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Evaluation of Different Methods of Cooling-lubrication in Cylindrical Grinding of Advanced Ceramic Dip

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The current work presents a study of alternative methods of cooling-lubrication for the external plunge grinding of advanced ceramics using diamond wheels. These two alternative methods, which are intended to reduce cutting fluid expenses, are commonly referred to as the optimized cooling-lubrication method and minimal quantity of lubrication (MQL). The techniques were evaluated by process monitoring and by the assessment of output variables such as tangential cutting force, G ratio, roundness errors, surface roughness, microstructure and residual stresses measured by X-ray diffraction. The obtained results showed that the two proposed techniques can replace the conventional cooling-lubrication method, i.e., flood coolant. In particular, optimized cooling-lubrication method reduced wheel wear and produced workpieces with the best geometric and dimensional finishes, while MQL significantly reduced the amount of fluid employed in the process without harming the workpiece quality.

Keywords: *grinding, advanced ceramics, cooling, minimum quantity lubrication (MQL)*

1. Introduction

Just as in the processing of metallic materials, grinding of ceramics is usually performed with the aid of cutting fluids. Cutting fluids are used to provide lubrication, cooling, chip removal and reduction of operational costs, i.e., power and tools. However, although they improve the machining quality, cutting fluids are also directly related to high processing costs[1,2]. In addition to the high purchase cost of cutting fluids, proper maintenance and disposal are also expensive. According to Astakhov[3], the costs related to cutting fluids, including the product price and the additional expenses related to maintenance and disposal, can be as large as approximately 17% of the total production cost. Besides these economic concerns, cutting fluids may also represent potential environmental risks due to their pollutant nature.

Several studies have been conducted towards alternative cooling-lubrication methods that could reduce the consumption of cutting fluid. The first systematic studies began at the end of the 1980's, focusing primarily on reducing the amount of fluid by optimizing the application conditions during grinding of metallic materials[4]. Currently, near-dry machining techniques are also known as minimal quantity of lubrication techniques, or simply MQL[5].

Select studies show that both optimization techniques for the application of cutting fluids and MQL techniques can significantly reduce the fluid consumption in grinding of metals. However, especially on ceramics, these techniques cause changes in the finished quality of the workpiece and significantly increase the consumption of cutting tools[6-8].

In this context, the evaluation of certain parameters associated with the grinding process and surface finish quality aids the understanding and improving the efficiency of grinding advanced ceramics. As stated by Hassui and Diniz[9], monitoring and control of grinding forces are extremely important, as they are associated with the grinding wheel lifetime, the duration of the grinding cycles, and the geometric, dimensional and surface quality of the workpieces. The average cutting forces values during machining are also significant because they determine the required power and the structural needs of the grinding machine. Tangential cutting force is also related to the workpiece temperature and its final surface roughness. According to Klöcke and Zunke[10], the quality of a workpiece after grinding can provide useful information about both the workpiece and the process, such as the minimum tolerances, effective conditions of cooling-lubrication, heat transfer and machine vibration.

Given the information presented previously, the present study aims to evaluate two alternatives to conventional (flood coolant) cooling-lubrication in grinding of advanced ceramics: optimized cooling-lubrication and MQL

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technique. The analysis will be conducted through the evaluation of the following output variables: tangential cutting forces, diametrical wheel wear, roundness errors surface roughness of the workpiece, morphology and surface residual stresses.

2. Material and Methods

In this work, experimental tests were conducted using a Sul Mecânica RUAP 515H cylindrical grinder, equipped with a Fagor CNC. The wheel was Dinser resin bond diamond wheel, with the following dimensions: 350 mm external diameter, 15 mm width, hardness N, concentration 50 and grain size 126 µm. Commercial ceramic rings were used as test specimens, having 54 mm external diameter, 30 mm internal diameter and 4 mm thickness, as illustrated in Figure 1. The ceramic is composed of 96% aluminum oxide in α phase (α-Al_2O_3), which is popularly known as α-alumina, with the remaining 4% consisting of oxides such as SiO_2, CaO and MgO.

2.1. Cooling-lubrication methods

Cooling-lubrication methods chosen for these experimental tests are distinguished primarily by the way the fluid is applied in the cutting zone. As this study is intended to evaluate the influence of the cooling-lubrication method on the process, three different techniques were used: conventional (flood coolant) cooling-lubrication, an optimized technique and the minimum quantity of lubricant technique (MQL).

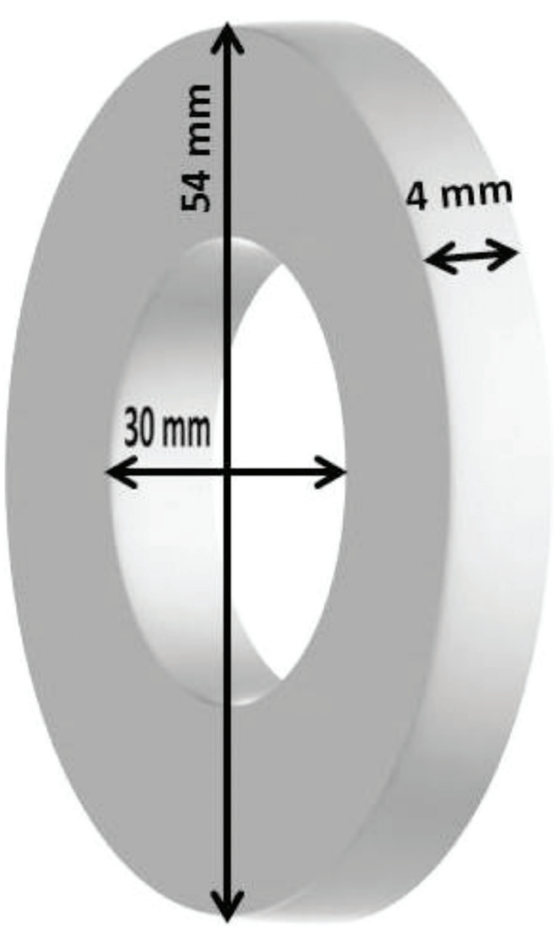


Figure 1. Ceramic specimen (dimensions in mm).

Conventional (flood coolant) cooling-lubrication system used in this study is the same used in most machining processes; it consists of a large fluid reservoir, pump, connection hoses, application nozzles and cutting fluid. Two different diffuser nozzles were used (Quimatic Fixoflex), both with 6.35 mm outlet diameters. The cutting fluid was applied with a flow rate of 1320 l/h at a pressure of 3.92×10^{-1} MPa.

Optimized cooling-lubrication was performed by replacing the traditional diffuser nozzle with a convergent one, specifically designed to penetrate the cutting zone more efficiently. This nozzle delivers a pressurized fluid jet with an outlet area similar to the dimensions of the area of contact between the wheel and workpiece, which reduces waste. The cutting fluid was applied at flow rate of 1200 l/h and at a pressure of 5.49×10^{-1} MPa.

The cutting fluid used for the conventional and optimized cooling-lubrication methods was an emulsion of 5% semi-synthetic oil (ROCOL Ultracut) in water.

The primary components of the MQL device consisted of an air compressor, a pressure regulator, an air flow regulator, a small oil reservoir, and a dosing device that allowed the separate regulation of the air and oil flow rates. Air and oil are separately drawn to the applicator nozzle, where the mixture occurs. The nozzle was specially designed to produce a fluid jet with an outlet area similar to that of the cutting zone, just as in the optimized method. For this technique, the air pressure was 6.37×10^{-1} MPa. The cutting fluid used in the MQL system was Accu-Lube LB 1000 biodegradable vegetable oil, which is manufactured by ITW Chemical Products Inc. The lubricant was applied at flow rate of 0.08 l/h.

2.2. Machining parameters

The machining parameters are presented in Table 1.

Three feed rate values were used: 0.75 mm/min, 1.00 mm/min and 1.25 mm/min. These feed rates correspond to three equivalent cut thicknesses (Equation 1): 0.0707 µm, 0.0940 µm and 0.1180 µm.

Table 1. Machining parameters.

Description	Parameter value
Feed rate: V_f (mm/min)	0.75, 1.00 and 1.25
Cutting speed: V_s (m/s)	30
Workpiece rotation: n_w (rpm)	204
Depth of cut: a_p (µm)	36.76, 49.02 and 61.27
Spark-out time: t_s (s)	5
Grinding width: b (mm)	4
Depth of dressing: a_d (mm)	0.04
Ceramic workpieces for the experiments: (rings)	13
Outlet fluid velocity (conventional cooling-lubrication, optimized method, MQL): (m/s)	30

$$h_{eq} = \frac{\pi d_W V_f}{V_s} \quad (1)$$

In Equation 1, V_s is the tangential wheel speed, V_f is the peripheral wheel speed and d_w is the workpiece external diameter[11].

In this study, each proposed cooling-lubrication technique (conventional, optimized and MQL) was analyzed with three equivalent cut thicknesses (h_{eq1}, h_{eq2} and h_{eq3}); for each equivalent cut thickness, the test was repeated three times. In each test, 13 workpieces were ground, as illustrated in Figure 2.

2.3. Evaluation of the grinding process

The evaluation of the grinding process was conducted through the monitoring of select output parameters, such as the tangential cutting force and diametrical wheel wear, and the workpiece integrity was evaluated in terms of surface roughness, roundness errors, surface morphology and residual stress.

Tangential cutting force (F_t) was obtained indirectly by monitoring the electric power from the wheel spindle, which was calculated by multiplying the voltage and electric current from the electric motor. Mechanical power (P_{mec}) could then be determined from the electric power. By obtaining the rotational frequency of the wheel (n_s), it is possible to calculate tangential force using Equation 2.

$$F_t = \frac{60 P_{mec}}{d_s n_s \pi} \quad (2)$$

where d_s is the wheel diameter[11].

Wheel wear was performed by monitoring the G-ratio (Equation 3), which is defined as the ratio between the volume of removed material (Z_w) and the volume of the worn wheel (Z_s)[11].

$$G = \frac{Z_w}{Z_s} \quad (3)$$

As already mentioned, the wheel width was 15 mm, while the workpiece wheel was only 4 mm. In that way, after the grinding cycles, a worn-unworn step was created on the wheel surface, and this difference is due to the wheel wear during grinding. The wear profile was measured indirectly by printing this wheel profile on another workpiece (AISI 1020 steel), and measuring the difference with a TESA TT10 meter. Figure 3 illustrates this procedure. It is important to note that after two grinding cycles, the wheel was redressed.

After the tests, the workpiece final quality was assessed. Roundness errors were obtained using a Taylor Hobson Talyrond 31C meter (Figure 4). Workpieces 1, 4, 7, 10 and 13 were analyzed to determine the increase in roundness errors as the test progressed. Five readings were performed on each specimen.

Surface roughness (R_a) was measured along transversely to the cutting direction using a Taylor Hobson Surtronic roughness meter.

Samples of each grinding condition were also analyzed by scanning electron microscopy (SEM) to observe microstructural alterations on the material surface and the possible formation of cracks due to the machining conditions.

Residual stresses on the ground surface were determined by X-ray diffraction, using elastic planar stresses. In this model, also known as the biaxial stress model, it is possible to determine a stress (σ_ϕ) as a function of angle, denominated by ψ, which corresponds to the angle between the normal lines of the crystallographic planes (h, k, l) and the sample surface.

According to Noyan and Cohen[12], the distance between the crystallographic planes under a stress σ_ϕ in the biaxial stress model is given by Equation 4.

$$\frac{d_{\phi\psi} - d_0}{d_0} = \frac{1+\upsilon}{E}\sigma_\phi\left(\sin^2\psi\right) - \frac{\upsilon}{E}\left(\sigma_1 + \sigma_2\right) \quad (4)$$

where $d_{\phi\psi}$ is the interplanar spacing of the family of planes (h, k, l) oriented towards a deformation, d_0 is the spacing between the planes of a stress-free sample, E and υ are elastic constants of the material and σ_1 and σ_2 are the tensor components. By algebraically manipulating Equation 4, the residual stress in a material (σ_ϕ) can be obtained from the angular coefficient of the line on a graph of $d_{\phi\psi}$ versus $\sin^2\psi$, and d_0 can be approximately determined by its linear coefficient. This can be observed in the equation for the interplanar spacing (Equation 5) below:

$$d_{\phi\psi} = \left[d_0 \frac{1+\upsilon}{E}\sigma_\phi\right]\left(\sin^2\psi\right) + d_0\left[1 - \frac{\upsilon}{E}\left(\sigma_1+\sigma_2\right)\right] \quad (5)$$

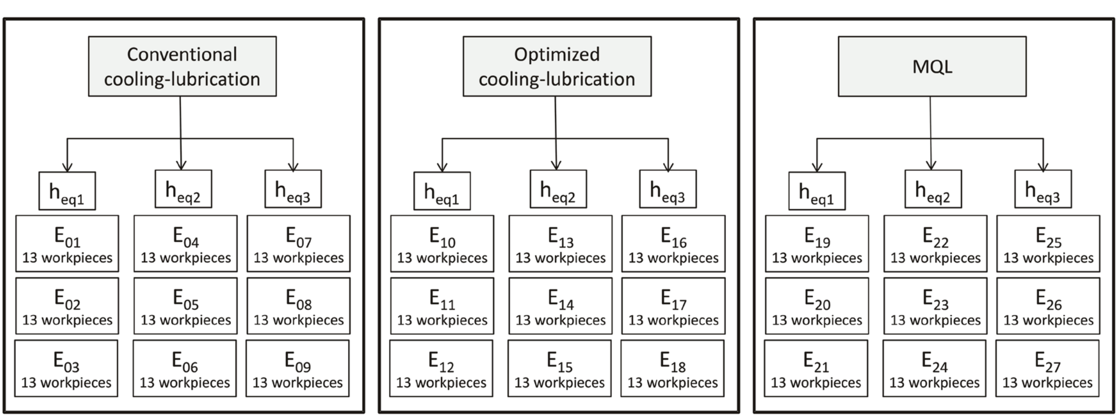


Figure 2. Experimental tests.

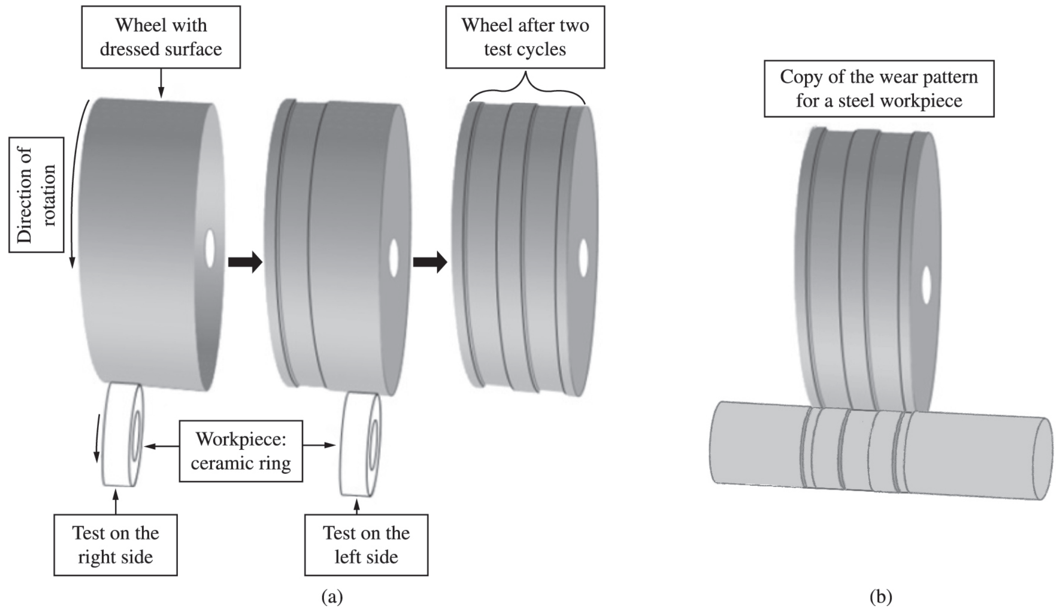


Figure 3. Indirect wheel wear measurement method: **(a)** profile generation during grinding cycles; **(b)** printing of the wheel profile on a AISI 1020 steel cylinder.

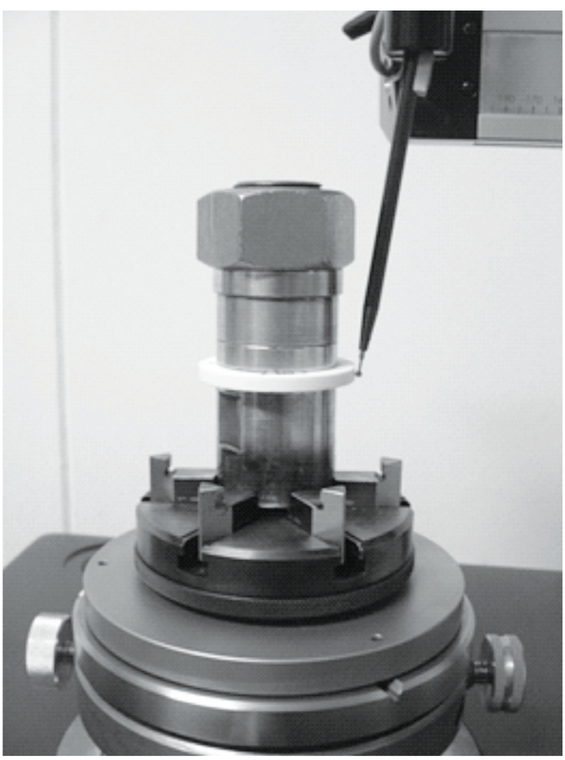


Figure 4. Measurement of roundness errors.

Measurements of X-ray diffraction were conducted on nine test specimens, with one sample for each cooling-lubrication method tested (conventional cooling-lubrication, optimized method and MQL) under each machining condition (equivalent thicknesses of cut h_{eq1}, h_{eq2} and h_{eq3}). Non-ground workpieces were also analyzed. These measurements were performed using a Rigaku diffractometer, model D/MAX 2A, equipped with a radiation source of Cu-Kα, with a Ni filter. The variation $\Delta 2\theta$ of the angle of diffraction $2\theta = 135.96°$, corresponding to the crystallographic planes with orientation (146), was determined as a function of $\sin^2\psi$. The angle ψ was varied from 0° to 75° in 25° increments: $\psi_1 = 0°$, $\psi_2 = 25°$, $\psi_3 = 50°$, $\psi_4 = 75°$. Thus, knowing the Poisson's ratio and the elastic modulus of α-alumina, which, according to Richerson[13] are $\upsilon = 0.26$ and E = 380 GPa, respectively, it was possible to determine the residual stresses on the ground surface by using Equation 6.

$$\sigma_\phi = \frac{E}{d_0\left(1+\upsilon\right)} \frac{d_{\phi\psi}}{\sin^2\psi} \quad (6)$$

3. Results and Discussion

The figures in this section present the experimental results for each cooling-lubrication method (conventional - flood coolant), optimized and MQL technique, under three different machining conditions (h_{eq1}, h_{eq2}, h_{eq3}). The following results will be presented: tangential cutting force, G-ratio, roundness errors, surface roughness, surface morphology and residual stress.

3.1. Tangential cutting force

Figure 5 presents the results for tangential cutting forces, for all the cooling-lubrication methods tested with equivalent cut thickness h_{eq1}.

It may be noted that, for the equivalent cut thickness h_{eq1}, there are significant differences between the three cooling-lubrication methods. MQL shows the highest values; however, it is interesting to observe that the magnitude of the cutting force for this method remained more uniform during the test sequence, whereas the tangential cutting force for the conventional (flood coolant) and optimized cooling-lubrication showed a significant increase.

Figure 6 presents the results for tangential cutting forces, for all the cooling-lubrication methods tested with equivalent cut thickness h_{eq2}.

For the equivalent cut thickness h_{eq2}, no significant differences between the conventional and optimized cooling-lubrication techniques were observed. It can also be noted that, in contrast to the results for h_{eq1}, tangential force showed no tendency to increase during the grinding cycles.

Figure 7 presents the results for tangential cutting forces, for all the cooling-lubrication methods tested with equivalent cut thickness h_{eq3}.

Figure 7 demonstrates that for conventional and optimized cooling-lubrication methods tangential cutting force values are significantly larger for h_{eq3}, than for h_{eq1} and h_{eq2}; when using MQL, however the results do not show any significant changes. This indicates that the lubrication capacity of the MQL fluid remains virtually identical for each equivalent cut thickness tested.

It should be noted that, for some points presented in Figures 5, 6 and 7, the standard deviation values for cutting forces were small enough to be statistically significant on the dimensions and scales used.

In general, the results show that optimized cooling-lubrication was more efficient for this particular output parameter. Since cutting forces are directly related to wheel wear, it can be inferred that the use of this technique would contribute to the increase of wheel service life. This can be demonstrated by connecting the results with an analysis of the diametrical wheel wear, presented below. From the results, it can also be noted that the tangential cutting force values tends to increase with equivalent cut thickness, for each cooling-lubrication method. This has been observed in the grinding of metallic materials by other authors and, more specifically, by Kim et al.[14] in the grinding of alumina. The results of regulated-force-feeding (RFF) grinding, with a conventional constant-speed-feeding (CSF) system, as a function of feeding depth, are showed in Figure 8. It must be noted that the work by Kim et al.[14] presents results only for conventional cooling-lubrication.

Specifically for MQL grinding, the higher values for tangential cutting forces could be explained by the excess of fluid on the wheel surface, causing an increase in the hydrodynamic pressure on the cutting zone, as reported by Emami et al.[15]. In those conditions, the wheel porosity is insufficient to lodge the amount of lubricant applied, thus promoting the formation of a grout (mixture of oil and machined chips), which increases also wheel wear, as should be discussed afterwards. This behavior is stable for all grinding cycles, and for all equivalent cut thicknesses, and can explain the differences between tangential cutting forces for MQL and the other cooling-lubrication methods, especially for h_{eq1}. The chip removal capacity for this equivalent cut thickness is progressively reduced, when considering conventional and optimized cooling-lubrication methods, causing an increase of the cutting forces during the tests.

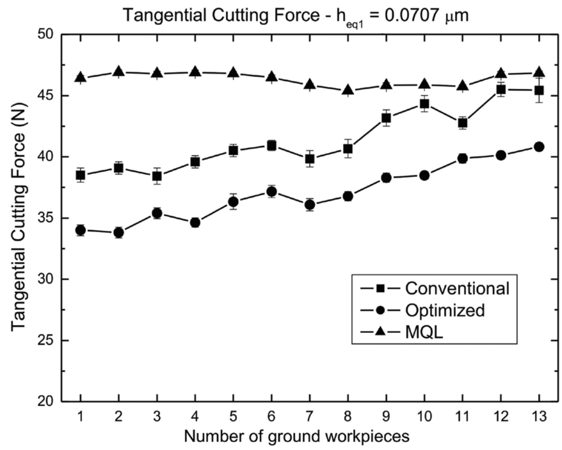


Figure 5. Tangential cutting force for each cooling-lubrication method using equivalent cut thickness h_{eq1}.

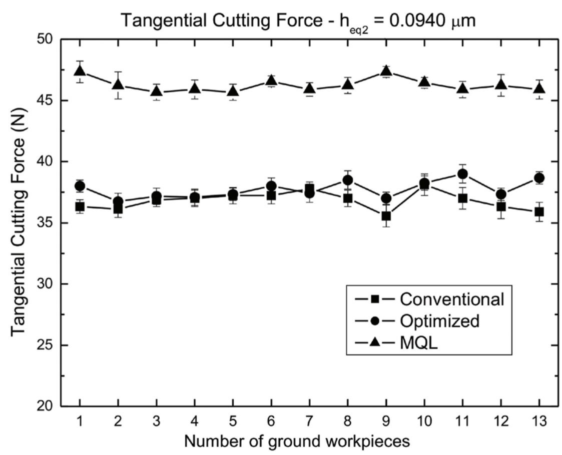


Figure 6. Tangential cutting force for each cooling-lubrication method with equivalent cut thickness h_{eq2}.

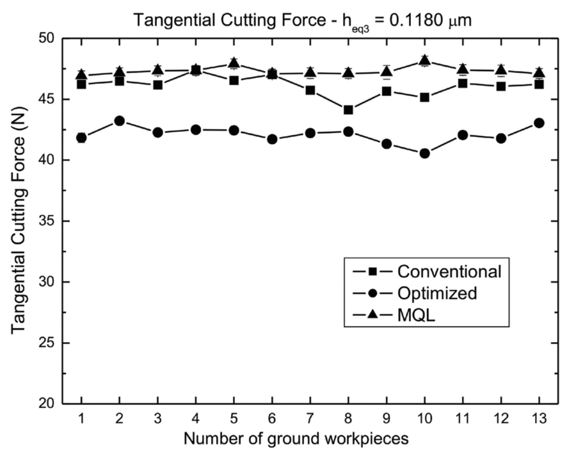


Figure 7. Tangential cutting force for each cooling-lubrication method with equivalent cut thickness h_{eq3}.

3.2. G-Ratio

This section presents the results for the G-Ratio obtained for all equivalent cut thickness and cooling-lubrication methods tested. By analyzing the data in Figure 9, it can be observed that the highest values for the G-Ratio were obtained with the optimized cooling-lubrication.

G-ratio is primarily associated to cutting forces and thermal dissipation on the wheel/workpiece contact zone. Thus, if cooling and lubrication are inefficient, cutting forces and wheel temperature tend to rise, causing a loss in the bond strength, as well as increasing wheel wear.

Results reveal that, for conventional cooling-lubrication, specific cut thickness exerts a considerable influence on wheel wear, when compared to optimized and MQL. Quantitatively, the increase in specific cut thickness (from h_{eq1} up to h_{eq3}) has caused a reduction in G-ratio of approximately 26% for optimized cooling-lubrication, 56% for conventional (flood coolant) and 22% for MQL. These results can be compared to those obtained for tangential cutting forces, where it is possible to observe the same tendency, since MQL grinding has proven less sensitive to the increase of specific cut thickness.

3.3. Roundness errors

The results for roundness errors represent arithmetic averages of all three tests under the same conditions (i.e., cooling-lubrication method and equivalent cut thickness). Specimen numbers were assigned according to the order of each test, and roundness errors of specimens 1, 4, 7, 10 and 13 were evaluated. The following figures present the comparative results between the three cooling-lubrication methods. Figures 10, 11 and 12 show the roundness error results for equivalent cut thicknesses h_{eq1}, h_{eq2} and h_{eq3}, respectively.

As observed in Figure 10, it can be noted that the best results were obtained with the optimized cooling-lubrication method, followed by the conventional (flood coolant) method and then by MQL.

From Figure 11, it can be observed that there is an increase of the relative roundness errors for the workpieces ground using conventional cooling-lubrication and for h_{eq2}. This increase causes the roundness error values for the conventional method to be closer to those obtained with MQL.

Figure 12 presents the most severe machining condition, i.e., equivalent cut thickness h_{eq3}. A larger increase in the roundness errors for MQL than for lower equivalent cut thicknesses can be noted.

By analyzing all the results for this variable, it can be concluded that optimized cooling-lubrication provided the best results for all equivalent cut thicknesses. It also appears that, despite the fact that MQL clearly features higher roundness errors, the results are not significantly different from those obtained with conventional cooling-lubrication. Also, no statistically significant differences between these two methods could be observed for h_{eq2} (1 and 10) and h_{eq3} (10 and 13).

Roundness errors are associated to temperature increase during grinding. Thus, the presented results show that MQL possesses a lower cooling capacity among the cooling-

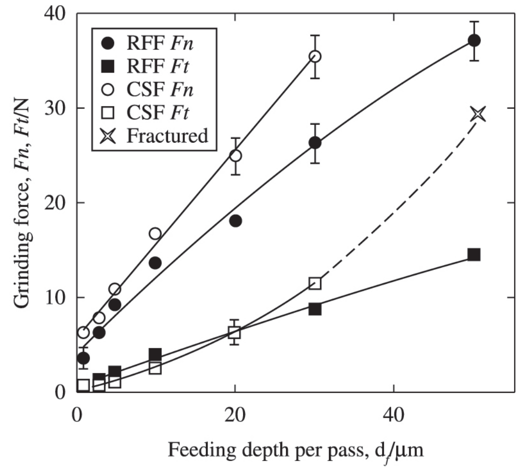


Figure 8. Grinding forces (normal force; F_n and tangential force; F_t) and table-feeding speed (v_f) versus feeding depth for Al_2O_3 on different grinding methods[14].

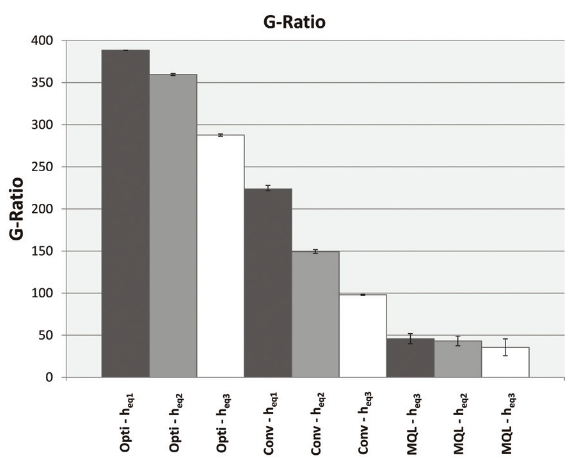


Figure 9. Results of the G-Ratio for all cooling-lubrication method tested.

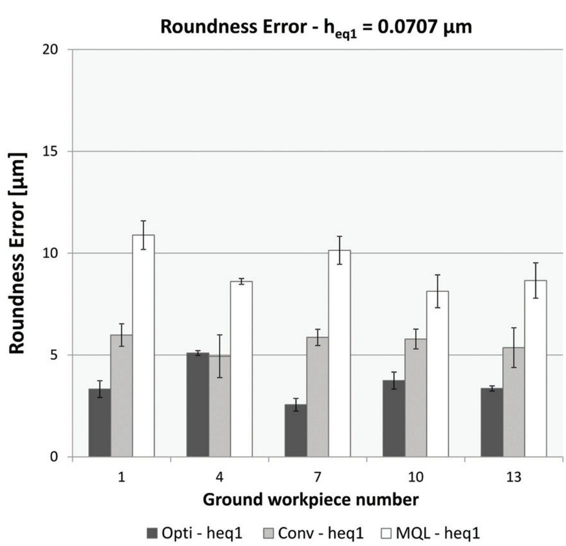


Figure 10. Results of roundness errors for each cooling-lubrication method with h_{eq1}.

lubrication conditions tested. The opposite is observed with conventional (flood coolant) cooling-lubrication. Since it uses a higher fluid flow, higher heat exchange occurs between wheel, workpiece and cutting fluid, reducing thus roundness errors.

It is also possible to notice a tendency in increasing roundness errors with specific cut thickness. This follows the behavior of previous results for tangential cutting forces and G-ratio, which are also associated to cooling-lubrication capacity of the methods tested. However, the results associated to roundness errors can also relate to non-controlled parameters, such as defects in the workpieces and machine vibration, which tend to increase with specific cut thickness.

3.4. Surface roughness (R_a)

Figures 13, 14 and 15 present the obtained results for the average surface roughness (R_a) for each cooling-lubrication method and for each equivalent cut thickness tested.

By analyzing the results for the three equivalent cut thicknesses, similar trends to those in the roundness errors can be observed, where the surface roughness for conventional and optimized cooling-lubrication methods are always lower than those from MQL. This can be attributed to the greater efficiency in chip removal for those two methods. When considering MQL, however, grout formation (mixture of cutting fluid and machined chips) significantly affects the roughness values due to scratching of the workpiece instead of cutting.

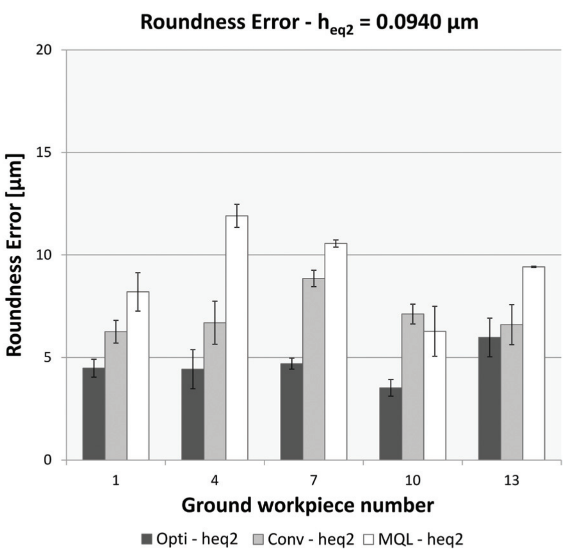


Figure 11. Results of roundness errors for each cooling-lubrication method with h_{eq2}.

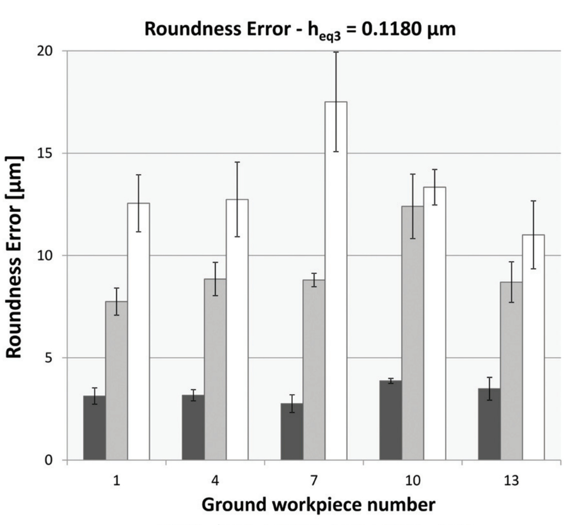


Figure 12. Results of roundness errors for each cooling-lubrication method with h_{eq3}.

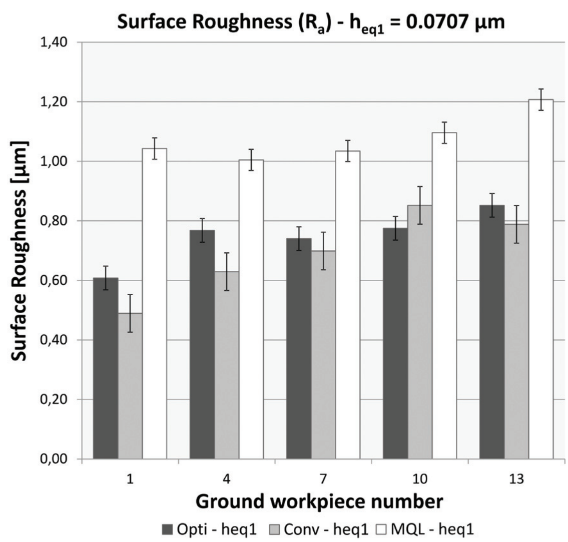


Figure 13. Surface roughness results for each cooling-lubrication method and h_{eq1}.

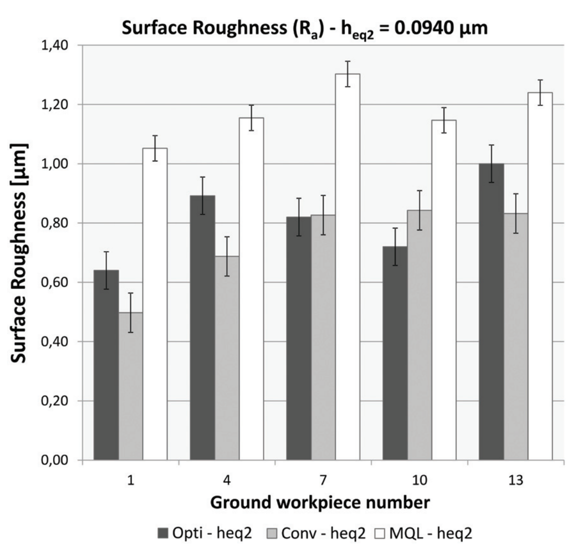


Figure 14. Surface roughness results for each cooling-lubrication method and h_{eq2}.

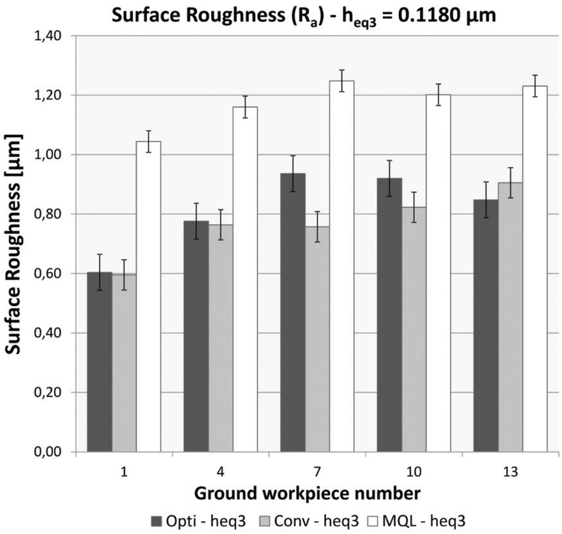


Figure 15. Surface roughness results for each cooling-lubrication method and h_{eq3}.

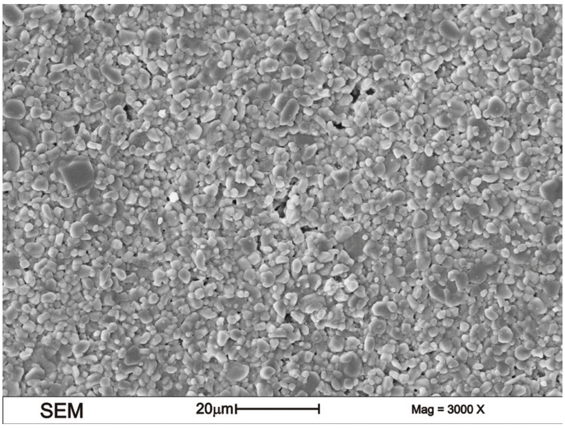


Figure 16. Scanning electron microscopy on the surface of a non-ground workpiece.

The evidence which gives consistency to the aforementioned grout formation during MQL grinding reveals itself when surface roughness results are analyzed along with the other variables, especially tangential cutting forces. It can be observed, thus, that tangential cutting forces for MQL, despite being not so sensitive with equivalent cut thickness, were always higher when compared to other cooling-lubrication methods.

It is possible to observe a tendency to increase the surface roughness with the equivalent cut thickness. This behavior is in accord with the theoretical assumptions, since a higher specific cut thickness implies in a more severe grinding condition, generation of more chips, and, consequently, higher surface roughness, as described theoretically and proved experimentally by Agarwal and Rao[16].

3.5. Surface morphology analyzed with scanning electron microscopy (SEM)

In order to compare the cooling-lubrication and machining conditions, Figure 6 presents SEM images of non-ground workpieces used as standards.

From Figure 16, a microstructural homogeneity and a uniform distribution of grains with porosity, characteristic of a ceramic material, can be observed on the non-ground workpiece surface. The grains have well-defined boundaries and dimensions.

Figure 17 shows images obtained from samples that were ground using the conventional cooling-lubrication method with equivalent cut thicknesses h_{eq1}, h_{eq2} and h_{eq3}.

It can be observed in Figure 17 (a) that fracture occurred uniformly across the sample surface, as the fragile mode of material removal is predominant for h_{eq1}. However, Figures 17 (b) and (c) display two distinct regions: regions where fragile mode of material removal occurred and regions with grooves, which are characteristic of the ductile mode of material removal. Although the two regions are well characterized, the fractured areas are relatively larger, indicating that the fragile mode was also predominant for equivalent cut thicknesses h_{eq2} and h_{eq3}.

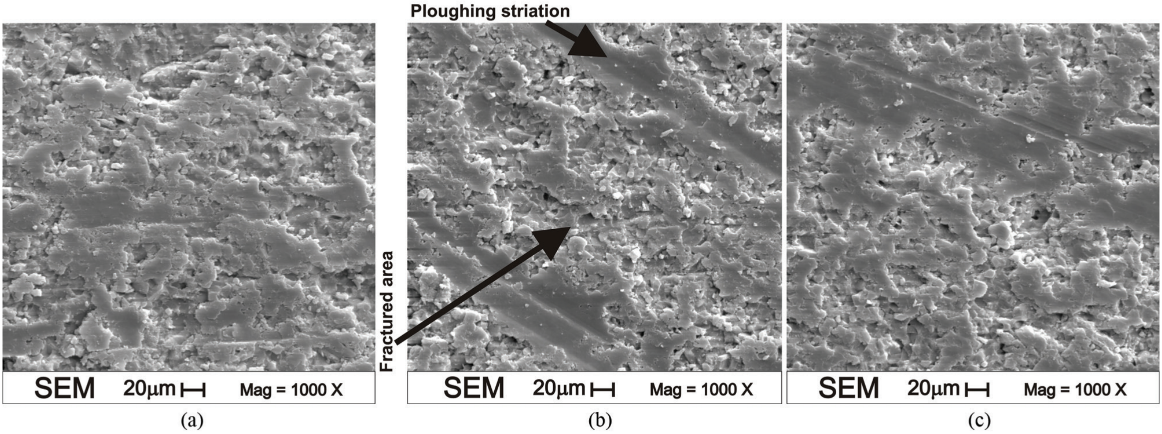


Figure 17. Scanning electron microscopy on the surface of the workpieces ground with conventional (flood coolant) method: **(a)** h_{eq1}, **(b)** h_{eq2} and **(c)** h_{eq3}.

Figure 18 shows images obtained for samples ground using the optimized cooling-lubrication method with equivalent cut thicknesses h_{eq1}, h_{eq2} and h_{eq3}.

From Figure 18, it can be noted that the surfaces ground with the optimized cooling-lubrication technique have a similar morphology to those ground with the conventional (flood coolant) method, indicating that the fragile mode of material removal was also the predominant mode in this condition.

Figure 19 shows images obtained for samples ground using the MQL method with equivalent cut thicknesses h_{eq1}, h_{eq2} and h_{eq3} and 1000 times magnification.

Figure 19 shows that the surfaces of the workpieces ground with MQL exhibit morphology that is markedly different from those presented for conventional (flood coolant) and optimized cooling-lubrication methods, for all equivalent cut thicknesses tested. Grooves can be observed, caused mainly by loosen abrasive particles of the wheel, along essentially the entire length of the sample surface. Such grooves indicate that the predominant removal mode was ductile. The difference in the surface characteristics of MQL grinding may be explained by the differences between the lubrication capacity of the integral oil used in MQL and the emulsion that is used in conventional and optimized cooling-lubrication methods. This difference is due to the fact that water-based fluids are best heat conductors, despite having lower lubrication capacity. Oils, on the other hand, are less efficient in conducting heat, but have higher lubrication capacity. A similar fact was observed by Toenshoff et al.[17], who compared the performance of integral oil and emulsions for the grinding of alumina, as illustrated in Figure 20.

3.6. Determination of residual stresses by X-ray diffraction

The determination of the interplanar distances of the orientation (146) as a function of $\sin^2\psi$ for each condition is presented below. Figure 21 shows the results for the equivalent cut thickness h_{eq1}, h_{eq2} and h_{eq3}. Figure 22 also presents the same analysis for a non-ground workpiece.

Figures 21 and 22 show that interplanar distance decreases linearly with increasing $\sin^2\psi$ for all machining conditions, including the non-ground workpiece; this indicates that residual stress values are negative. This fact denotes that residual stresses generated on the workpiece surface are compressive, i.e., the distance between the

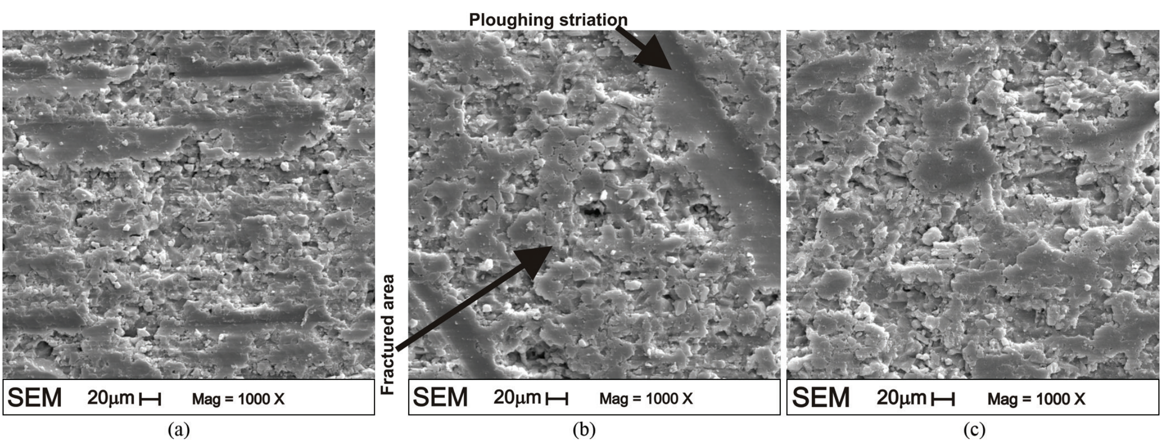


Figure 18. Scanning electron microscopy of the surface of the workpieces ground with the optimized cooling-lubrication method: **(a)** h_{eq1}, **(b)** h_{eq2} and **(c)** h_{eq3}.

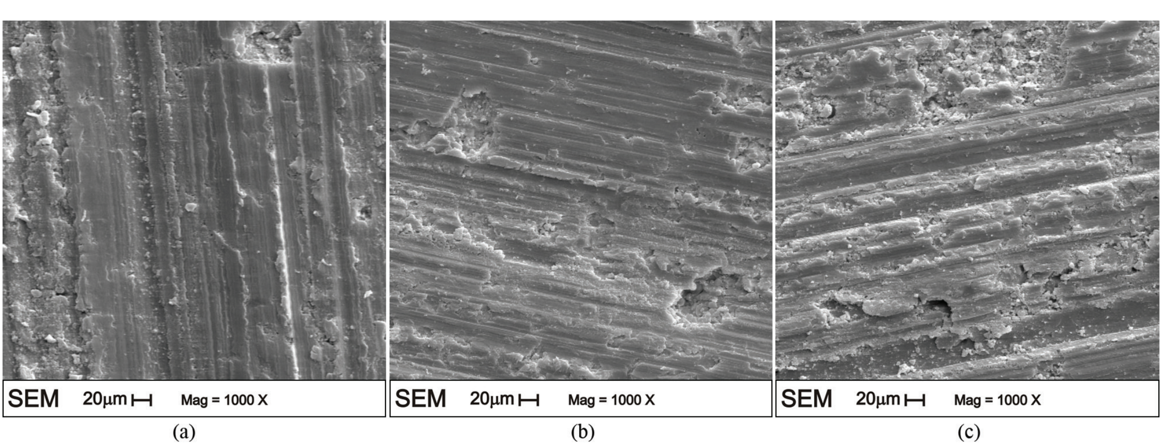


Figure 19. Scanning electron microscopy of the surface of the workpieces ground with the MQL method: **(a)** h_{eq1}, **(b)** h_{eq2} and **(c)** h_{eq3}.

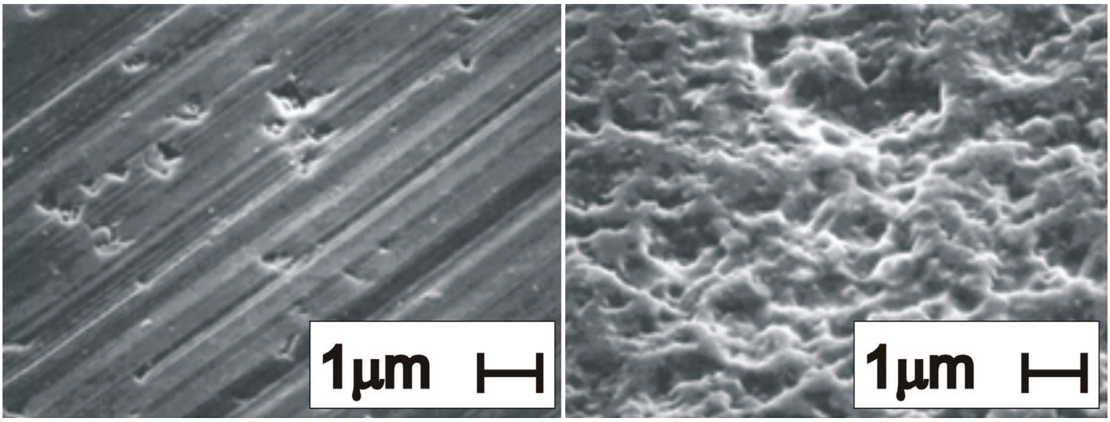
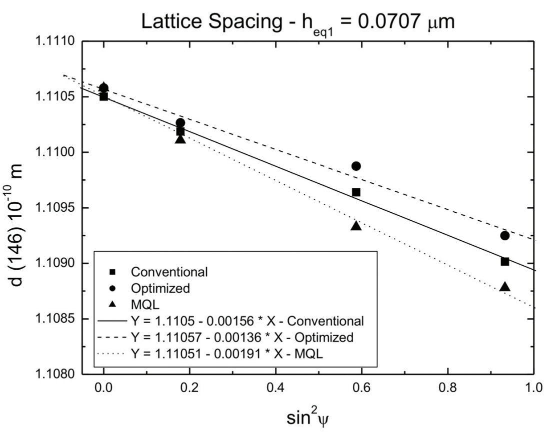
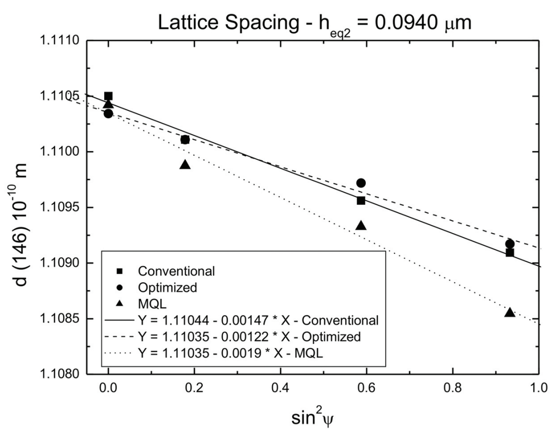


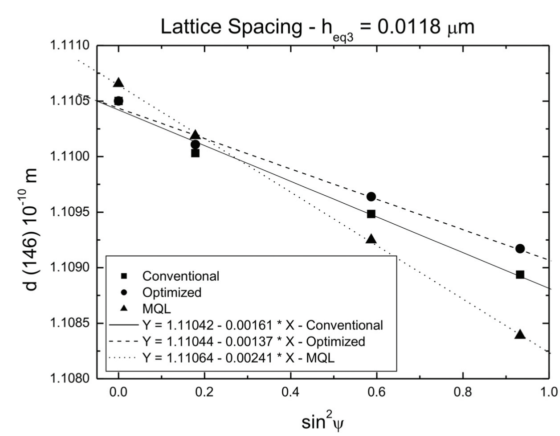
Figure 20. Scanning electron microscopy comparing the ground alumina surface using mineral oil (left) and emulsion (right) as cutting fluid[17].



(a)



(b)



(c)

Figure 21. Distance between orientation planes (146) as a function of $\sin^2\psi$ for each cooling-lubrication method with equivalent cut thicknesses **(a)** h_{eq1}, **(b)** h_{eq2} and **(c)** h_{eq3}.

crystal planes is smaller on the workpiece surface, gradually increasing normally to the ground surface, towards the bulk. In a macroscopic level, the increase of compressive residual stresses alters positively the mechanical properties of the material, reducing the susceptibility to nucleation and propagation of cracks in the layer just below the ground surface.

The residual stress values corresponding to the variations of the related interplanar distances obtained are shown in Figure 23.

The results show a significant difference in the residual stress values of the workpieces ground with MQL, which is associated with the higher cutting force values and mainly with the material removal modes during grinding, as explained in the scanning electron microscopy section.

Quantitatively, for h_{eq1}, the resultant residual stress in MQL grinding is 23% higher than for conventional cooling-lubrication and 41% higher than for optimized cooling-lubrication. For h_{eq2}, the value for MQL is 30% higher than conventional cooling-lubrication, and 55% higher than for optimized method. As for h_{eq3}, the value for MQL is 50% higher than for conventional cooling-lubrication, and 76% higher than for optimized method.

It can be also noted in Figure 23 that the results obtained for conventional (flood coolant) and optimized cooling-lubrication methods were very similar; the differences were not statistically significant for h_{eq1} and h_{eq3}. It can also be observed that the non-ground workpieces also accumulated residual stresses and provided lower modulus. This residual stress may have been created during previous thermal and mechanical processing that the materials underwent before grinding.

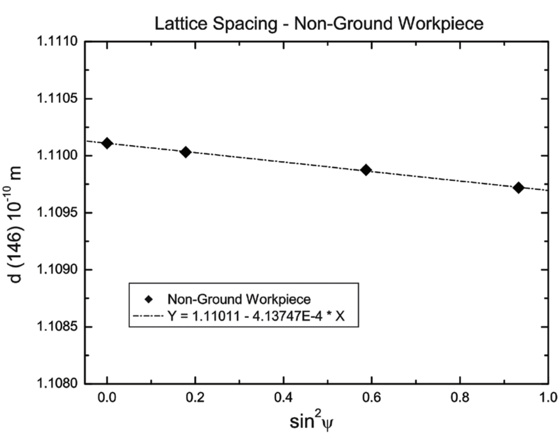


Figure 22. Distance between orientation planes (146) as a function of $\sin^2\psi$ for a non-ground workpiece.

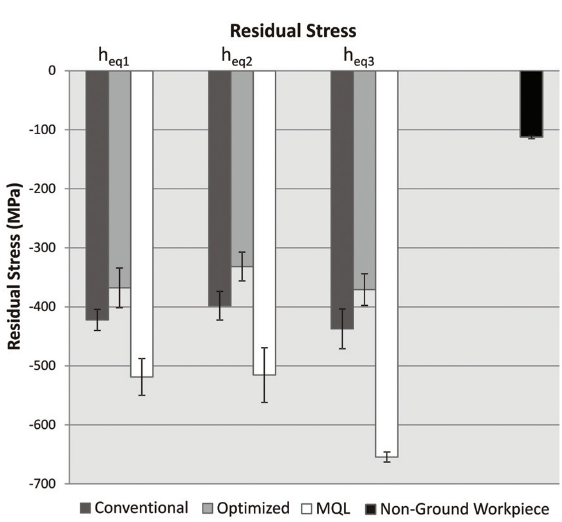


Figure 23. Residual stress values for each cooling-lubrication method and machining condition tested.

4. Conclusions

The experimental tests can lead to the following conclusions:

- MQL grinding provided results for tangential cutting forces significantly higher when compared to conventional (flood coolant) and optimized cooling-lubrication methods. Optimized method, on the other hand, provided the lowest results. However, the variation of cutting forces with the increase in equivalent cut thickness is less sensitive for MQL than for all the other methods tested;
- MQL caused higher wheel wear, reducing G-ratio values. This can be directly associated to higher cutting forces generated, as observed on the presented results. In contrast, optimized cooling-lubrication method presented the best results. It was also observed that increasing specific cut thickness also resulted in higher wheel wear;
- In some tests, despite the higher roundness errors observed for MQL technique, the results are not statistically different than for conventional (flood coolant) cooling-lubrication method. Again, optimized method proved the most efficient, considering this output variable;
- Optimized cooling-lubrication method generated lower surface roughness, while for MQL the highest values were observed. These results are compatible to tangential cutting forces, higher values must imply in higher surface roughness. For this variable, it can also be observed a tendency in increasing the specific cut thickness with surface roughness;
- Surface morphology analyses of the ground workpieces indicate that, for conventional (flood coolant) and optimized cooling-lubrication methods, the material removal mode was predominantly fragile, while ductile material removal mode occurred at times, when the specific cut thickness was increased. For MQL, however, ductile material removal mode is predominant;
- The workpieces ground using MQL presented higher compression residual stresses, which can be beneficial in terms of mechanical properties.

In summary, it can be concluded that grinding with the optimized cooling-lubrication method provides the best results in terms of the dimensional accuracy and morphology of the workpieces. MQL, however, provides the best results for residual stresses, since higher compressive stresses, without crack propagation, indicate higher mechanical strength. Besides, increasing the equivalent cut thickness also increases the process severity, causing more wheel wear and thus worsening the workpiece final quality.

The optimized cooling-lubrication technique can be used to improve grinding efficiency, which contributes to the reduction of the tangential cutting force, wheel wear and cutting fluid consumption, while providing better geometrical and dimensional finishing of the workpieces, in comparison to conventional (flood coolant) cooling-lubrication method. Additionally, minimum quantity of lubrication (MQL) proved to be a viable alternative for conventional cooling-lubrication when using low removal rate (or equivalent cut thickness). Also, particularly for conditions where tolerances may not be so strict, it can reduce the consumption of cutting fluids in more than 99,99%, in relation to conventional (flood coolant) and optimized cooling-lubrication methods, eliminating the costs of fluid disposal and maintenance.

Acknowledgments

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