12 selectable sensor controller and Festo magnetic end-of-stroke sensor. The sensor was used to detect the blocks, in order to begin and stop the contact.

Figure 2 presents the wheel cleaning system and its components.

The machining parameters were: wheel peripheral speed (V_s): 30 m/s; workpiece speed (V_w): 0.58 m/s; spark-out time: 3s; dressing speed (V_d): 0.3 mm/s; overlapping ratio (U_d): 12 (conglomerate dresser); and dressing feed rate: 0.02 mm/pass.

Surface roughness (Ra) measurements were recorded with aid of a Taylor Hobson Surtronic 3^+ surface roughness meter. The presented values are averages of 5 readings in different positions, with their respective standard deviations, for each of the three workpieces used in each cooling-lubrication condition.

In order to measure roundness errors, for all tests, Taylor Hobson Talyrond 31c meter was used, and five measurements in different positions of the ground workpieces were conducted.

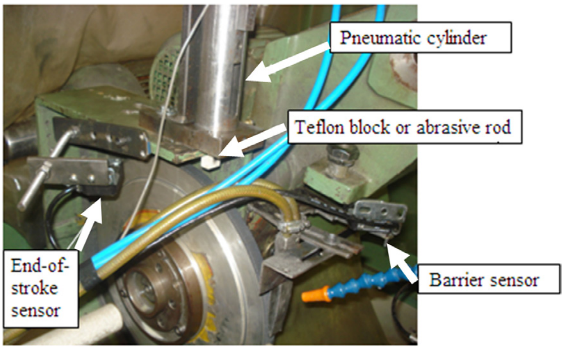


Figure 2. Proposed wheel cleaning system.

Measurements of Vickers microhardness were conducted in a Mitutoyo microhardness meter, with load of 500 g, and the values were then converted to Rockwell C scale.

The evaluation of diametrical wheel wear was conducted using an AISI 1020 steel cylinder, in order to print the wheel profile. This indirect measurement was made possible, since the wheel thickness was not totally used (from 15 mm of wheel thickness, only 4 mm - equivalent to workpiece thickness - is used). This way, the wheel profile can be marked on the workpiece, and then evaluated by Surtronic^{3+} profile meter. Five measurements were conducted on each workpiece, for each test.

4.2. *Experimental method*

The tests were conducted in order to evaluate the influence of the different machining and cooling-lubrication conditions on the output variables. A series of preliminary tests was realized to determine the best set of parameters.

Three experiments were conducted for each of the three feed rates evaluated (0.25 mm/min, 0.50 mm/min and 0.75 mm/min). The cooling-lubrication methods tested were conventional flood coolant, MQL without cleaning, and MQL with three different cleaning systems: compressed air jet, Teflon block and aluminum oxide rod.

In order to keep the same conditions at the start of each test, the CBN wheel was always dressed, using a depth of dressing of 2 μm.

The evaluation of the cutting fluid application methods was conducted through the following output variables: surface roughness (R_a), diametrical wheel wear, roundness errors, grinding power and acoustic emission signals (RMS).

5. Results and Discussion

5.1. *Surface roughness*

Figure 3 presents the average surface roughness (R_a) results for each cooling-lubrication condition (conventional flood coolant, MQL + compressed air, MQL + Teflon bar and MQL + aluminum oxide rod) and feed rate values. The presented values were defined by the average of five measurements in different positions.

By analyzing Figure 3, it is possible to notice that the best surface roughness results were obtained for conventional cooling-lubrication method. The higher flow

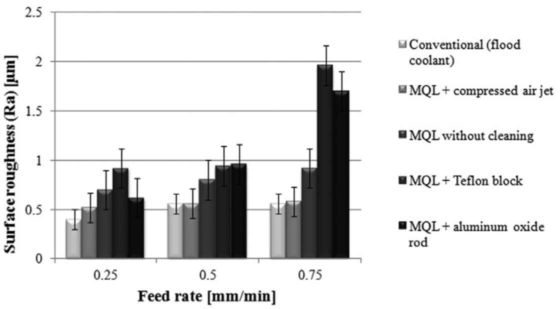


Figure 3. Average surface roughness results for each cooling-lubrication method.

rate of flood coolant is responsible for removing the chips from the cutting zone more efficiently[13]. Therefore, it could be stated that, in terms of surface roughness and cooling, this method can provide the best results, since an efficient cooling is important to obtain dimensional and geometric accuracy, as well as low surface roughness of the machined part[20].

Despite MQL providing efficient lubrication and reduction of specific grinding energy, when compared to conventional cooling-lubrication (soluble oil) in not so severe machining conditions, the surface roughness values obtained are not satisfactory, since a mixture of oil and chips (grout), lodged in the wheel pores, scratch the part surface[21].

In the present study, which attempts to evaluate different methods of removing this grout, the use of a Teflon block with MQL did not provide significant improvements in terms of surface roughness. This occurred due to the very low hardness of Teflon; when the block contacts the wheel, the mixture of oil and chips is removed from the cutting zone, but Teflon particles remain lodged, causing another wheel loading, which impairs grinding efficiency and surface finishing.

On the other hand, when using MQL with aluminum oxide rod, compared to conventional MQL (without cleaning), a lowering on the surface roughness could be noticed, for the lowest feed rate (0.25 mm/min). This may have been occurred, since aluminum oxide could have sharpened the cutting edges of the abrasive grains, while the grout was being removed from the wheel pores. However, as explained previously, due to the excessive rod wear, it was not possible to last a long period of time. Therefore, with the increase of feed rate, the contact with the loaded wheel could not last as much as to significantly improve the results.

The results obtained for MQL with compressed air were satisfactory, when compared to conventional cooling-lubrication, since for the feed rate of 0.50 mm/min the surface roughness values were similar. This improvement in surface roughness happened due to the efficiency of compressed air in removing the grout from the wheel pores. This phenomenon of cleaning is favored by the vector sum of the wheel peripheral velocity components and the compressed air velocity. With this combination, the resultant will transfer a higher quantity of movement to the grout, promoting its removal.

5.2. *Roundness errors*

Figure 4 presents the results of roundness errors (expressed in micrometers - µm) for each cooling-lubrication method tested.

Conventional cooling-lubrication provided the best results for roundness errors, since it possesses the higher cooling capacity. With that, thermal distortions were minimized, allowing for higher dimensional and geometric accuracy. The high friction generated during grinding (mainly between workpiece and wheel), can be considered a factor of extreme importance when it comes to roundness errors. In order to reduce friction and improve the part final quality, cutting fluids with good lubrication capacity becomes necessary[22].

When using MQL + compressed air (at 30° angle of incidence), the optimal resultant of the vector sum between the compressed air velocity and the wheel peripheral velocity components, and its high cooling and cleaning capacity (similar to conventional cooling-lubrication) provided the best roundness results.

Comparing the results between MQL and MQL + Teflon block, it can be noted that the latter provided lower roundness error values, proving that even with similar results, Teflon was efficient in terms of wheel cleaning, thus improving the final quality in this case.

However, on the other velocities, MQL + aluminum oxide rod provided higher roundness errors, which can be explained by the fact that the rod contacted (and thus impacted) the wheel periodically, harming geometric and dimensional accuracies. When the rod was contacting the wheel, cleaning occurred and the grinding conditions were different than when no contact was observed. Therefore, more and less efficient wheel cycles alternated when the rod was applied for wheel cleaning. This effect was aggravated due to the lower machining time used in these tests.

5.3. *Diametrical wheel wear*

Figure 5 presents the results obtained for diametrical wheel wear.

The diametrical wheel wear is caused by thermal degradation and high mechanical stresses. Therefore, for a less efficient heat dissipation from the cutting zone, higher will be the bond deterioration, and consequently, higher wheel wear[23].

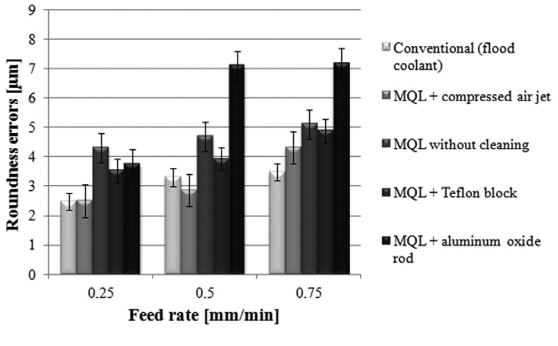


Figure 4. Roundness errors results for each cooling-lubrication method.

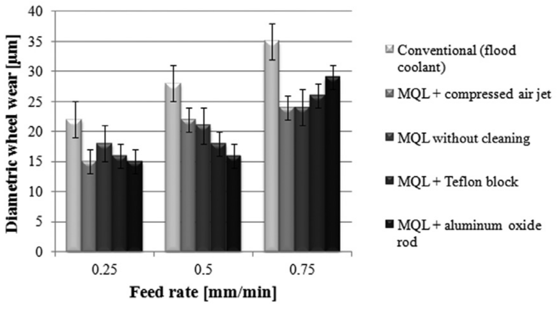


Figure 5. Diametrical wheel wear results for each cooling-lubrication condition.

According to this statement, it is possible to observe that minimum quantity lubrication, where air and oil are directed with high pressure to the interface between workpiece and tool, provided good results for wear, due to its capacity of cooling and lubricating efficiently the cutting zone.

When using the Teflon block and the aluminum rod, compared to MQL without cleaning, lower wheel wear values were obtained. The use of these cleaning materials for grout removal allowed more efficient cutting, thus reducing grinding forces and tool wear.

It could be also noted that, for the three types of cleaning, the aluminum oxide rod provided less wear in lower velocities, since the tests did not last so long as the others, due to its fast wear rate.

The cleaning methods of compressed air jet and Teflon block did not present significant difference in terms of diametrical wheel wear. Even with the air nozzle being more efficient in removing the grout, as proved by the surface roughness results, Teflon did not behave similarly; however, cleaning was possible to the point of lowering cutting forces, and thus reducing wheel wear.

From the analyzed methods, conventional cooling-lubrication (flood coolant) provided the higher wear values for all feed rates tested. This fact can be explained, since this method does not penetrate as efficiently in the cutting zone as when using MQL (with and without cleaning). That is due to the high pressure at which the MQL fluid is directed to the cutting zone.

When conventional cooling-lubrication is used, the high flow rate generates turbulence when the fluid contacts workpiece or wheel, hindering the efficient penetration in the interface. Therefore, the fluid is only capable to cool the workpiece and clean the wheel pores. However, the lubricating capacity is harmed. Consequently, the higher diametrical wheel wear obtained for conventional cooling-lubrication was caused probably by the lack of lubrication on the cutting interface, which increased the stresses on each grain, favoring wear.

5.4. *Grinding power*

Figure 6 presents the results of grinding power (W) data for each cooling-lubrication condition tested.

Minimum quantity lubrication without cleaning provided satisfactory cutting power results. This can be explained by the capacity of MQL in disrupting the air barrier formed due to wheel rotation. The compressed air is thus capable of introducing the lubricant in the cutting zone; however, no chip removal was possible because of low oil flow rate. With that, a more particles are in contact with the workpiece, increasing thus cutting power.

It can be noted that MQL with compressed air nozzle and aluminum oxide rod demanded lower grinding power, due to the fact that grout removal was more efficient, reducing friction and cutting forces.

MQL with the aluminum oxide rod also provided lower grinding power values, which is due to the fact that, in that case, the chips were not efficiently removed from the cutting zone. Consequently, no high reaction forces on the wheel were generated, which also did not cause a component tangent to the wheel rotation, hindering the increase of grinding power. Besides, during machining, the abrasive rod was able to sharpen the wheel, reducing cutting forces (and power).

Conventional cooling-lubrication (flood coolant), on the other hand, provided higher values than MQL with and without cleaning (except for Teflon block). The high flow rate with low pressure hinders the effective penetration in the cutting zone. Thus, a higher grinding power is required, since exists a greater friction at the tool/workpiece, and the wheel is subject to higher stresses.

Also, it must be remembered that conventional cooling-lubrication cleaned more efficiently the wheel pores, and thus created a reaction force on the wheel due to the flow rate. Despite resulting in lower surface roughness, the force component tangential to the wheel rotation increased grinding power.

The use of Teflon, responsible for grout removal, loaded the wheel with its own residues, increasing tool stresses and cutting power.

5.5. *Acoustic emission (RMS)*

In Figure 7, the results for RMS acoustic emission signals (in Volts) are presented for each cooling-lubrication condition.

Among all the methods analyzed, conventional cooling-lubrication allowed the lowest amount of chips in the cutting zone, since no grout is formed from the mixture with the cutting fluid. Therefore, satisfactory results can be obtained, but not as good as when using wheel cleaning (Teflon and aluminum oxide).

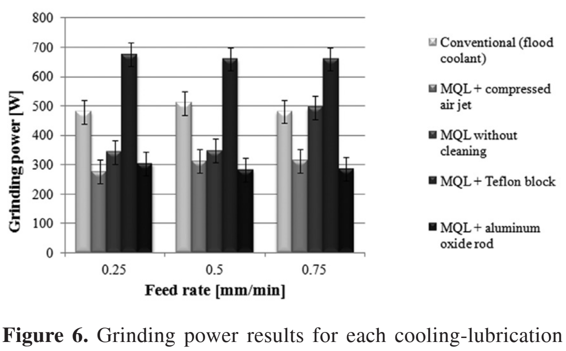


Figure 6. Grinding power results for each cooling-lubrication condition.

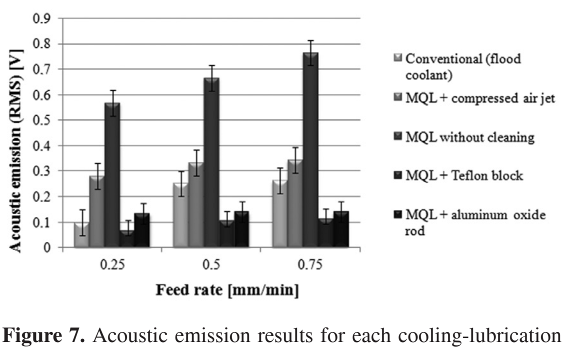


Figure 7. Acoustic emission results for each cooling-lubrication method.

Also, acoustic emission results did not behave as the other output variables, since for MQL + aluminum oxide rod or Teflon block, lower AE signal values were obtained. This happens due to, as more chips are removed from the wheel pores, lower will be the noise and friction between workpiece and tool, and lower will be the probability of defects during machining.

MQL without cleaning provided the highest AE signals (as expected), because this technique is not able to efficiently remove the lodged chips, thus increasing friction and noise.

Using a compressed air jet, on the other hand, made possible to obtain intermediate results, since this technique is also efficient in cleaning the wheel, but the high pressure and flow rate values generate more noise than the others.

5.6. *Optical microscopy and microhardness measurements*

Microstructural analyses were conducted in order to verify the occurrence of thermal damages, and to compare the ground workpieces with a non-ground workpiece, in terms of surface integrity.

When the ground workpiece is subject to high temperatures for enough period of time, microstructural alterations can occur. In relation to this, cooling-lubrication methods and wheel material play a major role in controlling temperature and heat dissipation. The workpieces were prepared, and the optical microscopy was conducted with a magnification of 500x.

5.6.1. Non-ground workpiece

When observing the non-ground workpiece (Figure 8), is it possible to notice that no signals of annealing and burn could be found, which indicates that no different phases were apparent. This reference will be used for comparison with the other ground workpieces, for each cooling-lubrication methods.

Besides, this workpiece did not present subsurface alterations. The amount of heat and plastic deformation during turning, quenching and annealing was not enough to produce significant microstructural modifications. The average microhardness (converted to Rockwell C scale) was 59 HRc.

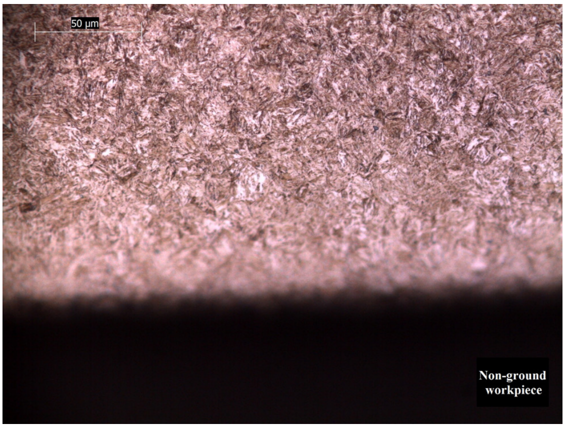


Figure 8. Optical microscopy of a non-ground workpiece (500x magnification).

5.6.2. Conventional (flood coolant) cooling-lubrication method

Figure 9 presents the optical microscopy results for conventional (flood coolant) cooling-lubrication method.

It can be observed that no surface burn (annealing) occurred during grinding. The microhardness values for this condition were 61.9, 58.0 and 60.7 HRc, for the feed rates of 0.25, 0.50 and 0.75 mm/min, respectively. The results were similar to the non-ground workpiece (59 HRc), which indicates that no hardness losses occurred, and thus surface integrity was maintained. It must be stated that the shadows under the ground surface were caused by a slight rounding during sanding and polishing.

5.6.3. MQL without cleaning

Figure 10 presents the optical microscopy results for MQL method without cleaning.

When observing the figure above, no surface burn can be detected; however, microstructural alterations could be observed when grinding with a feed rate of 0.75mm/min.

The microhardness results for MQL without cleaning were 57.0, 57.2 e 56.0 HRc, respectively, for the feed rates of 0.25, 0.50 and 0.75 mm/min. Despite the fact that annealing (surface burn) is not very clear, hardness losses occurred, when compared to non-ground workpiece and when using conventional (flood coolant) cooling-lubrication. This serves as evidence that MQL harmed the surface integrity of the workpiece, without causing burn. What could have happened is a slight annealing due to heating and cooling rate, which caused the hardness losses.

5.6.4. MQL with compressed air cleaning

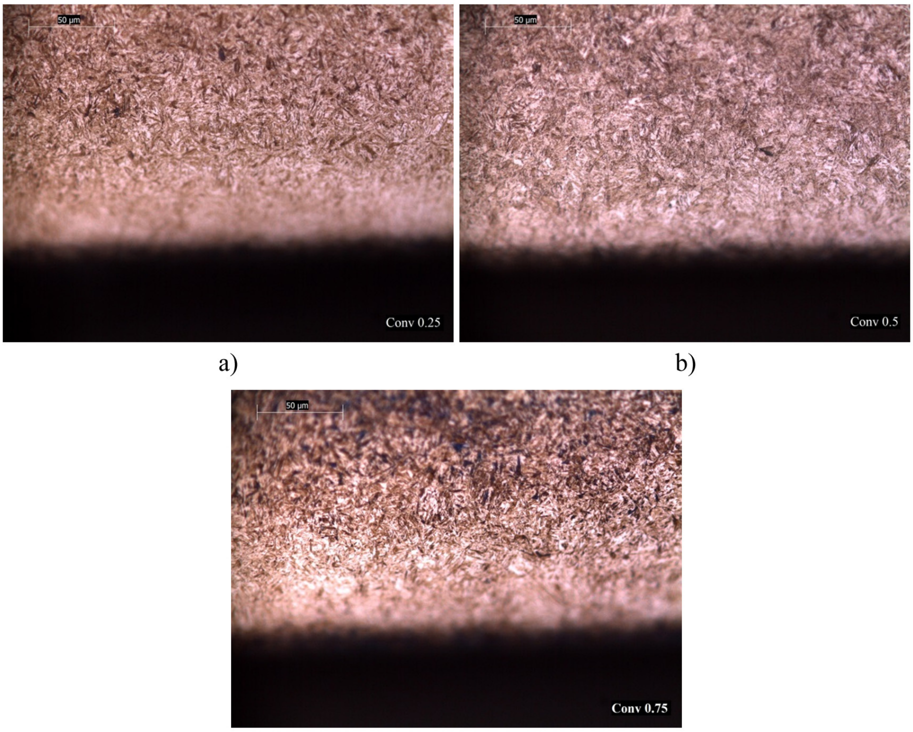
Figure 11 presents the optical microscopy results for MQL with cleaning by compressed air jet.

Analyzing the figures above, it can be noticed that no surface burn occurred. The microhardness values were: 60.9, 60.2 and 60.3 HRc, respectively, for the feed rates of 0.25, 0.50 and 0.75 mm/min. These results demonstrate that no microstructural alterations occurred, since no hardness losses could be observed, when comparing to the reference value (59 HRc) of the non-ground workpiece.

5.6.5. MQL with Teflon block cleaning

Figure 12 presents the optical microscopy results for MQL with cleaning by Teflon block.

It can be observed in Figure 12 that no surface burn (annealing) occurred during grinding. The microhardness results for this condition were 61, 59.6 and 64.2 HRc, respectively, for the feed rates of 0.25, 0.50 and 0.75 mm/min, which are very close to the non-ground workpiece (59 HRc). Surface integrity was thus maintained, except for 0.75 mm/min, which provided a higher microhardness, due probably to the heat generation during grinding. Despite the fact that strain hardening is not clear on the microscopy, even with the chip removal provided by the Teflon block, some of its particles still remained lodged, increasing the number of particles in contact with the workpiece, and thus increasing temperature and strain hardening. Higher hardness values, in comparison with MQL without cleaning, makes the material more brittle, harming fatigue resistance.



a) b)

c)

Figure 9. Optical microscopy of ground surfaces for conventional (flood coolant) cooling-lubrication method (500_x magnification). a) 0.25mm/min. b) 0.50 mm/min. c) 0.75mm/min.

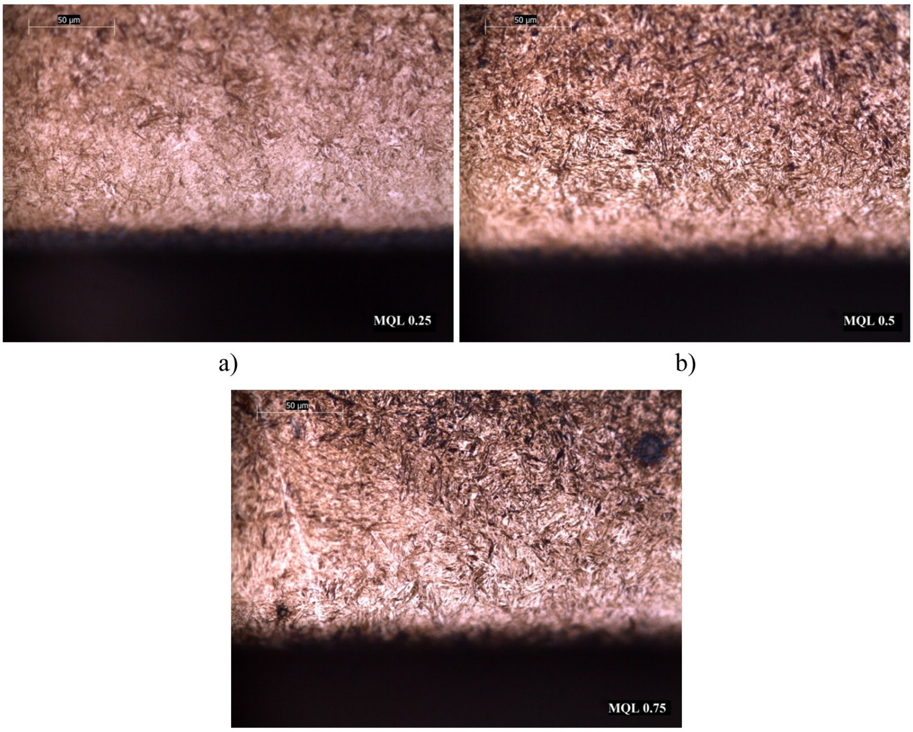


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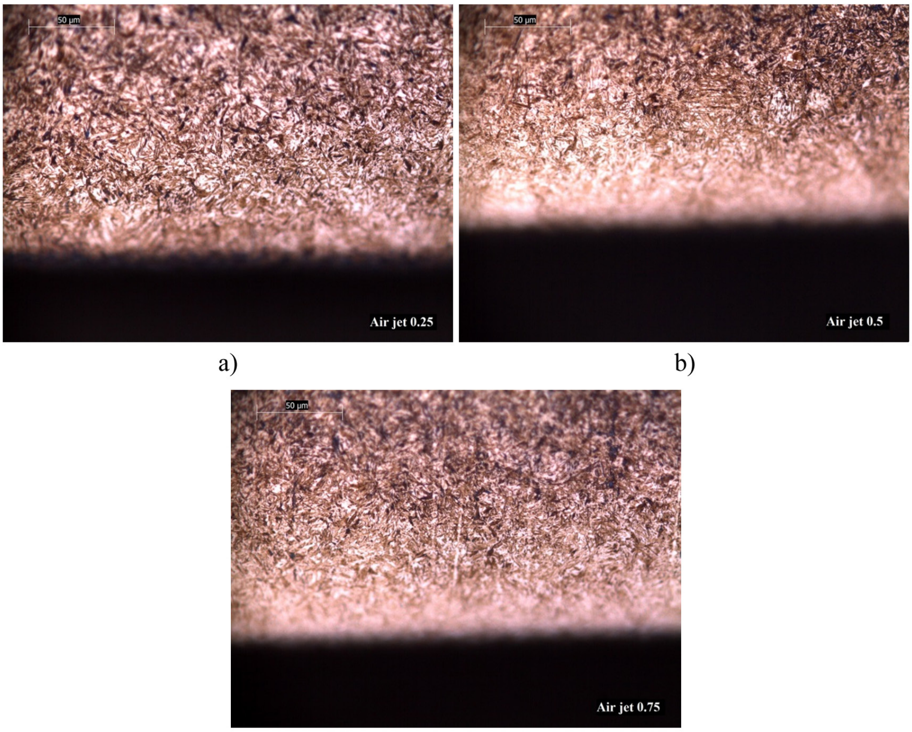
Figure 10. Optical microscopy of ground surfaces for MQL method without cleaning (500_x magnification). a) 0.25mm/min. b) 0.50 mm/min. c) 0.75mm/min.



a) b)

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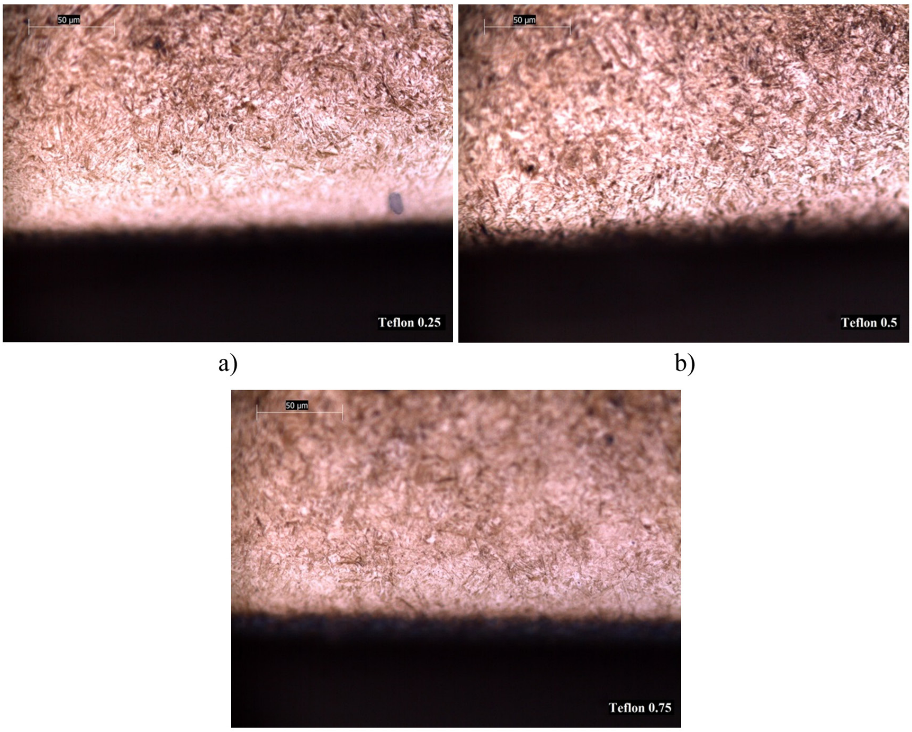
Figure 11. Optical microscopy of ground surfaces for MQL without cleaning by compressed air jet (500_x magnification). a) 0.25mm/min. b) 0.50 mm/min. c) 0.75mm/min.



a) b)

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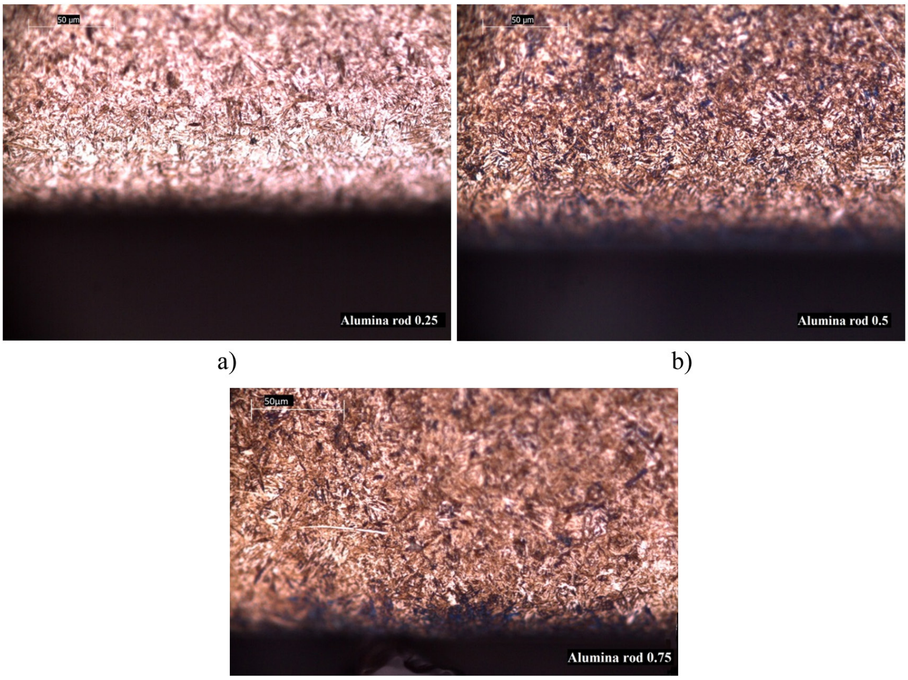
Figure 12. Optical microscopy of ground surfaces for MQL with cleaning by Teflon block (500_x magnification). a) 0.25 mm/min. b) 0.50 mm/min. c) 0.75 mm/min.



a) b)

c)

Figure 13. Optical microscopy of ground surfaces for MQL with cleaning by aluminum oxide rod (500_{X} magnification). a) 0.25mm/min. b) 0.50 mm/min. c) 0.75mm/min.

5.6.6. MQL with aluminum oxide rod cleaning

Figure 13 presents the optical microscopy results for MQL with cleaning by aluminum oxide rod.

For the feed rates of 0.50 and 0.75 mm/min, it is clear that surface burn occurred, mainly due to the severe machining conditions and high temperatures.

The microhardness values were 61.1, 61.3 e 61.0 HRc, respectively, for the feed rates of 0.25, 0.50 e 0.75 mm/min, which indicates a hardness increase in relation to the non-ground workpiece, adopted as reference (59 HRc). With surface burn, quenching occurs, since the material is austenitized, then annealed martensite is formed (when austenitizing temperature is reached). Thus, since aluminum rod did not provide efficient chip removal from the cutting zone, high temperatures were present, due to the higher number of particles in contact to the workpiece (higher friction).

6. Conclusions

Generally, the gathered results showed that the use of alminum oxide rod and Teflon block were efficient in removing the grout lodged in the wheel pores. However, they were not as efficient as the compressed air jet, previously tested. Still, further work is needed in the choice of materials to clean the wheel. It must be taken into account the wheel clogging and the interference on the wear of abrasive grains.

Due to more efficient results, the use of an aluminum oxide rod may indicate the tendency of material type used for wheel cleaning. However, the frequency in which the abrasive rod contacts the wheel should be taken into account, since it is a crucial factor for the occurrence and control of wheel clogging.

The widespread application of minimum quantity of lubrication is actually hindered by costs considerations, when it comes to the upfront investment for device installation. With the results of the present study, it was possible to contribute for the increase of economical benefits, which can be obtained by the use of MQL, since efficient solutions for wheel cleaning were proposed.

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