A STUDY OF LUBRI-REFRIGERATION AND WHEEL COMPOSITION EFFECTS IN INTERNAL PLUNGE GRINDING

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Abstract. *The precision internal plunge grinding is employed on machining responsibility parts of mechanical industry, as manufacturing bearing rings. However, there is a lack of knowledge about this operation, what makes clear the need of improvement, enabling the production of high geometric precision tolerances, typical of the abrasive machining, along with cost reduction. It is noteworthy, in relation to the present study, the reduced propagation regarding academic research, due to difficult execution of the process. There are three main problems to be solved: cutting fluid application, in virtue of the difficult penetration on the contact region between the workpiece and the wheel; tool bending, because of its reduced dimensions; and intense heat generation, being the cause of the prolonged contact time. This work aims to study the behavior of high speed internal plunge grinding, on hardened steel finishing, using three white aluminium oxide wheels of different composition and properties, one ceramic grain wheel and three cooling methods: conventional, minimum quantity lubrication (MQL) and the optimized proposed by Webster. The last two appear as optional choices concerning reduction or eliminating use of cutting fluids due to ecological regulations. The experimental method consisted in experimental machining testing, all with the same machining condition. The evaluation took place by means of output data as surface roughness, roudness errors, and diametral wheel wear. The optimized method of lubri-refrigeration presents itself as a viable alternative to the use of cutting fluids in industry, because it was possible to obtain good results in output variables, when compared to conventional and MQL methods. It is noteworthy that outlet fluid velocity must be the closest to the wheel cutting speed, in order to exist a better penetration of the fluid on the contact zone between wheel/workpiece.*
Keywords*: Internal plunge grinding, minimum quantity lubricant, Webster, ceramic wheel*

1. INTRODUCTION

Grinding is the most common designation used to define the machining process that makes use of abrasive particles to promote material removal. Grinding is traditionally considered as a finishing machining operation, capable of providing reduced roughness values (R_a from 0.05 μm to 3.2 μm) between narrow ranges of tolerance (dimensional between IT4 and IT6 and compatible geometrical tolerances) (Malkin, 1989; Chang and Szeri, 1998; Nathan *et al.*, 1999; Diniz *et al.*, 2000; Lee and Kim, 2001).

In grinding process, the interactions between abrasive grains of the tool and the workpiece are highly intense, causing the high required energy per unit of volume of removed material to be almost consummately transformed in heat, localized in the cutting zone. The high temperatures generated can produce several thermal damages to the workpiece, such as: superficial burns, micro-structural alterations involving phase changes, formation of residual stresses, deteriorating the final quality of the manufactured product (Malkin, 1989; Liao *et al.*, 2000).

The process improvement, aiming the control of thermal conditions during the operation, makes an increasingly focus on proper tool selection, in relation to the material to be ground. Also, the lubri-refrigeration method and types of cutting fluid used have the function of reducing friction and heat, being responsible, as well, for expelling the removed material (chips) from the cutting zone. Adopting those procedures, it can be possible to machine with high material removal rates, manufacturing products with high dimensional and geometric quality, providing the abrasive tool a greater life cycle (Sales *et al.*, 1999; Webster *et al.*, 1995a).

Webster *et al*. (1995a) emphasize that cutting fluid application has fundamental importance in grinding process, due to the intense friction between workpiece and tool, highly increasing the temperature in this region. Nevertheless, fluid jet is also important to promote removal of metal chips and loose abrasives during the process. The authors analyzed the conventional lubri-refrigeration methods, and verified that the removal of corners in nozzles could improve the cutting fluid flowing. Therefore, it was chosen a designed nozzle capable of providing an outlet velocity higher than 45 m/s, maximizing lubri-refrigeration effect on the contact zone. Moreover, authors observed that application relied fundamentally on nozzle placement, jet velocity and distance from the contact zone between tool and workpiece. Campbell (1995) noticed even the effects of the angular placement of the nozzle, because, according to the author, an improper direction of the flow can allow the appearance of air currents, which are harmful to the cutting fluid trajectory to the cutting zone.

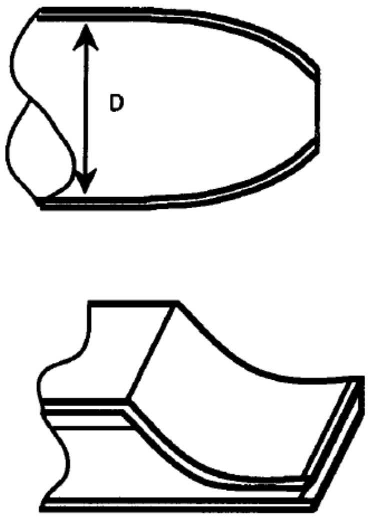
The main objective of the present work, however, is to verify the possible advantages in application and results of the optimized lubrication method proposed by Webster in relation to conventional and minimum quantity lubricant, in high speed internal plunge grinding of hardened steel, using four distinct wheels. This comparison will be made by the following output variables: surface roughness and roundness errors of the ground workpiece, and wheel diametral wear; thus, it would be possible to determine which parameters, including the lubri-refrigeration methods, flow rates and tangential speeds, will provide the best results.

1.1. Optimized method proposed by Webster

According to Webster et al. (1995b), it is possible to reduce considerably the temperature on cutting zone by using a fluid jet directed straightly to this area; however, high velocity values are required to its effective penetration. Making use of a circular nozzle, it was found the accented reduction of temperature, when compared to conventional nozzle, which has a dispersant and low speed flow.

Also according to Webster (1999), due to the industry productivity growth and the increasing use of grinding operation, great volumes of cutting fluid are becoming necessary. It should be watched out for the application of the water-based cutting fluids, with reduced density and presenting elevated dispersion when used with conventional nozzles. So, with the need of great volumes of fluid to compensate this loss, it is necessary to adopt grinders containing huge reservoirs, refrigeration units and more powerful pumps. On the other side, using the optimized method, there is an expectation of reducing the cutting fluid used and, consequently, the costs with application, storage and discard, generating thus savings for industries.

Other problem to be analyzed is the air barrier between the nozzle and the workpiece, that should be disrupted by cutting fluid; so, it is necessary, again, the application of an efficient nozzle. It should be taken into account its shape during the fluid inlet and outlet, as well as its internal surfaces. The concave ones provide a better effect, because they tend to approximate the fluid layers formed inside the nozzle. That reduces turbulence, on the contrary of the convex ones, whose tendency is to separate the fluid layers formed. Another very important aspect on the nozzle design is the presence of corners near the outlet opening, as presented in Fig. 1. This figure illustrates the circular nozzle used by Webster (1995a), and a traditional one.



(a)

(b)

Figure 1. Optimized (a) and conventional (b) shape nozzles

According to a research conducted by Webster (1995c), the speed with that the fluid penetrates the cutting zone must minimize the possible impacts fluid/tool during its penetration. That was found when the fluid velocity corresponds to the peripheral wheel velocity (unitary relation of velocities). In this case, there is a tendency to occur penetration of the fluid, with the same speed as the abrasive grain, eliminating significant interferences on the part of the grain during material removal.

1.2 Minimum quantity lubrication (MQL)

According to Klocke *et al*. (2000), it is extremely important on the process of grinding, the existence of a fluid flow directed to the contact region between workpiece and tool, which contributes to heat dissipation and removal of chips, easing the cutting operation.

On the MQL technique, the responsible element for refrigeration is air, which has lesser capacity of refrigeration than emulsions, due to its reduced specific heat capacity. For that reason, oils with excellent capacity of lubrication are used, aiming to compensate the insufficient performance of refrigerating air.

Therefore, according to Klocke *et al.* (2000), minimum quantity of lubricant (MQL) technique can be understood as a little amount of lubricating oil mixed with a compressed air flux, forming a mist which is perfused on the contact region between workpiece and tool. It is found, also, that the lubricating properties of the oil employed in MQL are responsible for reducing the friction, minimizing thus the heat flux generated, maintaining the tool in a range of temperatures that do not harm its performance.

Heisel *et al.* (1998), Dörr (1999) apud Silva (2004) and Klocke *et al.* (2000) listed some advantages of MQL technique compared to conventional lubri-refrigeration:

- Use of little amount of cutting fluid, exempting the installation of a circulation system;
- Filtering and recycling of lubricants can be avoided;
- Cutting fluids consumed in conventional process increase the need of maintenance and problems of discard and ejectment;
- Workpieces obtained at the end of process are almost dry, exempting the subsequent process of washing;
- The reduced percentage of oil mixed to the chips does not justify its recovery;
- The application of biocides, fungicides and preservatives can be eliminated, since the amount of existing oil at the reservoir is assesses for only shift, being therefore, constantly renewed and impeding the bacterial attack.

Heisel (1998) observed also that MQL utilization delays the appearance of thermal gradients. In the case of conventional fluids, the surface heat is removed in a faster speed than at regions closer to the center, because the superficial zone is covered by fluid. The gradients are responsible for bringing on heterogeneous micro-structural changes, resulting in internal stresses that will degrade the mechanical properties of the material.

However, it can be observed some disadvantages in MQL, comparing to conventional cooling, for example, the need of installing a pneumatic system capable of pressurize the air and other equipments, such as exhausters, responsible for suction of pollution suspended on air. Special attention must exist also concerning the noise generated by the air flow and the contact between workpiece and tool, harming some eventual communication during process execution (Novasky and Dörr, 1999; Klocke *et al.*, 2000).

2. MATERIALS AND METHODS

The experimental setup consisted in a CNC cylindrical grinder RUAP 515 H-CNC from SulMecânica, to which were attached some accessories, as: high rotation head for internal cylindrical grinding, where it was fixed the wheels; a support to fix the workpiece, manufactured in order to eliminate the localized stresses on the clamp fixation; optimized and conventional nozzles; and MQL pneumatic system. It was also used a dresser, to provide the resharpening of the wheel, and the workpieces, made of quenched and softened SAE 52100 steel (common in bearing manufacturing) hollow cylinders, with an average of 60 HR_c hardness.

The wheels used were conventional white alumina (Al_2O_3) wheels, one with specification of 38A100MVHB; a conventional white alumina wheel, with YT treatment (addition of sulfur), 38A100MVHBYT; a conventional white alumina wheel, with “12” treatment (addition of natural waxes), 38A100MVHB12; and a ceramic 5ES 100 M 10 VHB wheel. All wheels were provided by Saint-Gobain Abrasives Ltda. According to the manufacturer, the main objective of the alumina treatments is to increase lubrication of the contact workpiece/tool, avoiding burns and consequently improving the product final quality. Also, the wheel impregnated with sulfur is undesirable at the work environment, therefore the one with 12 natural waxes is unharmful; however, it may not have the same performance as the previous one. Both have superior cost in relation to conventional wheel, and for that reason it should be carried out a study to make its use viable.

In the present work, the workpieces were ground being subjected to three different flow rate values, for the optimized method of lubri-refrigeration: 21 l/min, 16 l/min and 12 l/min, which correspond to outlet velocities of 27 m/s, 20 m/s e 15 m/s, respectively. Conventional method was employed with a flow rate of 10 l/min; and MQL, a pressure of 784,5 kPa was kept constant. Before the start of each test, the abrasive tools were all dressed.

In the operation, for each test, 180 cycles of 8 μm radial feed were executed, removing an amount of 1.44 mm from the workpiece internal radius. After the tests, they were cleaned and the output variables (roughness, roundness errors, and diametral wear) were measured.

3. RESULTS AND DISCUSSION

3.1. Surface Roughness

Figure 2 illustrates surface roughness values, expressed in micrometers (μm), for each condition of lubri-refrigeration and wheel used.

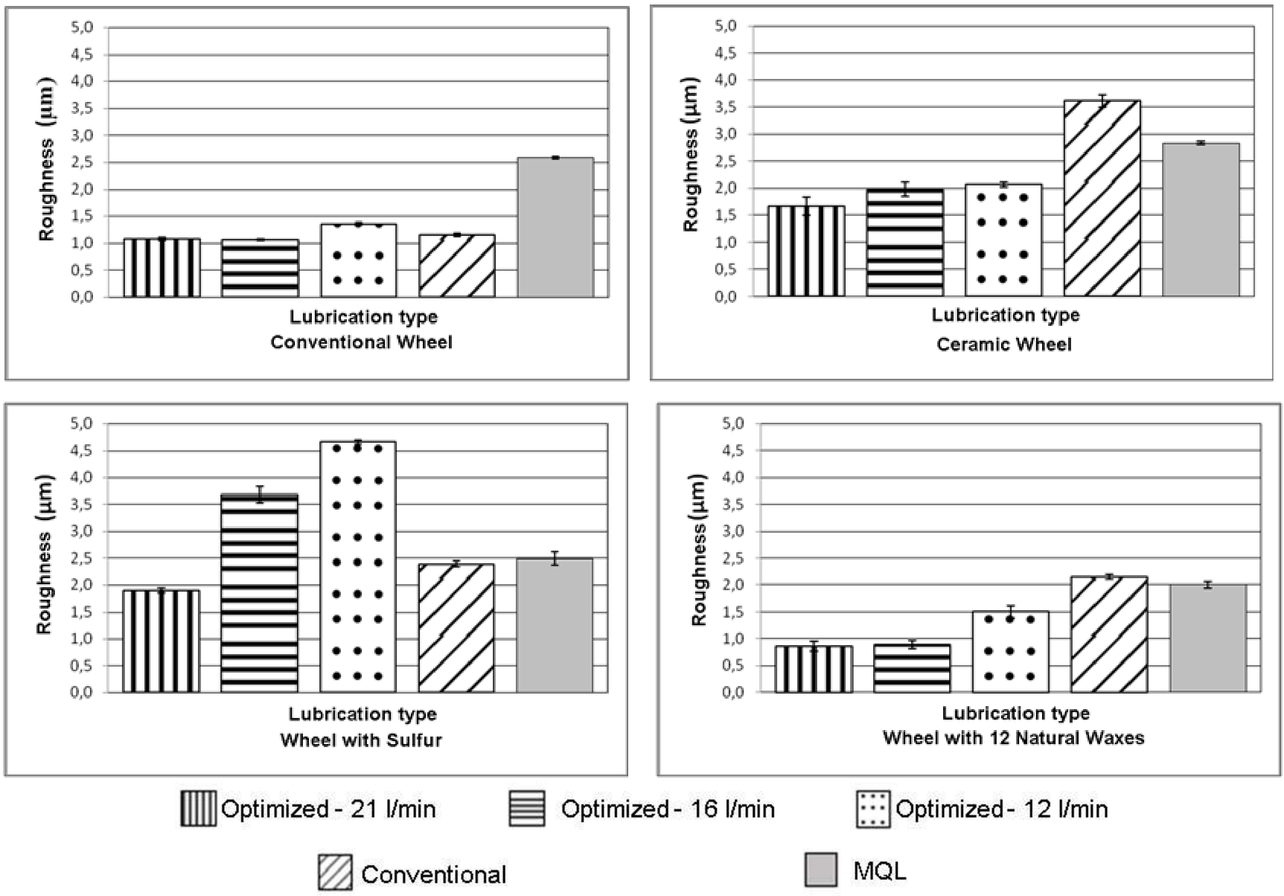


Figure 2. Roughness versus lubrication type

Analyzing, *a priori*, the results for conventional wheel, it can be verified that the flow rates of 21 l/min and 16 l/min probably provided a more efficient penetration of the cutting fluid in the contact zone between the workpiece and the wheel, due to the disruption of the aerodynamic barrier, in virtue of the higher closeness to the cutting speed (30 m/s), minimizing thus the friction, heat generation and cutting forces.

When the flow rate of 12 l/min was used, the efficiency of refrigeration was substantially reduced, causing the raise of surface roughness, because the aerodynamic barrier was probably not disrupted; it must be taken into account that the fluid jet is restricted, limiting the outlet area of the optimized nozzle (in relation to the conventional). However, nevertheless the result of this flow rate was more satisfactory than when MQL was used, for not ensuring effectively the chip expulsion from the contact zone, thus presenting the worst results of all tests.

For the ceramic wheel, it can be verified that optimized method of lubrication, independently of the flow rate, presented the best results, despite being worse than those from conventional wheel, being the causes the same previously mentioned. Restricting the analysis to the optimized method, it can be noted that the higher flow rate (21 l/min) provided the lower value of roughness; and that is no significant difference between those obtained from the lower ones (16 l/min and 12 l/min).

For all tools, the optimized lubri-refrigeration method, when properly applied, using outlet jet speed close to the cutting speed, provided the lower roughness values. Such fact can be explained by the better efficiency, on the contact zone, of heat removal, friction and cutting forces reduction. However, when flow rates of 12 l/min and 16 l/min were used, not always the method assured better performance, due to the fluid jet restriction, what prevents proper penetration on the contact and ineffective aerodynamic barrier disruption, as occurred on the wheel containing sulfur.

When MQL technique was used, the obtained results were always worse in relation to the higher flow rate optimized method. That is due to the inefficiency on chips removal, as they cluster with the lubricant and become a kind of grout which remains on the cutting zone and scratch the workpiece surface, deteriorating the finishing intended. It can be noted that, independently of the wheel used, MQL provided similar results for roughness. Also, it can be stated that MQL technique does not efficiently works in grinding operations, probably due to the centripetal acceleration that pushes away cutting fluid expected to get into the cutting zone.

Comparing the conventional wheels to the ceramic, it can be noticed that the latter presents a characteristic typical of high material remove rates, due to its grains shape (more sharpened); the obtained roughness, for same lubri-refrigeration method and same machining parameters were always superior to when used the conventional wheel.

The wheel containing sulfur did not provide good results, in relation to conventional, because its pores are already impregnate with this chemical element, so the chip cannot find a proper exit, diminishing the cutting capacity of the tool and harming the results.

The wheel with 12 natural waxes treatment, despite having also impregnated pores, provided very similar results comparing to the conventional wheel (excepting when used conventional refrigeration); however, its use is not justified due to its high cost in relation to the conventional alumina wheel.

3.2. Roundness errors

Figure 3 illustrates the roundness errors, expressed in micrometers (µm), for each lubri-refrigeration method and wheel used.

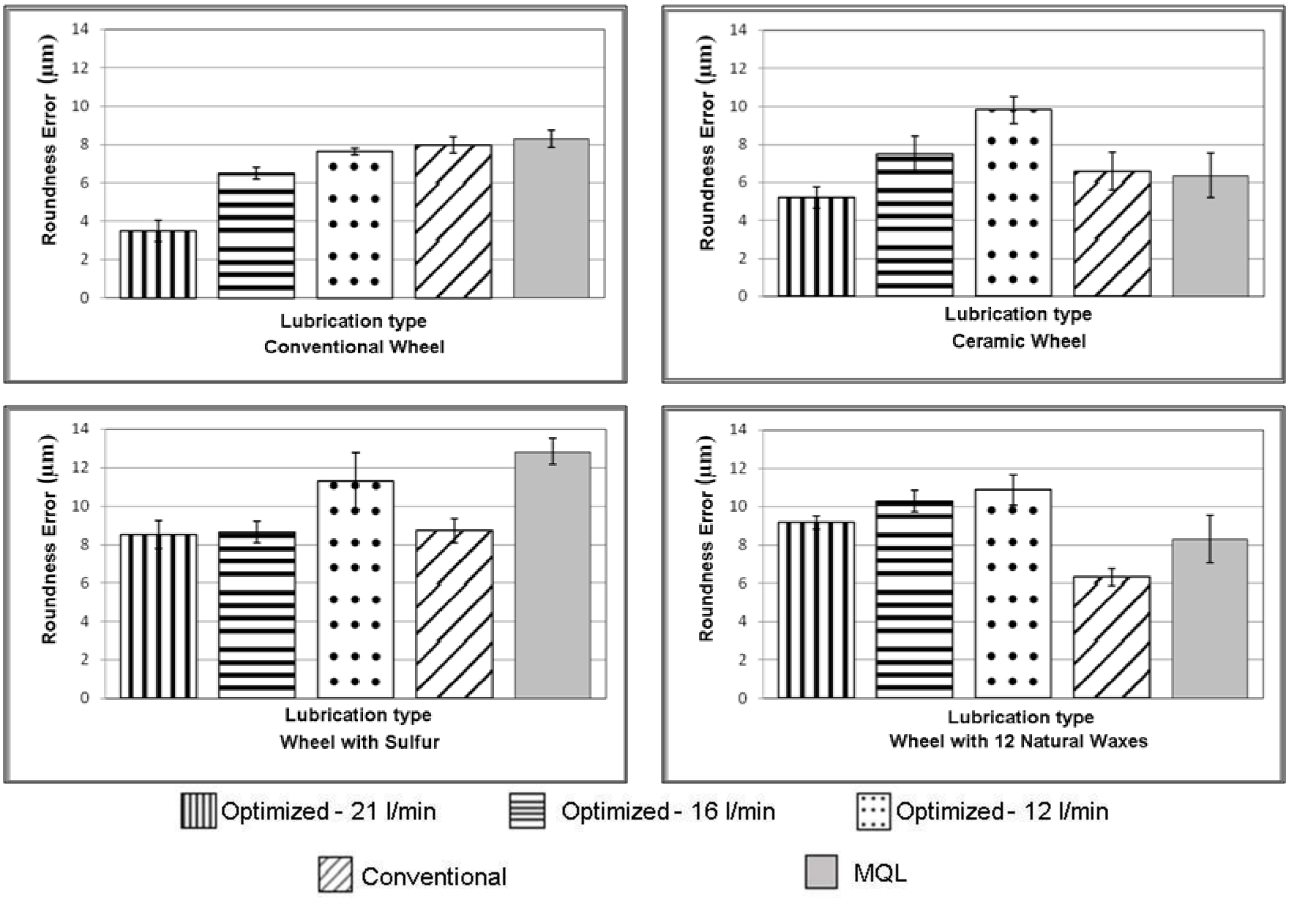


Figure 3. Roundness error versus lubrication type

In a similar way to what occurred with roughness, it can be verified that for conventional wheel, there was a reduction on roundness errors when used the higher fluid outlet velocities. This reduction was significantly accented with the flow rate of 21 l/min. That is due to the friction reduction between wheel and workpiece, minimizing cutting forces; resulting, thus in a lesser bending on the axis that supports the wheel. In that way, vibration produced by grinding on the grinder system is lower.

Analyzing the ceramic wheel, it can be found that the best result obtained was with the higher flow rate (21 l/min), from the optimized method, due to: the efficiency in disrupting the aerodynamic barrier, better lubrication of the contact zone and reduced cutting forces, diminishing the system vibration. When using 16 l/min and 12 l/min, it can be perceived a significant increase, in relation even to conventional and MQL methods. Such fact is caused by the difficulty in introducing the fluid on the contact zone, not only in virtue of the presence of an aerodynamic barrier, but the difficulty of the fluid in accessing the great contact area between workpiece and wheel, which contributes for a worse lubrication, and consequent loss of shape and increase in the system vibration.

In relation to MQL, it can be noticed that with the conventional wheel there was obtained the worst results, due to the higher wheel loss of shape, caused by friction, since this lubri-refrigeration method did not behave itself as lubricant as the other ones. In the case of using the ceramic wheel, the results obtained for MQL are similar to the conventional method, because in this case (one characteristic of the wheel, as explained by the manufacturer), is a better shape maintenance, thus reducing the roundness errors.

When used optimized method, the conventional wheel presented the best results, when compared to ceramic, evidencing that the more efficient the lubrication, the better is the performance concerning roundness errors. However, when the use of less efficient methods of lubri-refrigeration (conventional and MQL), the ceramic wheel presented the best results, in virtue of its shape maintenance characteristic (as previously explained), inexistent on the conventional, which loses its shape, by higher friction in more severe conditions, and system vibrations.

In the case of the wheel containing sulfur, optimized method with flow rate of 21 and 16 l/min did not present difference in relation to conventional, and all results obtained with this abrasive were significantly higher comparing to others. That occurs because, as there is sulfur impregnated on the pores, the chips do not find a proper exit surface, increasing thus the cutting forces involved. With that increase, there is an elevation of vibration and roundness errors. In other words, the lubrication effect generated by sulfur was not able to suppress the effect caused by obstruction of the wheel pores. That is evidenced clearly on the tests where the worst lubrication conditions were used (optimized method with 16 l/min and MQL), which presented the higher roundness error values.

The wheel containing 12 natural waxes, despite having also its pores impregnated, presented good performance when the application of conventional and MQL methods. That occurs, because this wheel can combine a satisfactory lubrication effect, in virtue of the waxes, with a better exit surface for the chips, providing thus better results on the more critical conditions of lubri-refrigeration. Observing the optimized method, it can be noticed a increase on the roundness errors with the reduction of fluid jet outlet velocity, in virtue of the stress increase caused by worse penetration of fluid in the contact zone, and the obstruction of pores ended in resulting worst results, in relation to the other lubri-refrigeration methods studied.

3.3. Wheel diametral wear

Wheel wear occurs due to three main factors: agglutinant wear, abrasive wear and grain friability (capacity of the grain of generating new cutting edges, when subjected to stresses). This variable has a great importance in grinding, since higher wear mean shorter wheel life cycles.

Figure 4 illustrates the wheel diametral wear, for each lubri-refrigeration method and wheel used.

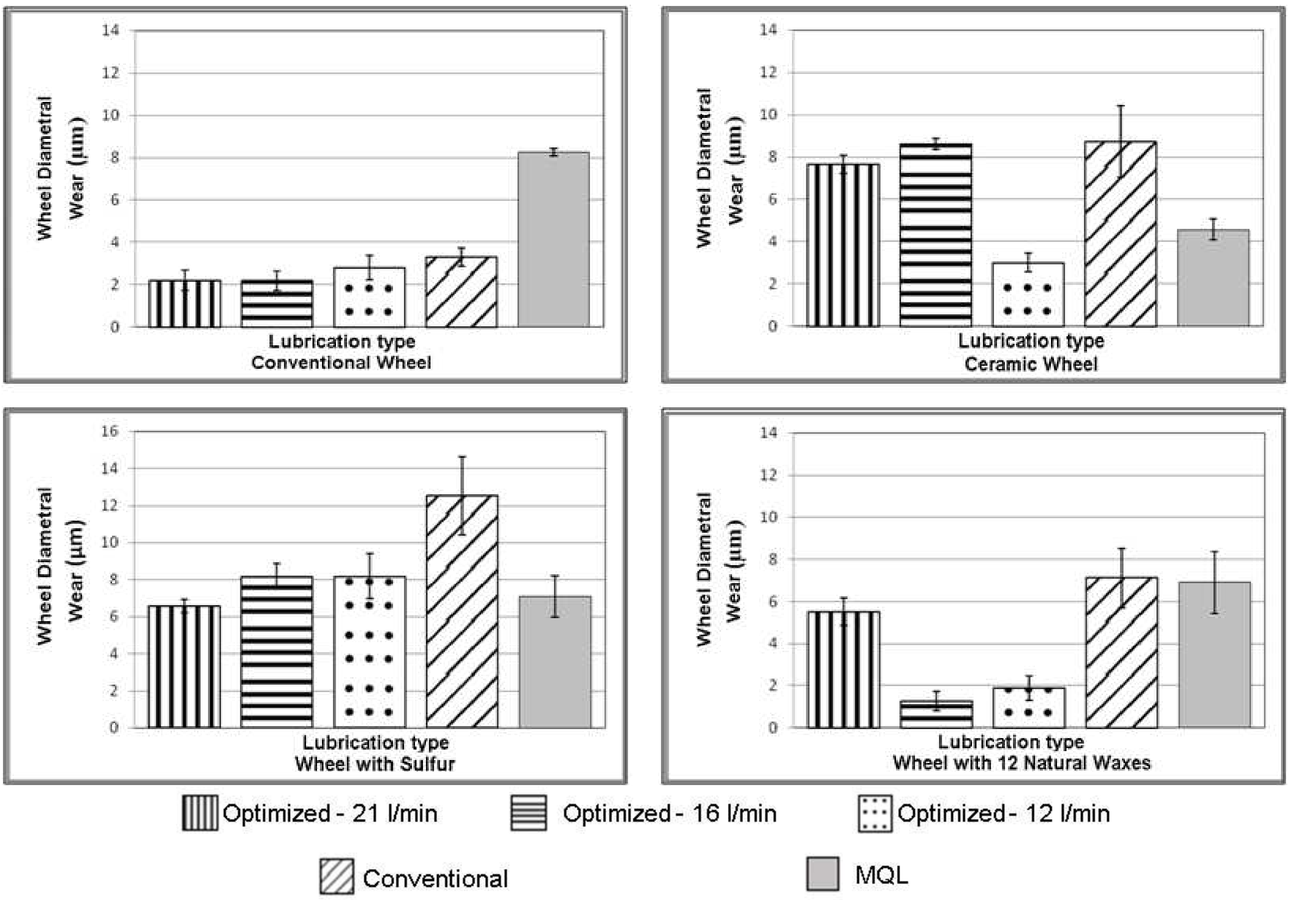


Figure 4. Diametral wheel wear versus lubrication type

It can be verified in Fig. 4, that for the conventional wheel where it was used the flow rates of 21 l/min and 16 l/min, there was obtained the best results; it can be noted a tendency to worst results, when used less efficient lubrication methods, due to increase of cutting forces, and consequently in wheel wear.

With the results from ceramic wheels and those treated with 12 natural waxes, it was not possible to notice any tendencies concerning the machining parameters, and the other relevant factors in grinding operation. That is mainly due to the way the tool is worn, and also in the case of sulfur wheel, where was an irregular wear due to system vibration generated by high cutting stresses, shaft bending and great contact area. This fact is presented clearly by the high standard deviance values found in some results.

It can be emphasized the difficulty in measuring this variable, since it was made by visual access in a CAD software, and the lack of a more efficient method to obtain the wheel diametral wear. Besides, the tool will always present an irregular wear on its surface, adversely affecting the accuracy in measuring, when used the applied method.

4. CONCLUSION

From the results obtained on the tests carried out with the three lubri-refrigeration methods (conventional, optimized and MQL), and the four types of grinding wheels (conventional, ceramic, with sulfur and treated with 12 natural waxes), it can be concluded that, for internal plunge grinding of SAE 52100 quenched and softened steel:

The disruption of the aerodynamic barrier and the higher efficiency of cutting fluid penetration on the contact region were better when using optimized refrigeration, with the higher flow rate of 21 l/min, in the majority of tests; in this case, there was a higher reduction of friction, cutting forces and temperature, causing the best results of roughness and roundness errors. The only exception occurs with the roundness error of the wheel treated with 12 natural waxes, that by having impregnated pores, prevented a better cutting fluid penetration, and thus better results.

The optimized method of lubri-refrigeration presents itself as a viable alternative to the use of cutting fluids in industry, because it was possible to obtain good results in output variables measured, when compared to conventional and MQL methods. It is noteworthy that outlet fluid velocity must be the closest to the wheel cutting speed, in order to exist a better penetration of the fluid on the contact zone.

The individual characteristic of each wheel was a determinant factor on the results, notably the ceramic wheel, that is clearly suited for higher material removal rates, in virtue of all results from this wheel generated higher values of roughness, in relation to conventional wheel. The use of impregnated lubricants (sulfur and 12 natural waxes) on the wheel pores increased machining forces, due to the difficulty of the ground chip to be expelled from the contact zone, what harms the results obtained. Thus, the use of ceramic wheels and ones with impregnated lubricants would not be viable, because conventional wheel is cheaper and presents a better performance.

The available method of measuring wheel diametral was inable to provide any conclusions, due to the irregular wear on the wheel surface and the difficulty to measure and quantify this variable. However, a tendency can be noticed only when using conventional wheel, which shows that a higher outlet fluid velocity provides better results of wheel wear, what can probably be an increase in wheel life.

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