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## Optimization of Ceramics Grinding

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### 1. Introduction

Grinding is the most common designation used to define the machining process which uses a tool consisting of abrasive particles to promote material removal. It is traditionally considered as a finishing operation, capable of providing reduced surface roughness values along with narrow ranges of dimensional and geometrical tolerances (Lee & Kim, 2001; Malkin, 1989).

The interactions between abrasive grains and workpiece are highly intense, causing the required energy per unit of volume of removed material to be almost consummately transformed in heat, which is restricted to the cutting zone. The temperatures generated can be deleterious to the machined part, causing damages such as surface and subsurface heating, allowing also for surface tempering and re-tempering. Formation of non-softened martensite may also occur, generating undesirable residual tensile stresses and reducing thus the ultimate fatigue strength of the component.

Moreover, uncontrolled thermal expansion and contraction during grinding contribute to dimensional and shape errors, leading mainly to roundness errors. The grinding severity used is limited by the maximum permissible temperatures during the process. When these are exceeded, they may lead to deterioration of the final quality (Liao et al., 2000; Silva et al., 2007). In order to optimize the process, aiming for the control of thermal conditions, an increasing focus on proper tool selection emerges, for each material to be ground. Also, the lubrication method and types of cutting fluid applied have the main roles 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, as well as to obtain products with high dimensional and shape quality, and also ensuring the abrasive tool a greater life (Webster, 1995).

Cutting fluids in machining have the specific function of providing lubrication and cooling, thus minimizing the heat produced due to friction during cutting. Its drastic reduction or even complete elimination can undoubtedly lead to higher temperatures, causing reduced cutting tool life, loss of dimensional and shape precision and even variations in the machine thermal behavior. An important and often forgotten function, which plays a decisive role in practice, is the ability to expel chips. When abrasive tools are used, a reduction in cutting fluid may render it difficult to keep the grinding wheel pores clean, favoring the tendency for clogging and thus contributing further to the aforementioned negative factors. However,

it is noteworthy that the relative importance of each function also depends on the material being machined, the type of tool employed, the machining conditions, the surface finish and the dimensional quality and shape required (Tawakoli & Azarhoushang, 2008).

### 1.1 Grinding of ceramics

Ramesh et al. (2001) mention that, during the process of sintering of ceramics, there is a shrinking of material, which cannot be completely avoided. Therefore it is needed to machine the material properly, in order to achieve the shape and geometrical tolerances required for the component.

Mamalis et al. (2002) explain that the material removal mechanism during grinding of ceramics differs considerably from classical grinding theory. In the latter case, in so-called ductile-type grinding, chip removal is accomplished by elasto-plastic change. In the brittle-type grinding of ceramics, material removal is carried out by crack formation (Figure 1), separation, and spalling of the material.

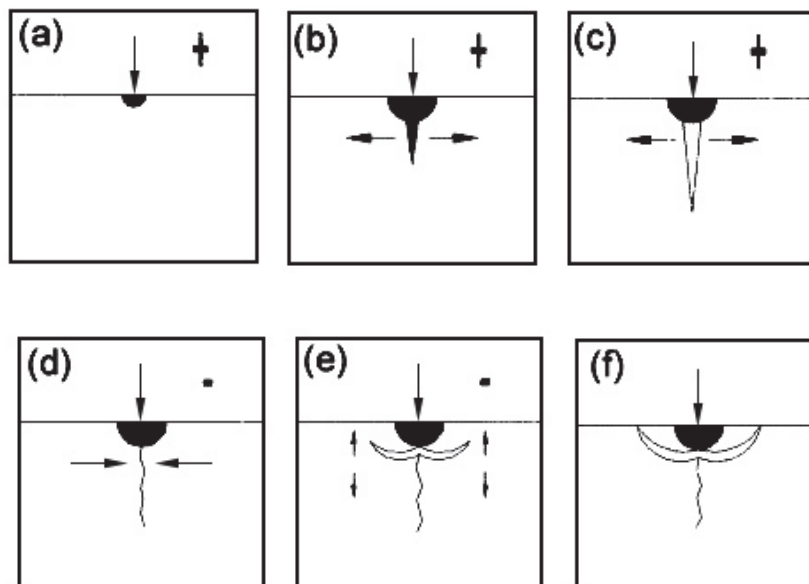


Fig. 1. Stages of crack formation under point indentation (Malkin & Hwang, 1996)

The six characteristic phases of crack formation can be seen in the same figure above. Initially, a plastic zone of small diameter is developed near the surface (Figure 1(a)), whereas subsequently, due to the developed tensile stress field, a small longitudinal crack initiates (Figure 1(b)), and propagates as the indentation goes on and increases in size (Figure 1(c)).

Decreasing the applied load results in the size reduction and/or closing of the longitudinal crack, where compressive stresses prevail (Figure 1(d)). Subsequent load decrease results in the formation of transverse cracks, due to lateral stresses (Figure 1(e)). After unloading, since the tensile residual stress field is developed, the size of the lateral cracks increases, leading to possible separation and/or spalling of the materials in form of chips (Figure 1 (f)). Malkin & Hwang (1996) also reported that the metal removal mechanism with spall formation may be the governing chip formation mechanism in precision grinding of ceramics; the particular effect on a precision ground ceramic is indicated in Figure 2:

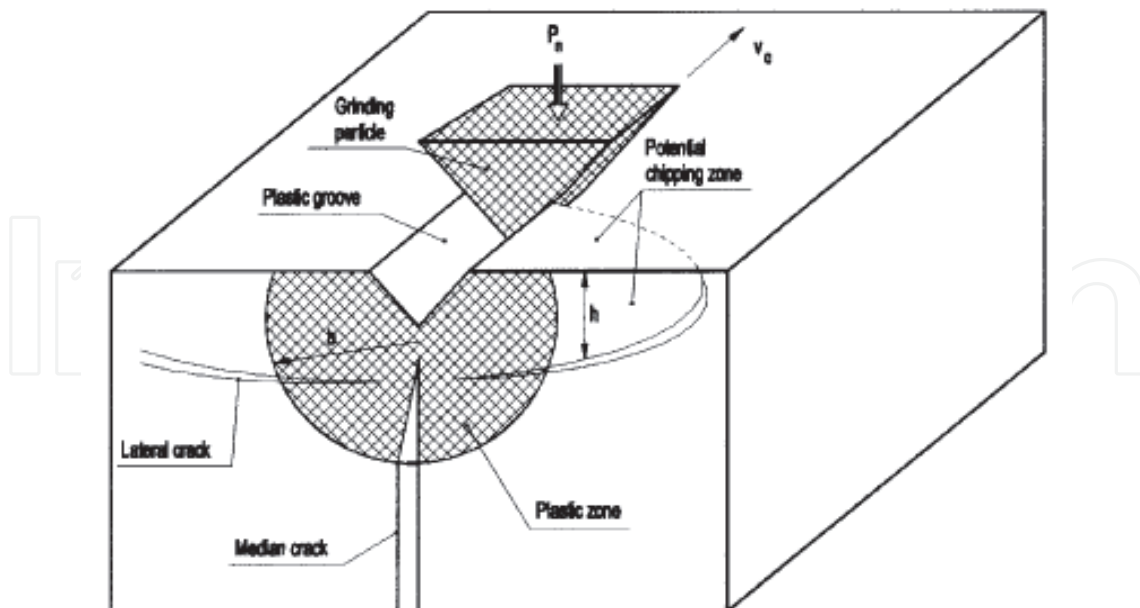


Fig. 2. Plastic zone and crack formation due to scratching by an abrasive grain. (Malkin & Hwang, 1996)

Note, also, that, when grinding ceramics, it must be taken into account that the real depth of cut is larger than the assumed value, because the movement of grains causes additional splintering, leading to a larger depth of cut (Figure 3).

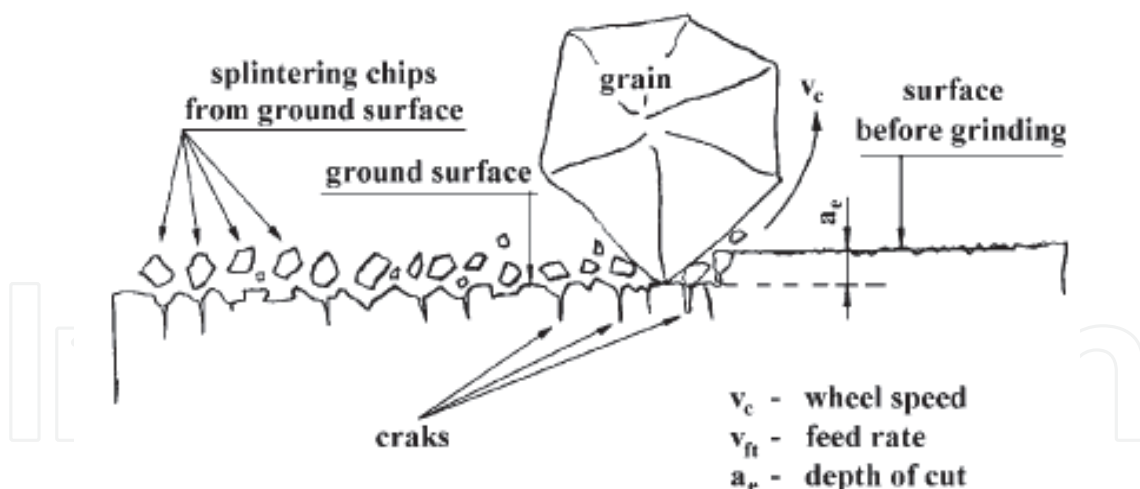


Fig. 3. Model of chip formation in grinding of advanced ceramics.

The main task in grinding ceramics is to define the conditions under which they can be ground economically, with minimal crack formation, thus assuring the part final quality.

### 1.2 Minimum quantity of lubrication (MQL)

Some limitations of dry machining can be overcome, in many cases, through the introduction of minimum quantity lubrication (MQL) method, whose action is based on the application of 10 to 100 ml/h of cutting fluid on a compressed air jet, under pressures

usually ranging from 4.0 to 6.5 kgf/cm<sup>2</sup> (Silva et al., 2007). In this technique, the function of lubrication is ensured by the oil, while that of cooling is mainly by the air. Although these advantages allow the foresight of a growing range of MQL applications, the influencing variables to be considered and its effects on the results have been the subject of very few studies (Klocke & Eisenblätter, 1997; Kocke et al., 2000; Silva et al., 2007).

Minimum quantity lubrication systems usually employ mainly non-water-soluble cutting fluids, especially mineral oils. It should be considered that, due to the reduced amounts of coolants used, the costs should not impede the use of high technology compositions in the field of basic and additives oils. It is not recommended to use fluids which are designed for conventional systems, in virtue of the occurrence of atomization and vaporization, deleterious to human health. Higher cutting speeds (which along with temperature, cause problems of this kind), makes indispensable the use of basic oils, with higher viscosity, and adaptations in terms of additives (anti-mist). The used lubricants should be environmentally correct (free of solvents and fluorated materials) and capable of high heat removal. (Heisel et al., 1998).

From a comparison with conventional cooling, many advantages follow (Heisel et al., 1998; Klocke & Eisenblätter, 1997; Kocke et al., 2000):

The ratio between the amount of fluid used and the machined part volume is many times lower than for conventional lubri-refrigeration;

Low consumption of fluid and elimination of a fluid circulation system;

Filtering materials and devices along with maintenance recycling can be avoided;

Low amount of oil remaining along with the machined chips does not justify its recovering;

Machined parts are removed almost dry, so in many cases it is unnecessary an ensuing washing;

The application of biocides and preservatives can be eliminated, due to only the quantity to be used in a work shift should be added to the MQL system reservoir.

Regarding economical aspects, in comparison with conventional cooling, MQL causes additional costs concerning air pressurization and technological supports, which are intrinsically required to overcome its restrictions. For example, special techniques or devices for chip removal could be necessary, and maybe the productivity would be reduced due to the thermal impacts on the machined components.

The oil vapour, mist and smoke generated during the use of minimum quantity lubrication can be considered undesired byproducts, for they contribute to increase the air pollution of the workplace, and thus becoming a factor of concern (being necessary, perhaps, an exhaustion system near the contact area). In pulverization, it is used a compressed air line which functions intermittently during the process. These lines generate a level of noise that usually surpasses the limits allowable by legislation. Therefore, beyond affecting human health, the noise also pollutes the environment and prejudices the communication (Klocke et al., 2000).

### 1.2.1 MQL in grinding

A relatively small amount of research has been conducted regarding the application of MQL in grinding. Some researchers investigated the effects of grinding parameters on AISI 4340 steel grinding using conventional lubrication and MQL. They found that the surface roughness, diametric wear, grinding forces and residual stress improved when using the latter, due to optimum lubrication of the grinding zone, providing rather grain slipping at



the contact zone (Silva et al., 2005; Silva et al., 2007). Brunner showed that the MQL grinding with a 4 ml/min ester oil (comparing to 11 ml/min mineral oil), when machining 16MnCr5 (SAE-5115) steel with microcrystalline aluminum oxide reduced the process normal and tangential forces to one third, however increasing the surface roughness by 50% (Tawakoli et al., 2009).

Investigations by Brinksmeier confirmed these results and showed in addition that the type of coolant used during MQL grinding (ester oil or emulsion) can considerably influence the process result (Tawakoli et al., 2009). Hafenbraedl and Malkin found that MQL provides efficient lubrication, reduces the grinding power and the specific energy to a level of performance comparable or superior to that obtained from conventional soluble oil (at a 5% concentration and a 5.3 l/min flow), while at the same time it significantly reduces the grinding wheel wear. However, it presented slightly higher surface roughness values ( $R_a$ ) (Hafenbraedl & Malkin, 2001; Silva et al., 2005; Silva et al., 2007).

The performance was also assessed when applying dry grinding. The results with the minimum quantity lubrication technique were obtained in the internal cylindrical plunge grinding of an AISI 51200 steel (quenched and tempered, detainer of an average hardness of 60 HRC), using conventional alumina wheels.

For MQL technique, a precision dozer providing ester oil at a specific flow rate (12ml/h) was attached to the grinder. A nozzle mixed the oil with compressed air at a pressure of 69 kPa, aiming to form a thin mist. The application of ester oil for internal grinding was unsatisfactory, in virtue of the restricted area to the nozzle access. Its design was optimized to stay as close as possible to the inlet of grinding zone. Also it was used a cold air gun, in an attempt to supply some cooling to the workpiece. The cold air ( $-2^{\circ}\text{C}$ ) left the nozzle at a flow rate of 3l/s and a pressure of 7.6 bar. It was evaluated, subsequently, that the available amount of cold air would not be capable of providing significant cooling. However, the main disadvantage of MQL was the poor cooling, resulting in high temperatures and the thermal dilatation of the workpiece.

Still in this line of thought, Baheti and others (1998) made some experiments using ester oil (10ml/h) with cold air ( $-10^{\circ}\text{C}$  at outlet) on surface grinding of carbon steel workpieces, using a conventional wheel. The authors proved that MQL technique presented lesser values of partition energy, temperature and specific energy, when compared to conventional cooling. When a comparison with soluble oil was made, MQL with cold air reduced the specific energy by a rate of 10 to 15%, the workpiece temperature by a rate of 20 to 25% and the partition energy to the piece (fraction of grinding energy which is received as heat) by a rate of 15 to 20%.

Tests were made in different lubri-cooling conditions: liquid nitrogen; soluble oil (5% concentration); dry; ester oil; cold air ( $-10^{\circ}\text{C}$ ) at a flow rate of 990l/min and pressure of 690kPa, and cold air along with ester oil. Dry condition presented higher partition energy values, which was already expected. On the other hand, the application of liquid nitrogen provided higher specific energy values.

The researchers concluded that is possible to eliminate or reduce the cutting fluid use, contributing to clean manufacturing. Environmentally safe, ester oil was capable of providing good lubrication and, when applied along with cold air, the cooling was more effective than with soluble oil. Ester oil is classified as an unhazardous and noncarcinogenic substance. At the same time, MQL proves that is a promising alternative to cutting fluids in grinding. Despite the liquid nitrogen provided better cooling, it presents weak lubricity, which results in high values of specific energy (Baheti et al., 1998).

Klocke and collaborators presented the behavior of normal and tangential specific forces in external cylindrical plunge grinding when comparing the cooling by a shoe nozzle (24l/min) and MQL technique (215ml/h), the latter resulting in a reduction on these forces. In what refers to microstructure, they revealed that no modifications happened, whatever the conditions employed. On the other hand, MQL application presented the worst surface roughness values ( $R_z$ ) when compared to wet grinding. The researches proved that, by several results with defined geometry tools, MQL can be used prosperously in grinding processes (Klocke et al., 2000).

However, extensive studies are necessary before this technology is applied industrially, mainly concerning to the lubricant employed. In this context, they are needed in order to verify the benefits and damages caused by this process, enabling it to become viable in industrial scale. These researches include optimization of lubrication composition along with modifications on the design of grinders, abrasive tools and monitoring strategies, to adapt to different conditions of machining.

According to Tawakoli, in order to make the MQL system proper to grinding, certain developments are necessary on the following: satisfactory systems for chip removal; optimized systems to supply cutting fluids in low flow rates; adjustment of the machining parameters, based on the complete understanding of MQL technology, for the chip thickness reach an optimum value; reduction of friction and optimized use of tools (Tawakoli, 2003).

The results obtained by several researches, until the present, using the MQL technology with defined geometry tools, show the possibility of its advantageous application in many cases, contributing to a clean manufacturing without harm to the environment and to human health. They proved that MQL systems result in increased tool life, higher cutting speeds, better surface finishing quality and lesser damages to the workpiece. MQL technology is perfectly qualified for manufacturing processes; however, it is indispensable to have aggregation of effort between users, tool and machine tools fabricants, to obtain better results. It should be remembered that, however, despite all optimistic results with defined geometry tools, in relation to grinding, MQL is still far from its decisive implementation (Tawakoli, 2003).

## **2. External cylindrical grinding**

### **2.1 Grinding with diamond wheels**

The main objective of the present study was to evaluate the technique of minimum quantity of lubrication (comparing to conventional cooling) in the external cylindrical grinding of advanced ceramics, using a diamond wheel, analyzing output variables such as roughness, acoustic emission, G-ratio, circularity errors and scanning electron microscopy (SEM) analysis.

#### **2.1.1 Materials and methods**

The experiments were performed in a SulMecânica 515 H RUAP CNC external cylindrical grinder, equipped with Computer Numerical Control (CNC).

Hollow cylinders of commercial alumina (96% of aluminum oxide and 4% of bond oxides as  $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{MgO}$ ) were ground. The apparent density of this material was  $3.7\text{g/cm}^3$ .

It was used a resin bonded diamond grinding wheel, having the following dimensions: 350mm (external diameter) x 15mm (width) x 5mm (abrasive layer), 127mm (internal diameter), specification code D107N115C50 from Nikkon Cutting Tools Ltd..

The cutting fluid was a semi-synthetic ROCOL 4847 Ultracut 370 emulsion of 5% concentration in water, which had already in its composition: anti-corrosives, biocides, fungicides, and other additives. To control the MQL, was employed an Accu-lube device provided by ITW Chemical Products Ltd., which uses a pulsating system for oil supply and allows the air and lubricant flow rates to be adjusted independently.

Measurements of acoustic emissions were made by a Sensis DM12 sensor, positioned at the head of the mobile near the tailstock. The roundness was measured on a Taylor Hobson Tayrond 31c. The surface roughness was obtained through a Surtronic<sup>3+</sup> profilometer (with a *cut-off* length of 0.8mm). The microstructure analysis was performed by scanning electron microscopy (SEM).

The wheel wear was measured by printing its profile on a 1010 steel workpiece, and then, with a TESA comparator gauge the data from this variable could be assessed.

For the tests were established the following machining conditions: plunge speed ( $V_f$ ) of 1 mm/min, wheel peripheral speed of 30m/s, depth of cut of 0.1mm, 5 seconds of spark-out, fluid flow rate in conventional cooling of 22l/min, fluid the flow rate in MQL of 100ml/h and air pressure of 8bar, outlet air velocity in MQL nozzle of 30m/s, and 13 workpieces per test.

The three feed rate were chosen: 0.75mm/min, 1mm/min and 1.25mm/min, corresponding to the respective equivalent thicknesses of cut  $h_{eq1} = 0.0707$ mm,  $h_{eq2} = 0.094$ mm and  $h_{eq3} = 0.118$ mm.

### 2.1.2 Acoustic emission

Figure 4 presents the results of acoustic emission (RMS), expressed in Volts (V), according to the number of ground pieces.

The values on the figure above indicate no significant differences in relation to acoustic emissions. It can be seen that the condition which showed lower values was the conventional cooling with  $h_{eq1}$  (smaller equivalent thickness of cut), while the one that showed higher values was the MQL technique with  $h_{eq1}$ .

One explanation for these phenomena is the small influence of the equivalent thickness of cut in MQL caused by other significant variables, such as the thermal dissipation of the cutting region. Since this method dissipates less heat, its removal occurs mainly by the thermal conduction of the grinding wheel, constant for all tests. As the equivalent thickness of cut is determined by the feed rate, the higher thickness of cut provides greater contact area, causing then more heat conduction.

It can be noted that this type of conclusion can be made just because that the workpiece has small thickness in relation to the thickness of the grinding wheel. For those with greater thickness, the thermal conduction of the wheel can be limited.

### 2.1.3 G-Ratio

This item presents the G-Ratio for each equivalent thickness of cut and lubri-cooling condition. This value was calculated by measuring the wheel wear and volume of worn material. The first could be measured due to the greater width (15mm) in relation to the workpiece (4mm).



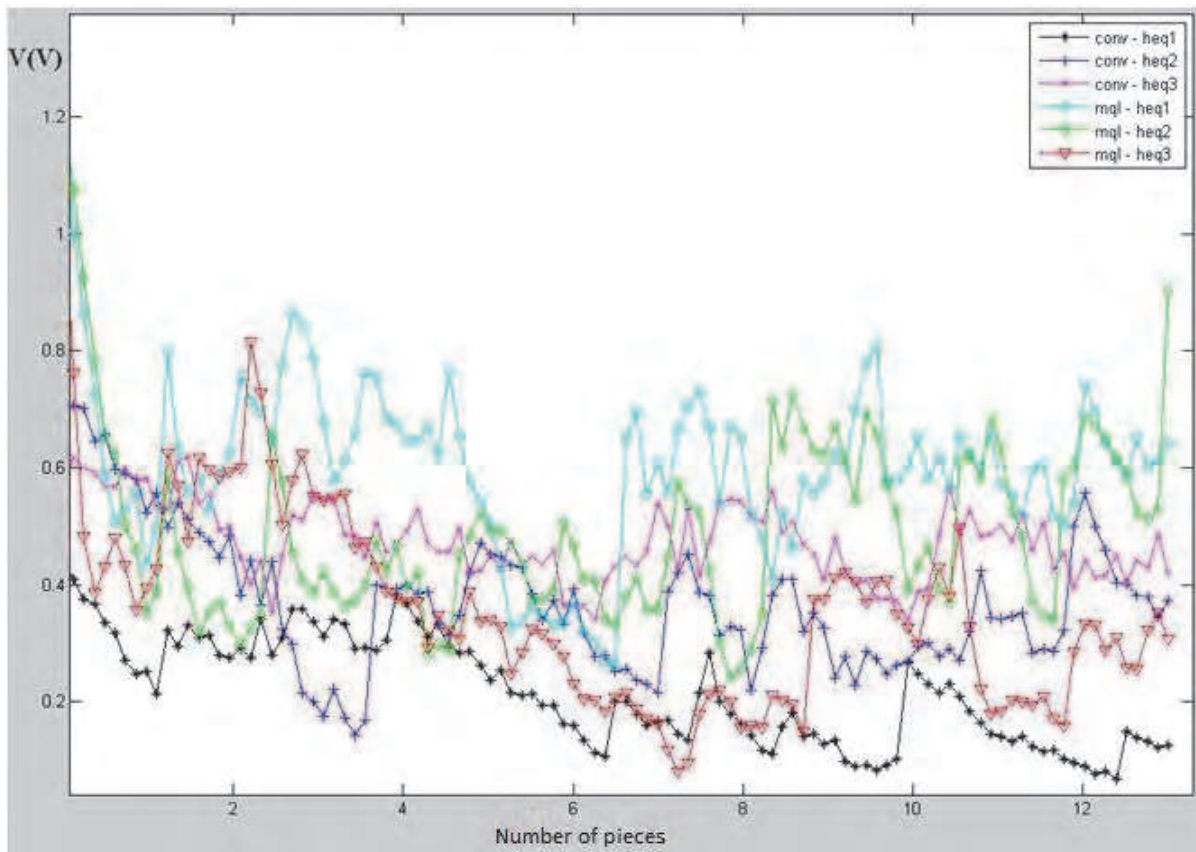


Fig. 4. Acoustic emission results.

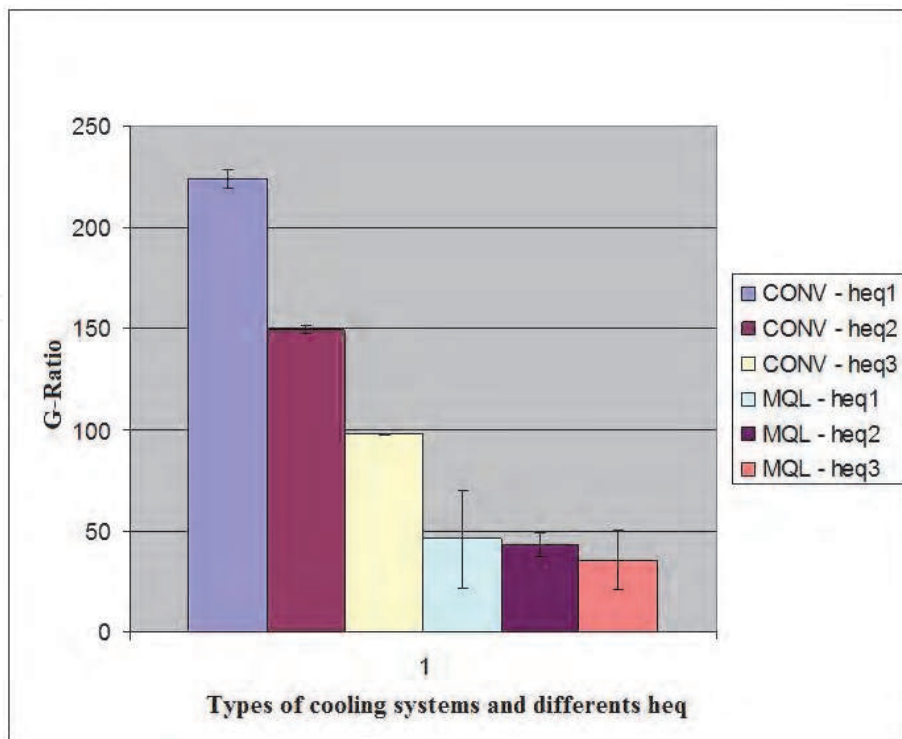


Fig. 5. G-Ratio results for each condition tested.

Through the analysis of the figure above, it can be noticed that the higher values for the G-Ratio were obtained for conventional cooling. One possible reason of these is the lower heat dissipation in the cutting region caused by the MQL, resulting in losing of bond resistance, thus wearing more the grinding wheel.

It can be also seen that, for the conventional cooling, the equivalent thickness of cut is a great factor of influence concerning wheel wear, therefore the G-Ratio. The higher its value, the more accentuated the wear, consequently, providing lower values for the G-Ratio.

For the MQL technique, the equivalent thickness of the cut could not influence effectively in the G-Ratio. This can be explained by other factors which probably prevailed in the wear, i.e., the lower heat dissipation on the cutting zone, making the influence of equivalent thickness of cut almost imperceptible.

#### 2.1.4 Scanning electron microscopy (SEM)

Figure 6 represents the results for scanning electron microscopy (SEM) obtained conventional lubri-refrigeration (1000x zoom).

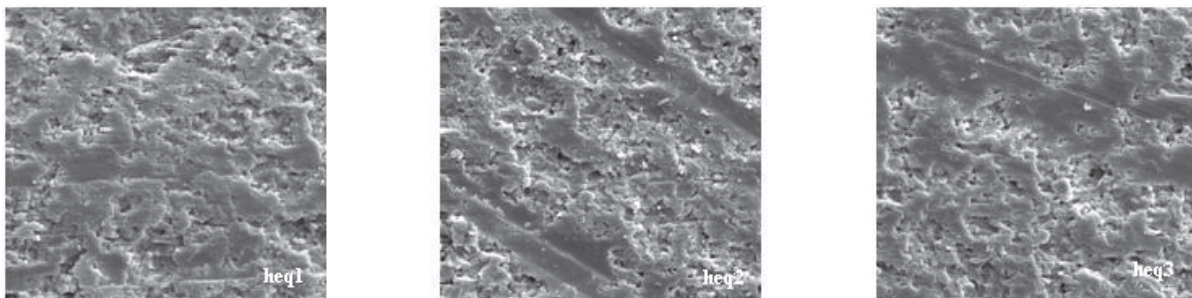


Fig. 6. SEM for conventional cooling with  $h_{eq1}$ ,  $h_{eq2}$  and  $h_{eq3}$ .

In the conventional cooling occurred the fragile mode of material removal. The tendency to ductile mode removal increases as does the equivalent thickness of cut, providing an improvement the workpiece finishing.

Figure 7 represents the results for the MQL technique (1000x zoom).

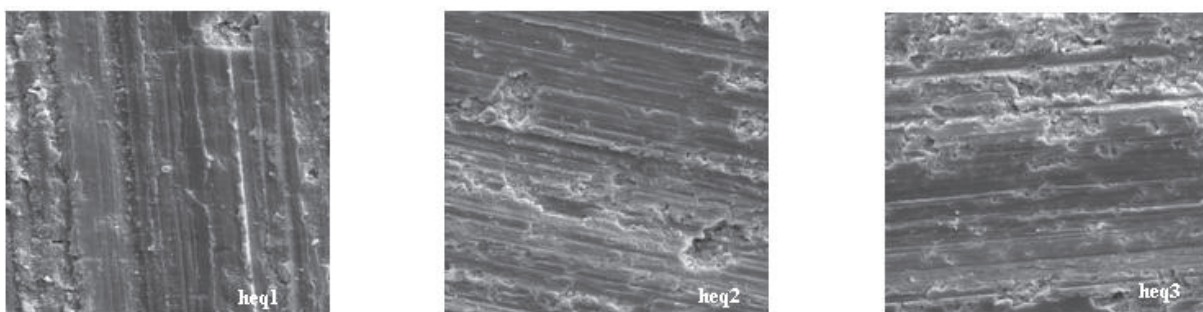


Fig. 7. SEM for cooling the MQL for  $h_{eq1}$ ,  $h_{eq2}$  and  $h_{eq3}$ .

It can be noticed that the predominant mode of material removal using MQL was the ductile, which provides optimal conditions for surface finish with the strength of the material due to the reduction of micro-fractures, responsible for stress concentrators. By observing the figures, it can be seen that, the lower the equivalent thickness of cut, the more ductile is the process of material removal.

The better surface characterization with MQL may be explained by the greater power of the lubricating oil used, in comparison to the emulsion employed in conventional cooling.

### 2.1.5 Roundness

Figure 8 shows an evolution of the roundness for all conditions tested.

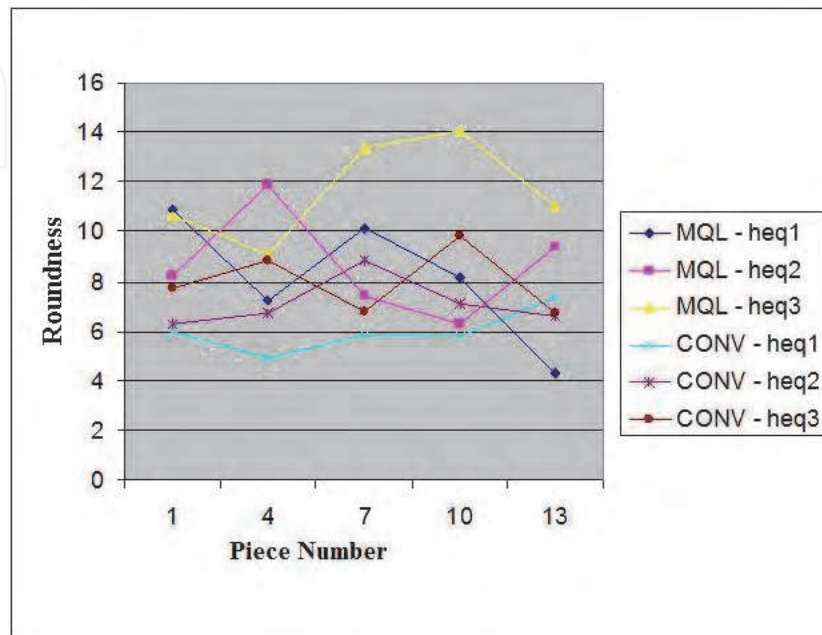


Fig. 8. Evolution of roundness errors.

It can be noted that only for the more severe condition of MQL lubrication, the roundness has increased dramatically.

Analyzing the results obtained as a whole, the values for less severe conditions using MQL did not differ significantly.

On the roundness, there were no significant differences between both methods, with  $h_{eq1}$  and  $h_{eq2}$ .

### 2.1.6 Surface roughness

The figure below shows the results for the average surface roughness ( $R_a$ ), on the comparison between conventional lubri-cooling and MQL (in micrometers). The values shown are averages of five measurements at different positions, for each of the 3 tests, with their respective standard deviations.

In general, the values were lower for the conventional lubri-cooling method than with MQL, possibly due to the better chip removal from the cutting zone, by conventional cooling. When applying the MQL technique there was formed a paste of fluid and chips, even with compressed air at high speeds. This affected considerably the values of surface roughness.

The lower values for MQL are observed in the lowest values of  $h_{eq}$ , proving that the smaller thicknesses of cut allows smaller values of surface roughness, due to lower material removal rate and greater lubrication achieved.

The surface roughness is mainly influenced by the lubrication condition. The emulsion presents the characteristics of low lubrication but great cooling, thus affecting this variable.

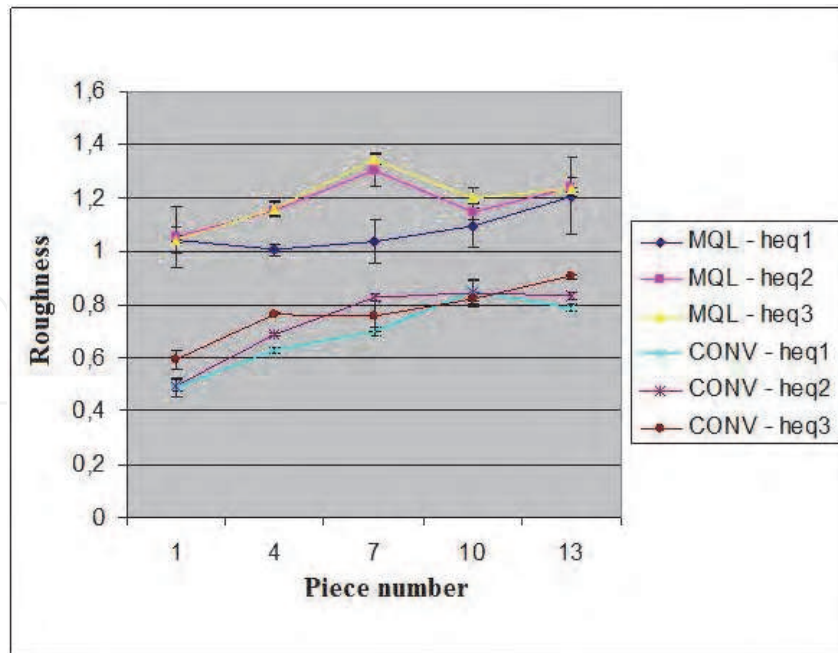


Fig. 9. Evolution of surface roughness during the tests.

**2.2 Application of MQL with water (H<sub>2</sub>O)**

Silva et al. (2007) showed that surface roughness values and diametral wheel wear are significantly lower when using MQL technique, as well as tangential cutting forces and specific energy, demonstrating thus the good capability of lubrication by MQL. Yoshimura et al. (2005) state that minimum quantity lubrication with water, known as Oil-on-Water (OoW), presents high cooling capability, due to the water droplets covered by a layer of oil, which evaporate easily on the part and tool surfaces, and cool them due to its sensitivity and latency to heat.

The concept of water droplets covered by an oil layer can be seen in Figure 10.

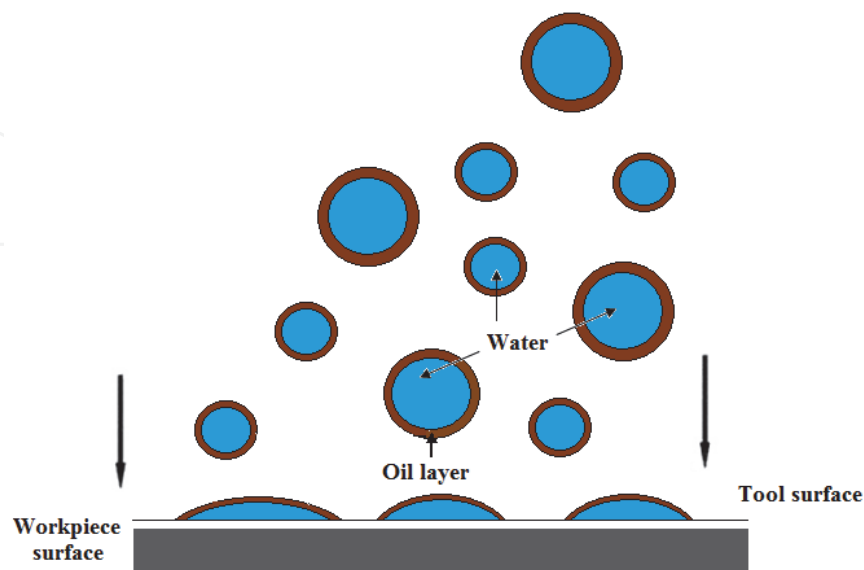


Fig. 10. Water droplets covered by an oil layer



Itoigawa et al. (2006) also presented that cooling capacity due to the water droplets is not important only to the dimensional precision, but also to avoid some deleterious effects between tool and workpiece surface, such as adhesion.

### 2.2.1 Materials and methods

Machining conditions were determined after some preliminary tests, which provided the best values to assess the viability of OoW grinding. These values are presented in Table 1.

Grinding mode	External Cylindrical Grinding
Abrasive Tool	D140 N100V
Grinding Machine	SulMecânica RUAP 515 H-CNC.
Cutting speed ( $V_c$ )	$V_c = 30\text{m/s}$
Depth of cut ( $a_e$ )	$a_e = 0.1\text{mm}$
Lubrication-cooling method	Conventional, MQL
Cutting fluid (Conventional)	Rocol 4847 Ultracut 370 with 5% concentration
Oil flow rate (MQL)	$Q = 100\text{ml/h}$
Cutting fluid (MQL)	Rocol Cleancut
Air pressure	$P = 8\text{ bar}$
Workpiece material	Comercial alumina ( $D_e = 54\text{mm}$ , $D_i = 30\text{mm}$ , $e = 4\text{mm}$ )
Dresser	<i>Fliese</i> multigranular dresser
Depth of dressing ( $a_d$ )	$a_d = 0.04\text{mm}$
Feed rates	$f = 0.25\text{ mm/rev}$ ; $0.50\text{ mm/rev}$ ; $0.75\text{ mm/rev}$

Table 1. Machining conditions

Three different lubri-refrigeration modes were used: conventional lubri-refrigeration, MQL method, and MQL with water (OoW), with oil/water ratio of 1:1.

It was used a wheel cleaning system by compressed air jets, with two nozzles directed tangentially to the wheel surface, which assures better results for cylindrical grinding of advanced ceramics, as proved by the preliminary tests.

Before each test, the wheel was dressed, allowing for the same initial conditions of the tool. After dressing, the ceramic workpiece was normalized parallel to the grinding wheel. For each test, five hollow cylinders were used.

In order to use the whole wheel width, two tests were conducted before each dressing. After these two tests, the wheel wear was measured by printing its profile on steel cylinders, and then the tool was dressed.

Before each conventional lubri-refrigeration test, the cutting fluid concentration was evaluated by an Atago N-1 E manual refractometer, and then corrected if needed (by adding more water or cutting fluid into the reservoir).

The wheel diametral wear was obtained through the printing of its profile on a steel workpiece, and then it was measured by Talymap Silver software, which provided the mean values for this variable, considering each lubri-refrigeration condition.



Surface roughness values were obtained using a Taylor Hobson Surtronic 3+ rugosimeter, while the roundness values were obtained by a Taylor Hobson Talyrond 31C roundness meter.

Data acquisition of grinding power and acoustic emission data were obtained by Labview 7.1. The signals were then filtered and treated in Matlab, which provided average values for both variables.

Acoustic emission signals were gathered by a Sensis DM12 sensor, which was fixed on the grinding machine tailstock, aiming to detect the possible variations of this variable, and consequently making it possible to relate it with the other output variables.

### 2.2.2 Surface roughness

For the surface roughness values, it can be seen in Figure 11 that conventional lubri-refrigeration provided the lower values for all feed rates tested, due to the better capability to remove machined chips from the cutting zone (abundant fluid flow).

Traditional MQL method provided medium surface roughness values, about 65% higher than when using conventional lubri-refrigeration, due to the formation of a grout (oil+chips) which lodged into the wheel pores, and is very difficult to remove. Those microchips lodged in the wheel scratch the workpiece surface, increasing its surface roughness. Part of this grout was removed by the compressed air jet, which cleans the wheel, providing then better results on the workpiece finishing, compared to MQL without wheel cleaning.

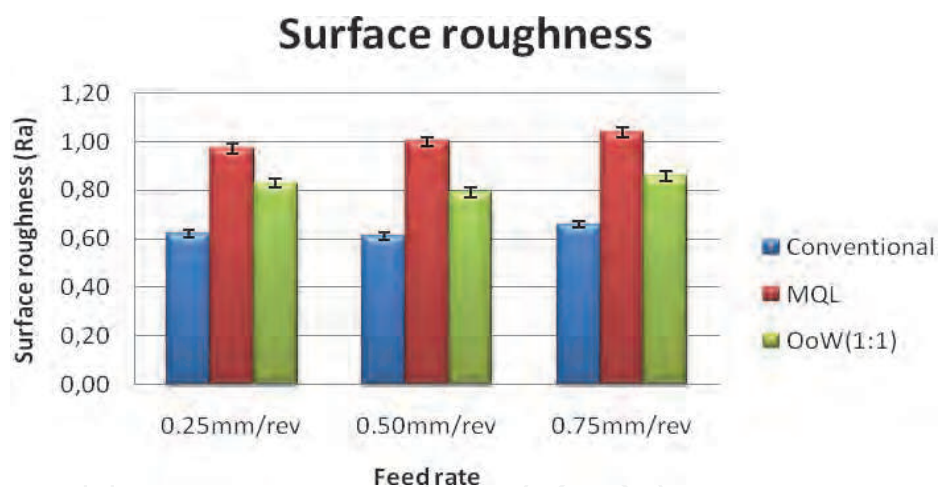


Fig. 11. Surface roughness results for each lubri-refrigeration condition

However, it can be seen that MQL with water provided lower values for surface roughness, than when using traditional MQL. OoW (1:1) tended to decrease this variable, being 35% higher compared to conventional lubri-refrigeration, and 20% lower compared to traditional MQL. A possible explanation for this better performance of air-oil-water mixture, in relation to air-oil (traditional MQL) is the fact that, following the same reasoning presented above, the water lower viscosity makes the grout less adherent to the wheel, and consequently easier to be removed from the wheel pores.

### 2.2.3 Roundness

For the roundness values presented in Figure 12, the conventional lubri-refrigeration also presented the best results for all feed rates tested, due to the better ability of cleaning the wheel provided by this method.

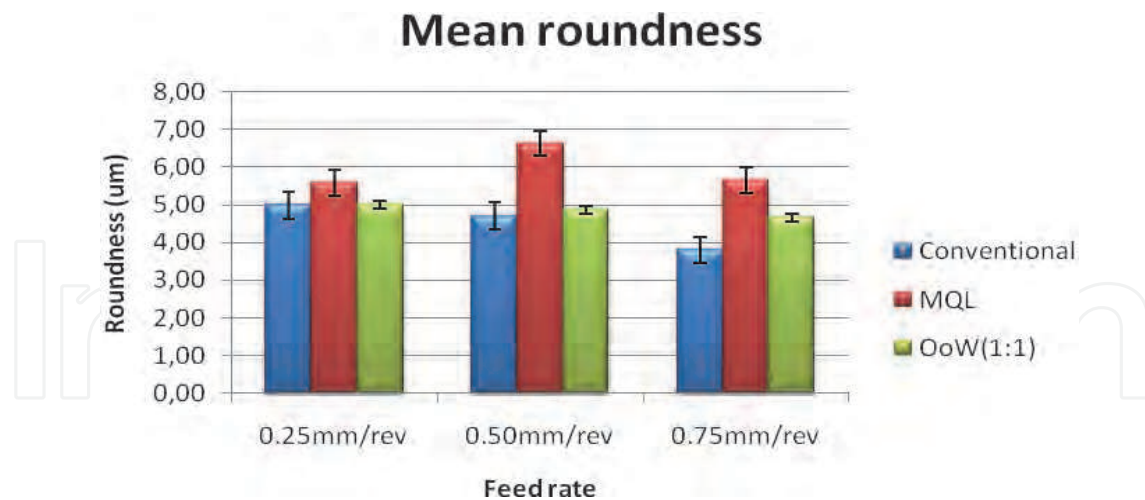


Fig. 12. Roundness results for each lubri-refrigeration condition

Again it can be seen that the presence of water in the air-oil combination increases the roundness values, since they increased when using OoW. That was caused by the reduction of lubrication capability of this mixture, since there are lower amounts of oil. On the other side, when using only oil in combination with air (traditional MQL), that it, when the lubrication capability is higher (for MQL systems), the roundness values were higher than when using OoW (1:1). This is possibly due to the fact that, despite the increase in the lubricating capability of traditional MQL, the combination of air-oil loses wheel cleaning capability, which also influences the results for roundness.

#### 2.2.4 Acoustic emission

For the acoustic emission values, it can be observed that conventional lubri-refrigeration provided the higher results, while the others provided relatively lower values, about 75% of the conventional, as shown in Figure 13.

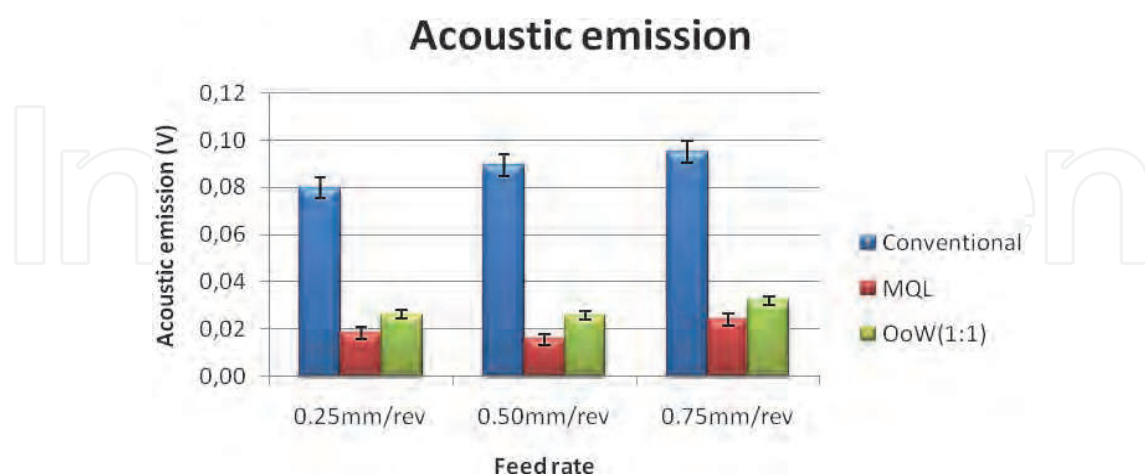


Fig. 13. Acoustic emission results for each lubri-refrigeration condition

It can be concluded that acoustic emission was mainly influenced by the lubrication capability of the lubri-refrigeration method, and less influenced by the wheel cleanliness. As the lubrication capability increased, and wheel cleaning capability decreased, acoustic

emission values were lower. Even when the wheel had machined chips lodged into its pores (as when using traditional MQL), the presence of oil on the grout provided less friction between the grains (and lodged chips) and the workpiece.

### 2.2.5 Grinding power

Observing Figure 14, it can be noticed that the lower values of grinding power were obtained when using conventional lubri-refrigeration. This same decreasing tendency was observed for OoW, with oil/water ratio of 1:1. This occurs because in conventional lubri-refrigeration, the capability of cooling the wheel/workpiece interface is the better, among the conditions tested.

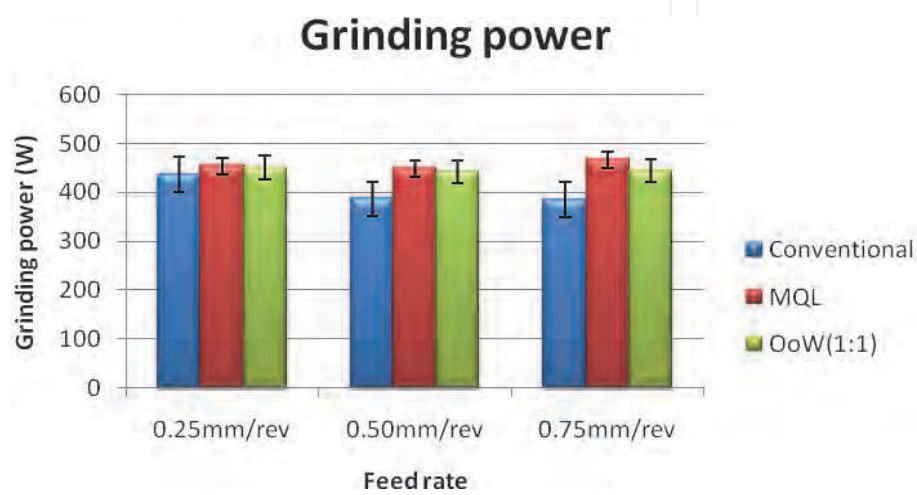


Fig. 14. Grinding power results for each lubri-refrigeration condition

When used traditional MQL, it can be seen that the required power tended to be slightly higher than when using OoW (1:1) method. This can be explained by the fact that, when using only oil the cooling is less efficient, probably causing thermal deformations of the machine/workpiece/wheel system, which requires more power. On the other hand, OoW (1:1) combines efficient cooling and lubrication in a way that grinding power necessary is lower.

### 2.2.6 Diametral wheel wear

According to the results presented in Figure 15, it can be observed that, for all feed rates tested, MQL was the lubri-refrigeration method which provided the higher wear values, about 28% higher than conventional lubri-refrigeration, for the feed rate of 0,25mm/rev, 25% higher for 0,50mm/rev and 14% higher for 0,75mm/rev.

As previously mentioned, traditional MQL was the lubri-refrigeration method which was less effective in cleaning the wheel, that is, it is the condition on which more chips remained lodged in the wheel pores. Then, the friction between these adhered chips and the workpiece contributed to wear the wheel more intensely. On the other side, the most efficient method for wheel cleaning, which was conventional lubri-refrigeration, did not provide lower diametral wheel wear values, as it could be supposed by the aforementioned reasons. It is possible that the factor which caused high wheel wear was the low capability of lubrication of this abundant flow, which consists of oil diluted in water.

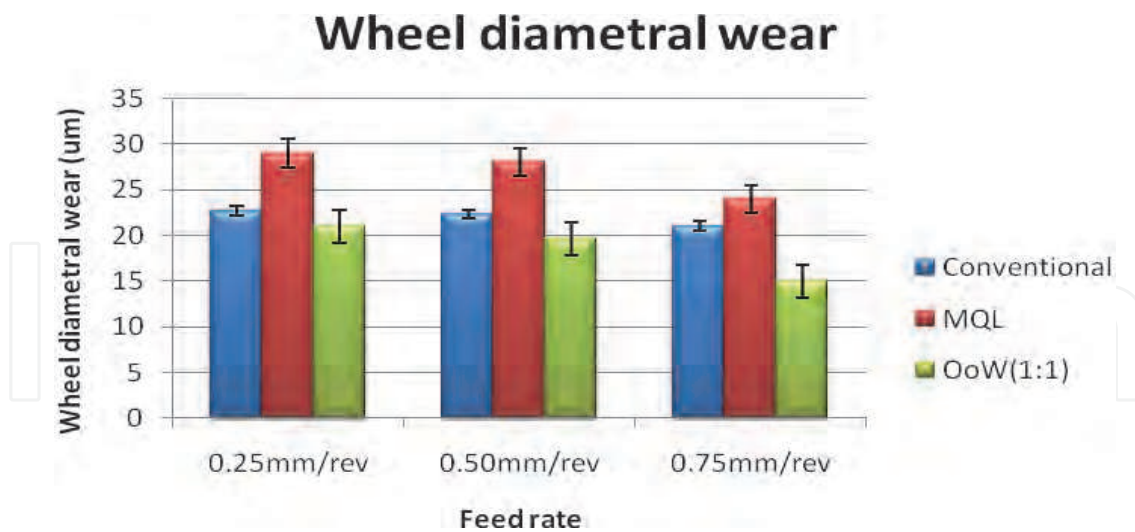


Fig. 15. Diametral wheel wear for each lubri-refrigeration condition

When used a lubri-refrigeration method which is intermediary in terms of wheel cleaning and lubrication capability (OoW), it was obtained a satisfactory combination of both variables, and the diametral wheel wear was not as high as the one obtained when using conventional lubri-refrigeration.

### 2.2.7 Conclusions

Based on the obtained results on this work, it can be concluded that, when grinding ceramics with diamond wheels, in similar conditions to the ones tested:

In terms of surface roughness, conventional lubri-refrigeration was the method which provided the best results, due to its better ability to clean the wheel, by removing the machined chips which lodge in the wheel pores. Traditional MQL presented the worst results, because, despite being very efficient in lubricating the wheel/workpiece interface, it was the worst condition for wheel cleaning.

In terms of roundness, the results were similar to surface roughness. Conventional lubri-refrigeration was the most satisfactory method, while traditional MQL was the less satisfactory.

Acoustic emission signals generated from the process was strongly influenced by lubrication capability of the lubri-refrigeration methods (it can be inferred that it is an indirect measurement of this capability). Thus, the higher acoustic emission values were obtained when using conventional lubri-refrigeration, while the lower was obtained for traditional MQL.

The lubri-refrigeration condition which provided the higher diametral wheel wear was the less efficient when considering wheel cleaning (traditional MQL). However, the condition most efficient in cleaning the wheel (abundant fluid flow) was not the one which provided lower wheel wear, since it has poor lubrication capability.

### 2.3 Wheel cleaning by a compressed air jet

According to Lee et al. (2002), an alternative to overcome the issue of having oil and impurities lodged on the Wheel pores, when using MQL technique, would be the application of compressed air jets, directed straightly onto the cutting zone, which would clean the wheel surface.



The depth of cut can be thus increased, since the diametral Wheel wear would be lower, and, beyond that, it is possible to obtain better surface quality, reducing surface roughness and fulfilling efficiently the geometrical and shape requirements of the component.

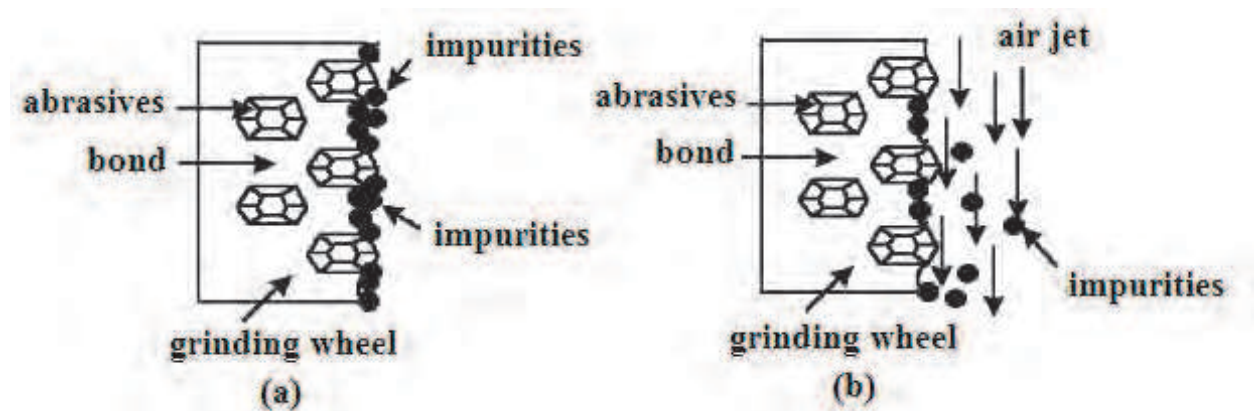


Fig. 16. Effect of compressed air jet. (a) grinding without wheel cleaning, (b) grinding with wheel cleaning (Lee et al., 2002).

### 2.3.1 Materials and methods

The tests were conducted on a SulMecânica RUAP 515 H-CNC surface grinder, equipped with computer numerical control (CNC). Workpieces were made from commercial alumina 96% of aluminium oxide, 4% of other oxides like  $\text{SiO}_2$ ,  $\text{CaO}$  and  $\text{MgO}$ ). The apparent density was  $3.7 \text{ g/cm}^3$ . The grinding wheel was a resin bonded diamond wheel (D140N100V) with dimensions of: 350mm (external diameter)  $\times$  15mm (width)  $\times$  5mm (layer) and internal diameter of 125mm.

The cutting fluid used for minimal quantity of lubricant was a Rocol Cleancut, and the MQL application device was an ITW Chemical Accu-Lube, which allow independent flow rate regulation of oil and air. The air flow rate used was monitored with a turbine type flow rate meter, calibrated to a pressure of  $8 \text{ kgf/cm}^2$ .

For the wheel cleaning compressed air jet, the air flow rate was  $8.0 \cdot 10^{-3} \text{ m}^3/\text{s}$  and the pressure was  $7.0 \cdot 10^5 \text{ Pa}$  at the nozzle.

The cutting fluid for conventional lubri-refrigeration was soluble semi-synthetic oil (Rocol Ultracut 370), with 5% concentration on water.

The measurement of roundness was conducted by a Taylor Hobson Talyrond 31C roundness meter, which provided the average value for each test.

Surface roughness ( $R_a$ ) was measured five times for each workpiece, obtaining an average value for each test, using a Taylor Hobson Surtronic<sup>3+</sup> rugosimeter.

Diametral wheel wear was measured by printing the wheel profile on an AISI 1020 steel workpiece. Then the average value was calculated by the software Talymap Silver.

The microstructural analysis was made through the analysis of SEM micrographs, after adequate preparation of the workpieces.

The grinding power data were gathered in real-time with the data acquisition software NI LABView.

Each test was repeated twice, and five workpieces were used. The feed rate used was  $0.50 \text{ mm/min}$ .



The lubri-refrigeration conditions were: Conventional lubri-refrigeration (abundant flow); MQL without wheel cleaning; and MQL with wheel cleaning, with four different incident angles for the compressed air jet on the tool surface (tangent, 30°, 60° and 90°). The cleaning nozzle placement is shown in Figure 17.

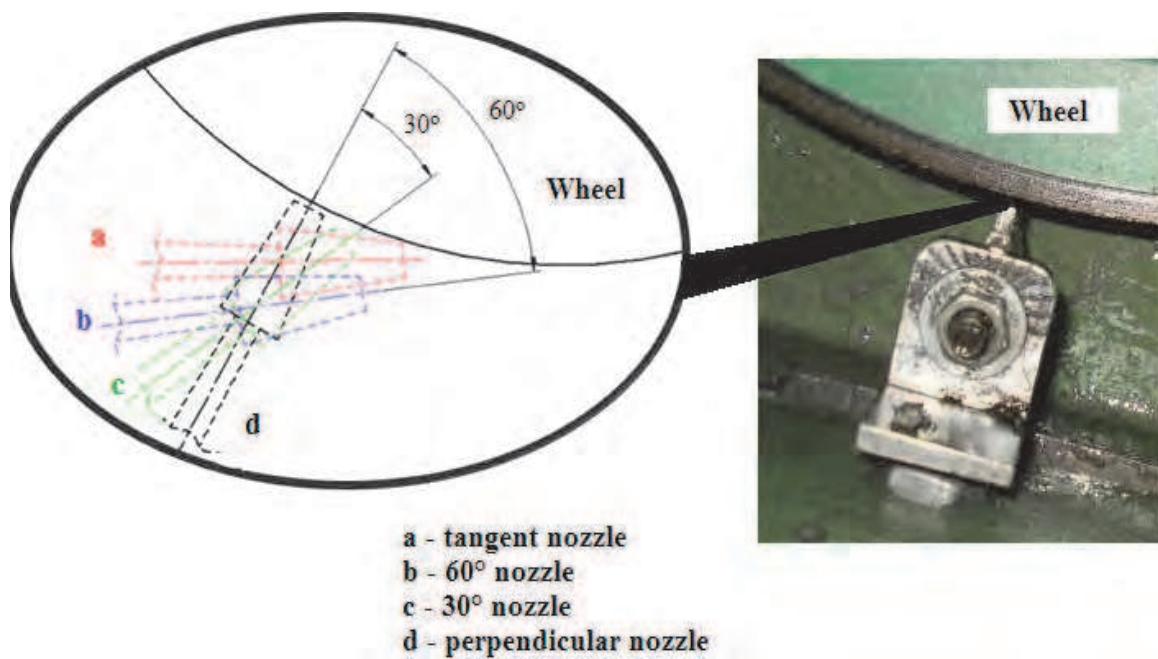


Fig. 17. Incidence angles for compressed air jet.

### 2.3.2 Surface roughness

Figure 18 presents the results obtained for the average surface roughness ( $R_a$ ).

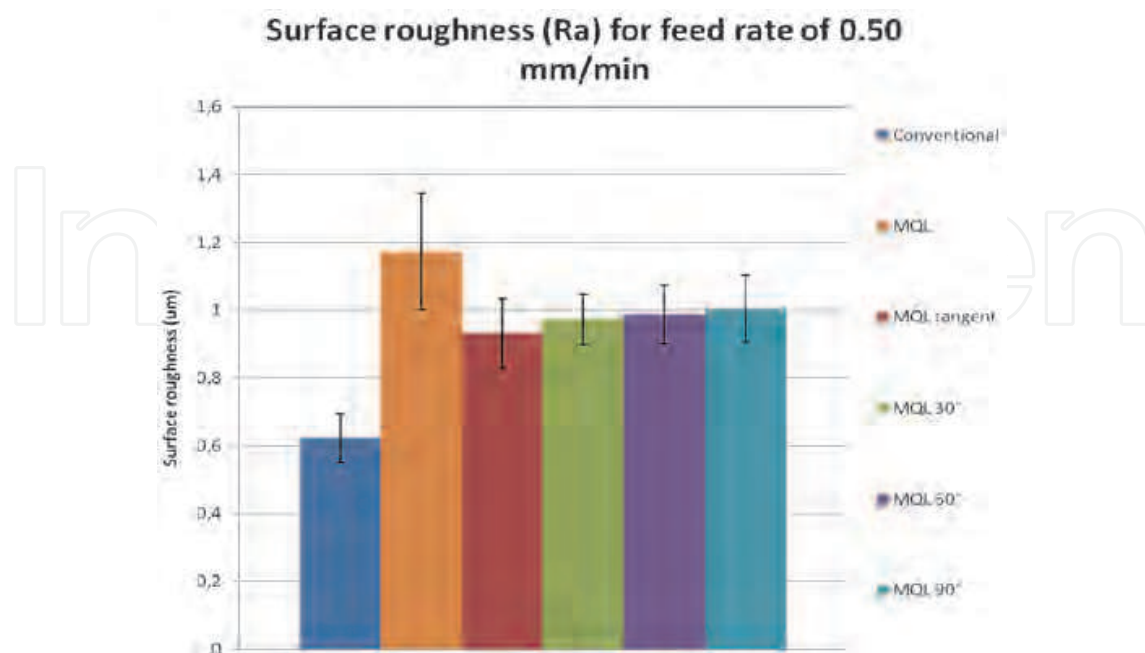


Fig. 18. Surface roughness results for each lubri-refrigeration condition

Analyzing the results obtained, it can be observed that the surface roughness value was lower for conventional lubri-refrigeration, in comparison to MQL technique, possibly caused by the better removal of machined chips from the cutting zone. When using MQL, a grout is formed (mixture of oil and chips), which is difficult to remove, causing an increase on the surface roughness.

In relation to MQL with wheel cleaning, it can be seen clearly an improvement of the results for this variable, when comparing to traditional MQL (without wheel cleaning), but they still remained worse than the results for conventional lubri-refrigeration. This is due to the worse capability of removing the grout formed, and the heat generated on the cutting zone, when using MQL. Considering the average values for surface roughness for conventional lubri-refrigeration, in comparison to the tangent angle for the cleaning air jet (best condition of wheel cleaning), it can be seen that the conventional lubri-refrigeration provided values almost 40% lower.

In relation to the efficiency of the cleaning system by compressed air, it is a function of the air jet incident angle, since the pressure and flow rate were kept constant.

Thus, it can be noticed that the wheel cleaning conditions provided better results than when using traditional MQL, for all incident angles tested. Besides that, the angle which provided the best results was the tangent angle.

### 2.3.3 Diametral wheel wear

Figure 19 shows the results obtained for diametral wheel wear, using as a reference the conventional lubri-refrigeration, since it is widely applied on the industries.

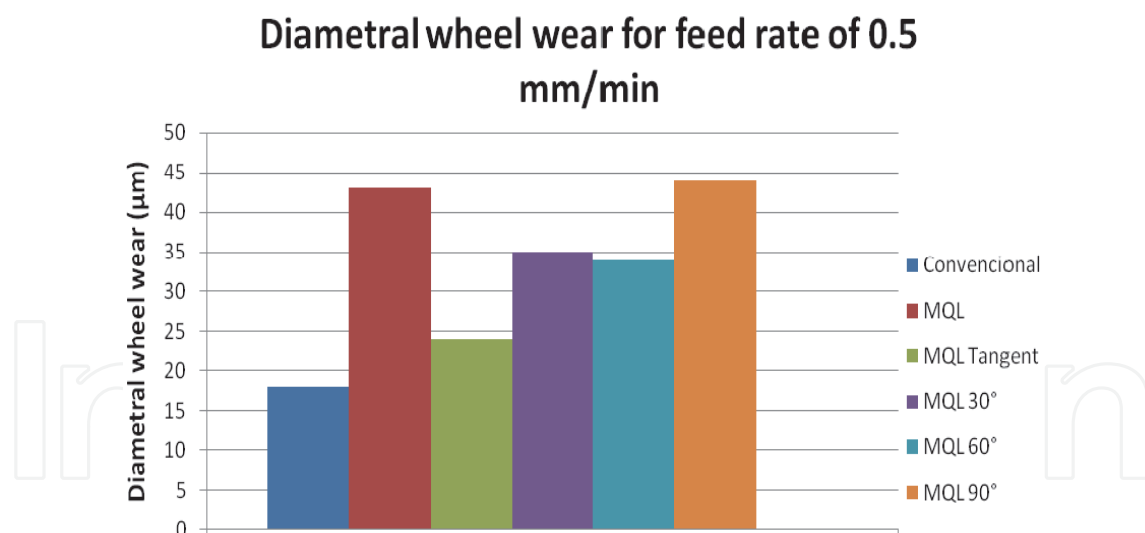


Fig. 19. Diametral wheel wear results for each lubri-refrigeration condition tested.

Analyzing the results obtained, it can be seen that conventional lubri-refrigeration obtained again the best results, and the wheel cleaning method provide clear improvements when comparing to traditional MQL, with exceptions to the normal angle in this case (which was very close to traditional MQL).

When considering diametral wheel wear, the tangent angle was the most efficient, as occurred for surface roughness results, being about 40% higher in comparison to

conventional lubri-refrigeration. Again, as the wheel cleaning was not so efficient in removing the material lodged, the results were harmed; however, this prejudice was lower when using the air jet with an incident angle tangent to the tool surface. Thus, it can be noted a coherence with the results obtained for surface roughness and diametral wheel wear.

### 2.3.4 Roundness

Figure 20 presents the results obtained for roundness errors, for a clear comparison among the lubri-refrigeration conditions tested.

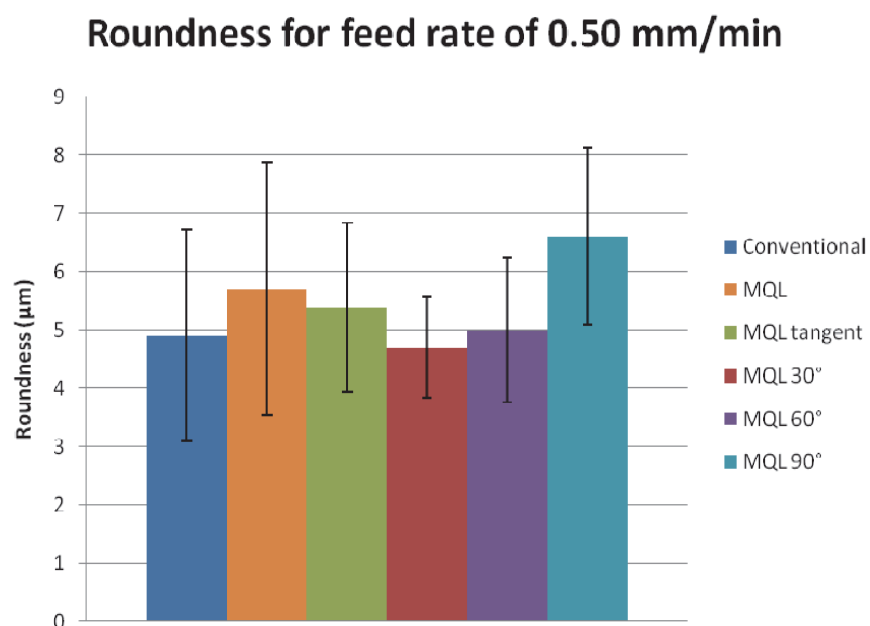


Fig. 20. Roundness results for each lubri-refrigeration conditions

It can be noticed that, generally, the average values were close, being the wheel cleaning jet with incidence angle of 30° the best condition. However, wheel cleaning for other angles presented worse results than when using conventional lubri-refrigeration. It can be also observed that, with exception to normal jet (90°), all angles improved the results in comparison with traditional MQL.

The incidence angle of 30° provided very satisfactory results, even better than when using conventional lubri-refrigeration. With that, the most efficient angle was not the tangentially directed, as in surface roughness and wheel wear results. However, this angle provided also better results than traditional MQL, becoming also viable. The difference between the average values of roundness results for conventional lubri-refrigeration and MQL with wheel cleaning (30°) was only about 2%.

The results for roundness did not behave as the expected, when considering surface roughness and Wheel wear, because this variable is more sensitive to the stiffness of the process, i.e., grinding machine, tool, workpiece, and others.

An example for these unexpected values is that the incidence angle of 30° provided better results than conventional lubri-refrigeration, which did not occur in surface roughness and wheel wear results. Another one is the fact that the tangent angle was not the most efficient condition of wheel cleaning, as in the previous output variables evaluated.

### 2.3.5 Grinding power

Figure 21 presents the results obtained for grinding power (gathered in real-time), for each lubri-refrigeration condition.

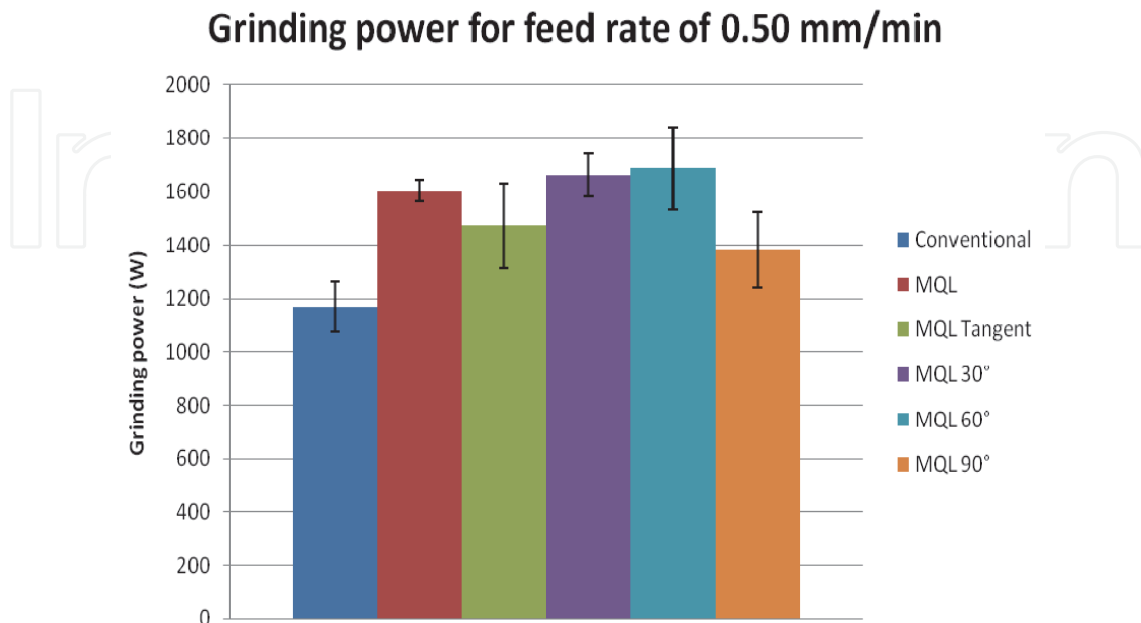


Fig. 21. Results of grinding power for different lubri-refrigeration condition.

It can be noted that the conventional lubri-refrigeration test provided the lower grinding Power values, which is coherent with the results of surface roughness and diametral wheel wear. That occurs probably due to the more efficient chip removal from the cutting zone, favoured by this lubri-refrigeration method.

Also, traditional MQL did not provide the worst result, because MQL with wheel cleaning jets using 30° and 60° provided higher grinding power values. When using the wheel cleaning jet with incidence angles of 30° and 60°, it can be observed that the results for surface roughness were better, in comparison to traditional MQL, because the compressed air jet creates higher reaction forces on the grinding wheel, which contributes to the removal of lodged chips, reducing then the surface roughness. At the same time, this reaction generates higher components of tangential force, against wheel rotation, increasing thus grinding power values. This explains the fact that this variable, for the wheel cleaning incidence angles of 30° and 60°, was higher than for traditional MQL.

This also explains why the grinding power values, for the wheel cleaning jet with incidence angle of 90° (normal to wheel surface), were lower than when using compressed air jet directed tangentially (which provided lower surface roughness, in comparison to the first). Tangential compressed air jet generates higher forces against the wheel rotation, increasing then the grinding power.

### 2.3.6 Scanning electron microscopy (SEM)

Surface integrity is of undeniable importance, when concerning grinding operation. Damages caused to the material surface can affect it negatively, harming wear resistance, causing nucleation and propagation of cracks, and accelerating fatigue.

Scanning electron microscopy is a powerful technique of microstructural assessment and characterization, making possible to analyze the material surface as a consequence of each condition of grinding, specifically in the present situation.

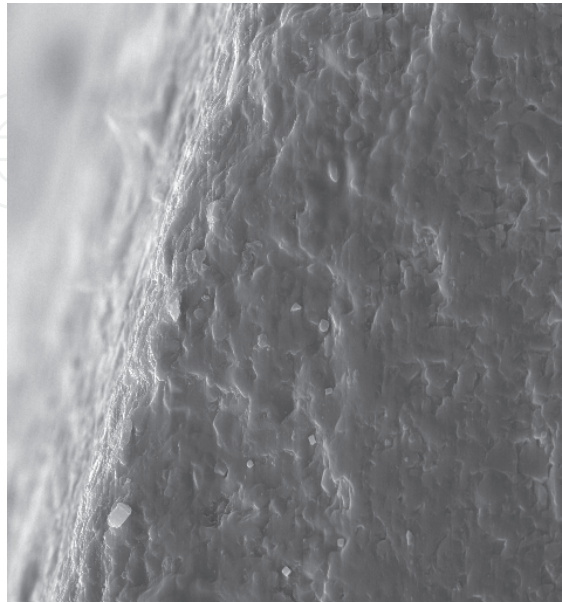


Fig. 22. Scanning electron micrograph for conventional lubri-refrigeration tests (1000x)

Analyzing Figure 22, it is possible to notice that, when using conventional lubri-refrigeration, the fragile material removal mechanism prevailed. It is also noteworthy the good finishing surface, despite the fragile removal, which can cause microcracks.

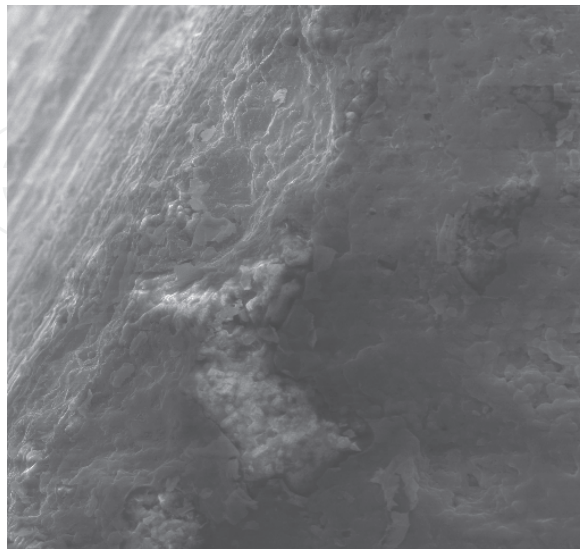


Fig. 23. Scanning electron micrograph for MQL lubri-refrigeration tests (1000x)



Analysing Figure 23, it can be seen that, when using MQL lubri-refrigeration, ductile material removal mode prevailed, which provided optimal conditions of surface finishing, in relation to material strength, due to the reduced presence of microcracks, which are stress concentration agents.

The best surface characterization of the ground workpiece A melhor caracterização da superfície da peça retificada com a refrigeração utilizando a técnica do MQL em relação à peça retificada com a refrigeração convencional pode ser explicada pelo maior poder lubrificante do óleo utilizado na técnica do MQL em comparação ao fluido de corte emulsificado utilizado na refrigeração convencional.

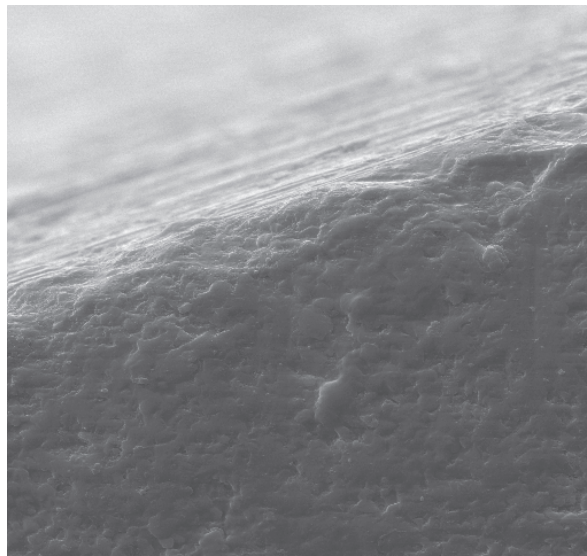


Fig. 24. Scanning electron micrograph for MQL technique with tangent wheel cleaning (1000x)

When observing Figure 24, it can be noticed that ductile mode of material removal also prevailed, due to the use of the same cutting fluid as when applying traditional MQL. Moreover, this finishing surface is even better than when using MQL without Wheel cleaning, because this method could effectively remove the grout lodged in the pores, providing consequently better surface finishing.

### 2.3.7 Conclusions

A general analysis of the presented results indicates that conventional lubri-refrigeration is the method which provided better results for surface roughness, roundness and wheel wear. However, MQL with wheel cleaning system is also viable, when comparing to traditional MQL, since it provided better results concerning surface quality and wheel wear, in comparison with the latter.

The tangent jet from the wheel cleaning system was the best incidence angle tested. It clearly improved MQL technique; however, it could not provide results as good as when using conventional lubri-refrigeration. Nevertheless, MQL with wheel cleaning system has its own advantages, when concerning environmental and health hazards of cutting fluids,

combining the vantages provided by MQL with better results, closer to the conventional lubri-refrigeration.

Grinding power presented inversely proportional results, when comparing to surface roughness, diametral wheel wear and roundness, for the MQL with wheel cleaning jet. This is due to the fact that, besides the influence of material removal, there is also the influence of fluid flow forces from the air jet (wheel cleaning system). The higher the cleaning efficiency, higher grinding power values can be observed.

Thus, it is possible to replace traditional lubri-refrigeration methods for new ones, as when using MQL with compressed air jets which, directed to the cutting surface, aim to clean the wheel, which improves its performance for the external cylindrical grinding.

### 3. Conclusions

As can be seen, minimum quantity lubrication – MQL can be widely applied in different machining processes, including grinding (in many different application modes). The increasing need of sustainable manufacture stimulated the researchers (and the research itself), for it was aimed to study alternative lubri-cooling methods, such as the wheel cleaning and MQL with water, when grinding advanced ceramics.

Nevertheless, if carefully applied in grinding, minimum quantity lubrication can provide satisfactory results concerning surface quality and microstructural integrity of the ceramics workpieces. Moreover, it results in environmentally friendly and technologically relevant gains.

An open door for future research in this branch is the optimization of nozzles, cutting fluid composition and control of the machining parameters, allied with some computational modeling and simulation concerning thermal distribution and fluid flow.

In addition, cost estimations should be done for each case, in order to enable more efficient applications of MQL in ceramic grinding. The costs related to this technology can be offset by lack of need for maintenance and disposal of cutting fluid, which today represents a considerable cost, due to the current standards aiming the environment preservation.

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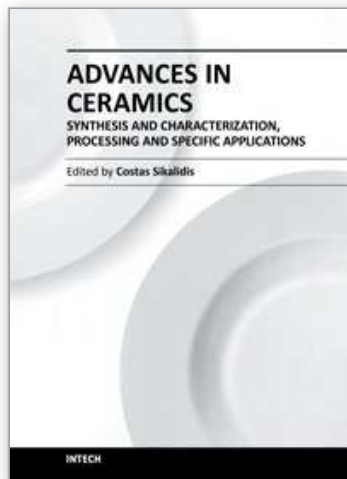
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**Advances in Ceramics - Synthesis and Characterization,  
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The current book contains twenty-two chapters and is divided into three sections. Section I consists of nine chapters which discuss synthesis through innovative as well as modified conventional techniques of certain advanced ceramics (e.g. target materials, high strength porous ceramics, optical and thermo-luminescent ceramics, ceramic powders and fibers) and their characterization using a combination of well known and advanced techniques. Section II is also composed of nine chapters, which are dealing with the aqueous processing of nitride ceramics, the shape and size optimization of ceramic components through design methodologies and manufacturing technologies, the sinterability and properties of ZnNb oxide ceramics, the grinding optimization, the redox behaviour of ceria based and related materials, the alloy reinforcement by ceramic particles addition, the sintering study through dihedral surface angle using AFM and the surface modification and properties induced by a laser beam in pressings of ceramic powders. Section III includes four chapters which are dealing with the deposition of ceramic powders for oxide fuel cells preparation, the perovskite type ceramics for solid fuel cells, the ceramics for laser applications and fabrication and the characterization and modeling of protonic ceramics.

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