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ORIGINAL ARTICLE

Application of minimum quantity lubrication with addition of water in the grinding of alumina

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Abstract

Among the alternatives to reduce the application of cutting fluid in machining industry, minimum quantity lubrication (MQL) technique has been promising, although it can impair cooling properties and the ability of the fluid to penetrate the cutting region. In order to further reduce the quantity of oil and to improve the characteristics of the cooling lubrication method, this work aims to compare the effect of MQL with different ratios of oil/water (1:1, 1:3, and 1:5) on the performance of plunge cylindrical grinding of alumina. Lubricating effect and effective penetration of fluid in the cutting zone are considered the most relevant factors. The lowest surface roughness value was obtained with the application of conventional flood cooling, followed by MQL 1:1. In comparison to conventional MQL technique, reduced surface roughness and grinding wheel wear could be obtained by applying MQL with water.

Keywords Plunge grinding · Alumina · Minimum quantity lubrication

1 Introduction

Advanced ceramics have often been applied in the modern industry due to their superior properties in comparison to metals, like thermal and chemical stability at high temperatures, high strength and hardness, low deformability, and low specific weight. However, such characteristics are also responsible for several difficulties associated with grinding of ceramic components. Material removal mechanism corresponds predominantly to brittle fracture, which leads to crack formation and damage of the component surface. Moreover, the reduced material volume removed by each abrasive grain leads to significant friction and ploughing, increasing specific energy. Regarding to this, an appropriate choice of process conditions plays an important role for improving part quality and reducing grinding wheel wear.

In order to investigate the material removal mechanism of an aluminum oxide-carbide ceramic, Tanovic et al. [1] applied a micro-cutting process with a single diamond grain. Besides crushing of ceramic grains, they observed the occurrence of plastic deformation followed by median cracks (caused by the penetration of the grain) and lateral cracks (initiated during unloading). For analyzing the material removal of a mixed oxide ceramic, Denkena et al. [2] used a quick-stop device and observed three different characteristic regions on the surface: brittle erosion, a transition zone, and ductile grooves. The latter occurred in a higher proportion, mainly when a resin-bonded diamond grinding wheel was applied in comparison to a metal-bonded one. Huang and Liu [3] observed two different areas after grinding an alumina workpiece: a fractured area and a smeared area. Ploughing marks were hardly verified. The authors also detected a decrease of surface roughness with higher depths of cut, which was explained by the increase of temperature due to the difficulty of the cutting fluid to penetrate the cutting region in these cases. This could have led to a reduction of cooling effect and softening of the material surface. However, Inasaki [4] noted the

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occurrence of brittle fracture and high values of surface roughness mainly when high workpiece speeds and depths of cut were applied at constant material removal rates.

Ramesh et al. [5] varied cutting speeds in grinding of Al_2O_3 and observed that higher values of this parameter contributed to a smoother surface, as material flow occurred by plastic deformation due to the thermal shocks caused by cooling of the workpiece. An increase in cutting speed also improved the grinding ratio. The same material was ground by Zhang et al. [6], who verified that surface damage was characterized by pulverization and micro-cracking. They also noted that larger grinding wheel-abrasive grains lead to deeper damage in the workpiece subsurface. Zhang and Howes [7] showed that material pulverization is the dominant material removal mechanism when depths of cut smaller than a critical value (2 μm for alumina) are used. Cracks were observed for higher depths.

After grinding an Al_2O_3 workpiece, Kuzin and Fedorov [8] observed an increase in average roughness and waviness with higher values of feed rate, depth, and width of cut. A very irregular surface with the presence of depressions, pores, layers of plastically deformed material, grooves, and cracks was observed, characterizing the simultaneous occurrence of brittle and ductile removal. Aiming to correlate the surface characteristics of the ground alumina workpieces with tribological parameters, Kuzin et al. [9] performed tribotests and found that low values of surface roughness lead to low tangential forces and friction coefficients.

Few authors have studied the diamond wheel wear after grinding of ceramic materials. Liao et al. [10, 11] demonstrated that, in creep-feed grinding of silicon nitride, with an increase in material removal, abrasive grains become flat and grain protrusion decreases. It was also verified that attrition, grain fracture, and pullout of grains occur simultaneously, but the latter mechanism is predominant at the very beginning of the process, while attrition takes over thereafter. The authors also observed that, in this case, self-sharpening effect does not take place. In terms of material removal, Li et al. [12] affirm that hard and sharp wheels are advantageous, as a localized surface pressure is ensured.

Another relevant aspect to be considered in grinding of ceramic materials corresponds to the characteristics (cooling and lubricating properties) and application method of cutting fluids. In the mentioned works, emulsions with high values of flow rate (in the order of liters per minute) are mainly used. However, current efforts have been directed to the investigation of different approaches in order to reduce or even avoid the use of fluids due to environmental and health problems. In this context, researchers have tried the minimum quantity lubrication technique.

Sadeghi et al. [13] compared MQL with conventional flood cooling in grinding of a titanium alloy with an aluminum oxide grinding wheel and observed that the MQL system helped to keep the wheel sharp for longer periods, which led to higher roughness values due to the shearing marks left on the surface. Moreover, the lubricating effect of MQL contributed to the reduction of tangential force. Tawakoli et al. [14] and Sadeghi et al. [15] found similar results after grinding soft and hardened steels with the same kind of grinding wheel, and Tawakoli et al. [16] observed that even better results could be obtained when the nozzle is positioned toward the abrasive wheel layer at an angular position between 10° and 20°. All these authors concluded that MQL technique provides a more effective penetration of the fluid in the cutting zone, which allows a better process performance in comparison to the application of conventional flood cooling. However, it should be highlighted that such penetration efficiency is dependent on the abrasive grain size and the volume of pores in the wheel binder. This can be confirmed by the investigations carried out by Hadad and Hadi [17], who demonstrated that the application of MQL combined with soft and coarse wheels increases the grindability of an aluminum alloy and a hardened stainless steel in terms of grinding forces and surface roughness when compared to conventional flood cooling. Additionally, Hadad et al. [18] concluded from the results obtained after grinding a hardened steel that wheels with porous vitrified bond and coarse grains are a key technology to make the application of MQL possible. Considering the cooling efficiency, however, the same authors verified that approximately 75% of the generated heat is transferred to the workpiece when MQL is applied with an aluminum oxide grinding wheel, while with conventional flood cooling, the energy partition is reduced to 36%.

Aiming to improve the efficiency of MQL technique regarding clogging of a CBN grinding wheel due to adhered chips of a hardened steel, Oliveira et al. [19] used an air jet directed to the abrasive surface and achieved an efficient wheel cleaning by positioning the cleaning nozzle with an incidence angle of 30°. With this configuration, surface roughness, roundness deviation, and wheel wear presented lower values than those obtained for grinding with conventional flood cooling. Bianchi et al. [20] carried out experiments with the application of the same technique, but with an aluminum oxide grinding wheel. The obtained results also demonstrated that the application of MQL combined with a cleaning jet corresponds to a viable alternative to the use of conventional flood cooling. By applying MQL without such improvement, however, Damasceno et al. [21] obtained high roughness values after grinding a hardened steel with a CBN grinding wheel, due to wheel clogging. With low depths of cut, some oil could reach the cutting region and reduce wheel wear, but at higher depths, larger chips were produced, increasing clogging, friction, and diametral wheel wear.

In order to further improve the efficiency of MQL technique, Ruzzi et al. [22] used a cleaning air jet combined with oil–water MQL. They ground a hardened steel with a CBN grinding wheel and found that the addition of water made it easier for the cutting fluid to penetrate wheel pores and the

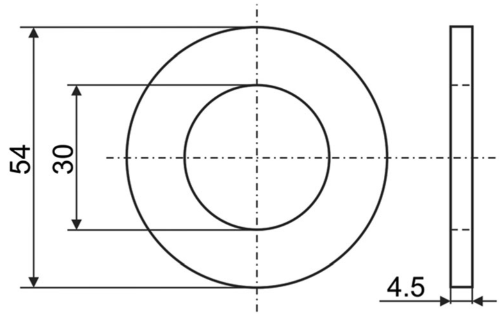


Fig. 1 Dimensions of the alumina workpiece applied in the grinding tests

cutting zone, promoting a more intensive reduction of clogging effect and, as a consequence, of surface roughness and roundness deviation. The increase in water volume decreased the influence of the cleaning air jet on workpiece quality and improved cooling capacity, which in turn reduced wheel wear. Mao et al. [23] compared oil–water MQL with pure oil MQL in grinding of a hardened steel with an alumina grinding wheel. They verified that pure oil MQL has better lubricating properties, providing lower roughness values. Otherwise, oil–water MQL contributes with cooling, reducing grinding temperature and the thickness of the affected zone in the subsurface.

Considering the literature review, a gap of knowledge regarding the application of MQL technique to grinding of engineering ceramics is noted. Therefore, considering the potential of MQL to reduce the consumption of oil and improve process performance and the challenges associated with grinding of engineering ceramics, the present paper proposes an investigation on the use of oil–water MQL combined with a cleaning air jet in grinding of an Al_2O_3 ceramic material. For comparison purposes, conventional flood cooling and pure oil MQL were also tested. The process performance was assessed by measurements of surface roughness, diametral wheel wear, roundness deviation, and acoustic emission signal.

2 Experimental procedure

Workpieces of alumina (see dimensions in Fig. 1) composed of 96% aluminum oxide and 4% melting oxides (SiO_2, CaO, and MgO), with a density of 3.7 g/cm^3, were plunge ground in a CNC cylindrical grinding machine Sulmecânica RUAP515H. Three values of radial feed rate (0.25, 0.50, and 0.75 mm/min), a cutting speed of 30 m/s, and a spark out time of 5 s were applied. Each test was characterized by a reduction of 4 mm in the diameter of the workpiece (total volume of removed material ≅ 1470 mm^3) and was repeated three times. After each single test, a new workpiece with the same dimensions was used.

The workpiece rotation was kept constant (204 rpm). This means that the tangential speed of the workpiece changed with the variation of its diameter (from 54 to 50 mm). However, this variation was neglected, as it corresponds only to 7% (workpiece speed of 0.57 m/s for a diameter of 54 mm and workpiece speed of 0.53 m/s for a diameter of 50 mm).

A resin-bonded diamond grinding wheel SD126MN50B2 (hardness N, concentration C50, abrasive grain size of 126 μm), manufactured by Dinser Ferramentas Diamantadas was used in the tests. The wheel has an external diameter of 350 mm, width of 15 mm, and an abrasive layer with thickness of 5 mm. Before each test, the grinding wheel was dressed with a multi-grain diamond dresser positioned to remove 2 μm of the abrasive layer in each of the 20 passes, performed with an axial feed rate of 500 mm/min. Afterwards, sharpening was conducted with a SiC block fed radially to the

Fig. 2 **a** Wheel wear after the test, **b** measurement set-up, and **c** printed wear profile

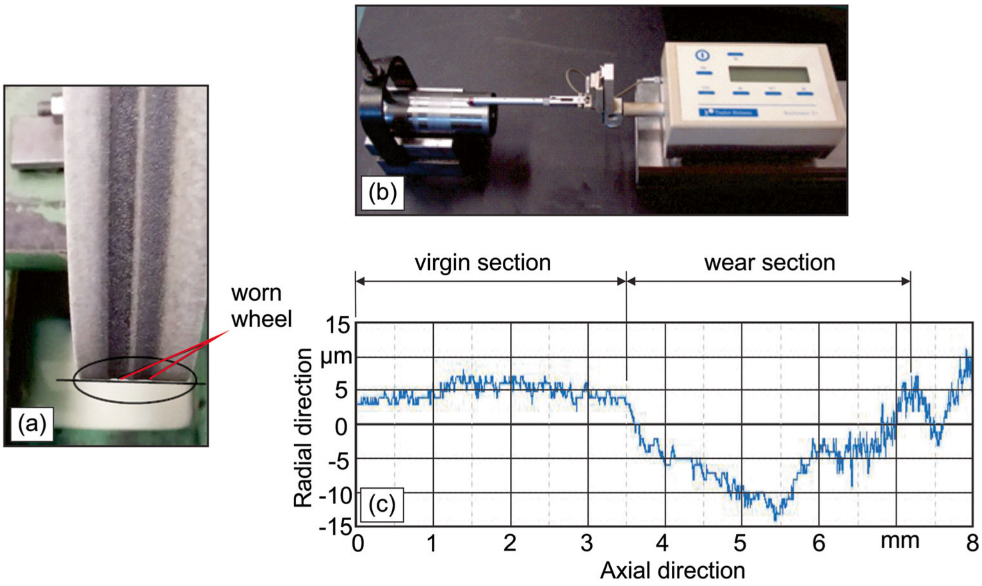
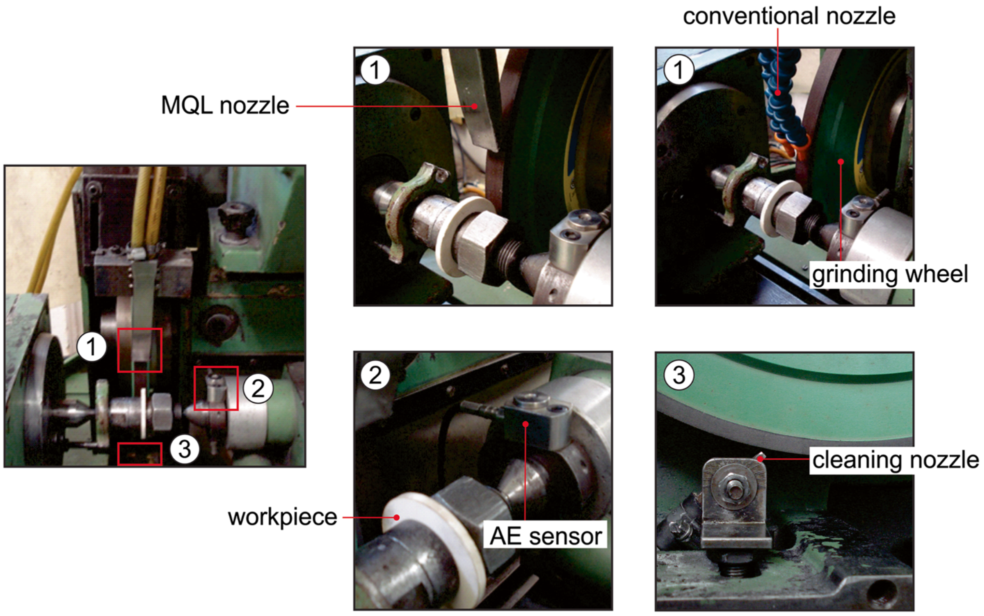


Fig. 3 Grinding system set-up



grinding wheel. In both situations, a tangential wheel speed of 30 m/s was used.

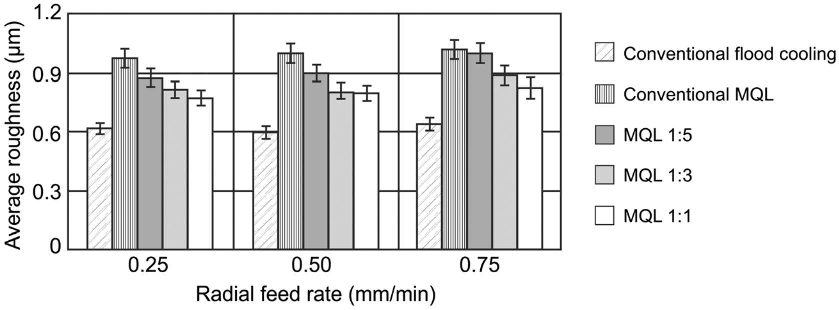
In order to investigate the influence of the cooling lubrication technique on the grinding process performance, conventional flood cooling (flow rate of 10 l/min and pressure of 1.3 bar, emulsion with 5% of semi-synthetic oil Rocol 4847 Ultracut 370 in water), conventional MQL (oil Rocol Cleancut), and MQL with three concentrations of oil/water (1:1, 1:3, and 1:5) were applied. An Accu-lube application system is responsible for regulating oil and air flow during grinding. Aiming to minimize clogging of the grinding wheel, a cleaning system by compressed air for removing adhered material from the abrasive surface was applied during all the tests. A nozzle positioned at approximately 45° and 1 mm away from the abrasive layer is connected to a compressor and directs the air jet to the wheel with high pressure, ensuring its cleaning.

Four output parameters were considered to assess the performance of the process with the application of different cooling lubrication techniques, namely average surface roughness, roundness deviation, diametral wheel wear, and acoustic emission. The average surface roughness was measured in 10 different positions of the ground workpiece by a profilometer Taylor Hobson Surtronic 3+ adjusted with a cut-off of 0.25 mm. The same device was used for measuring the diametral wheel wear. After each test, the profile of the worn grinding wheel (Fig. 2a) was printed in a cylindrical part of AISI 1020 steel, which was then measured by the mentioned profilometer (Fig. 2b,c). This measurement was possible due to the non-use of the total grinding wheel width. Moreover, the material used (AISI 1020) is a soft steel and does not influence wheel wear. Reliable results using this method were obtained in [19–22].

Roundness deviation was measured at three different positions by a roundness measuring device Taylor Hobson Talyround 31C, and RMS values of acoustic emission (AE) signals were acquired through an acquisition system Sensis DM12 with an acquisition rate of 1 kHz. The AE sensor was mounted on the tailstock of the grinding machine. Acoustic emission signal enables an online monitoring of process performance, providing information about grinding wheel wear and workpiece surface quality. Considering the consolidated application of such monitoring system, its use can provide additional evidence of the observed phenomena.

A set-up of the experimental apparatus is given in Fig. 3.

Fig. 4 Average surface roughness after grinding ceramic workpieces with different feed rates and cooling lubrication methods



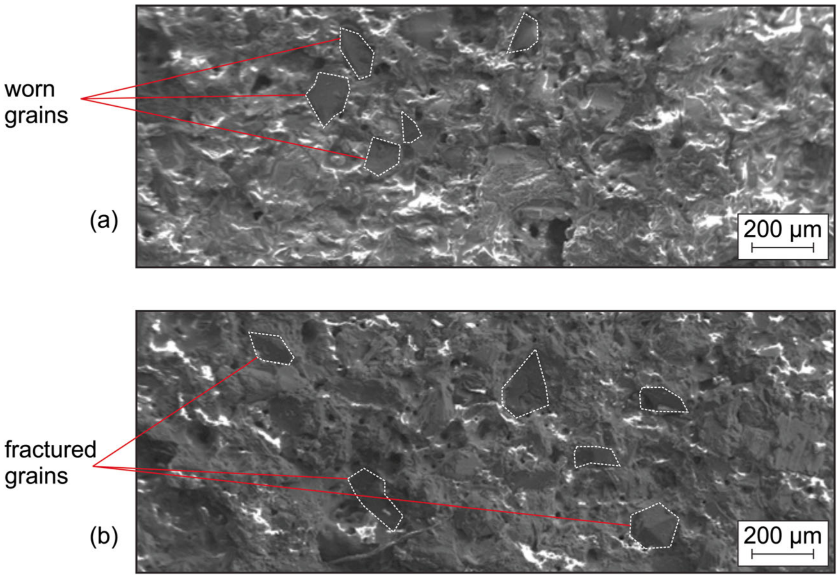


Fig. 5 SEM photos of grinding wheel abrasive layer after grinding ceramic workpieces with radial feed rate of 0.5 mm/min and (**a**) conventional flood cooling, as well as (**b**) MQL 1:5

3 Results and discussion

In this section, the output parameters are analyzed and discussed based on the cooling lubrication methods applied in the grinding experiments. The graphs present average values and standard deviations of three tests.

Figure 4 shows the average surface roughness obtained for the different cases. Higher values of feed rate tend to increase surface roughness due to the thicker chips generated during grinding. However, this variation could be barely observed in the presented results because of the use of a spark out time, which reduced the influence of such parameter on surface quality. Regarding the application of the cutting fluid through different techniques, conventional flood cooling led to the smallest roughness value, while conventional MQL produced the highest. Intermediary average roughnesses were obtained by using MQL with different oil/water concentrations.

Due to the high flow rate during its application, conventional flood cooling can be considered the most effective technique in view of penetration of fluid in the cutting zone in comparison to the other methods. This contributed to the reduction of friction and a smoother material removal, leading to

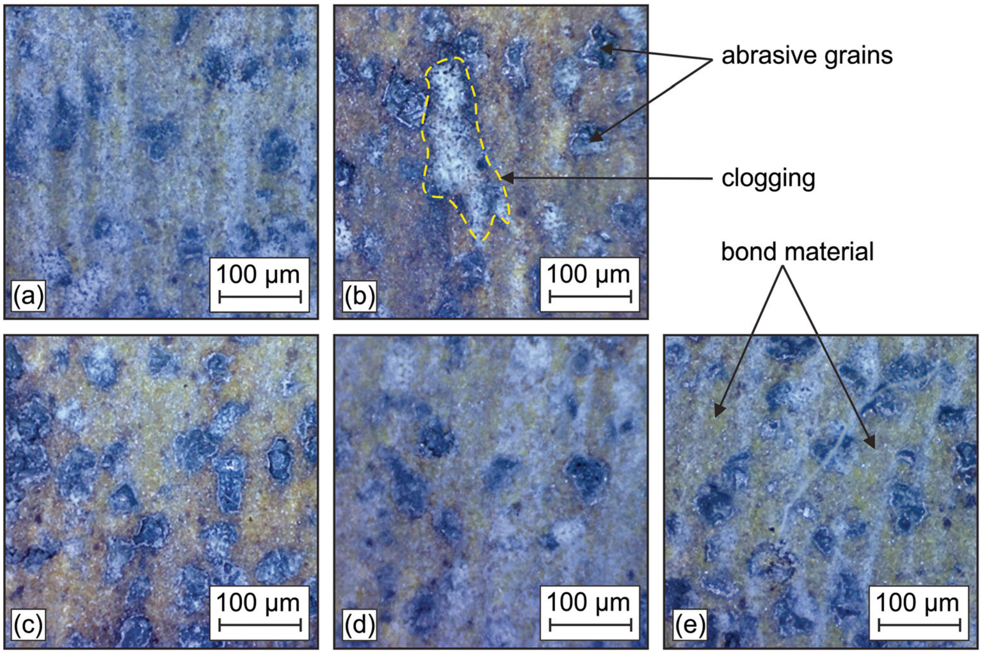
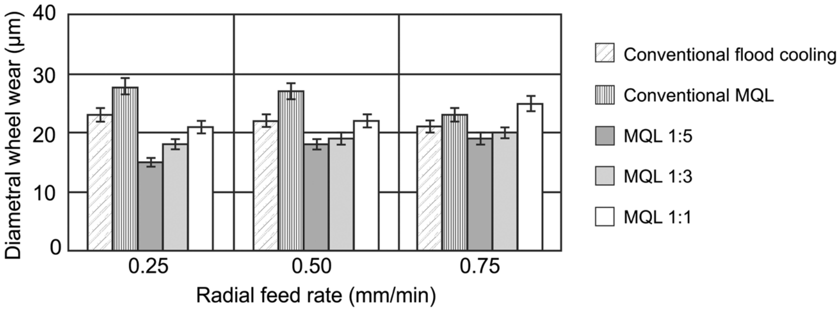


Fig. 6 Images of grinding wheel abrasive layer after grinding ceramic workpieces with radial feed rate of 0.75 mm/min and different cooling lubrication methods: (**a**) conventional flood cooling, (**b**) conventional MQL, (**c**) MQL 1:5, (**d**) MQL 1:3, (**e**) MQL 1:1

Fig. 7 Diametral wheel wear after grinding ceramic workpieces with different feed rates and cooling lubrication methods



smaller roughness values. Otherwise, despite the high pressures applied, conventional MQL was not sufficient to effectively lubricate the cutting region. As a result, it did not present a good performance and higher roughness values were obtained. Due to the decrease of viscosity, the addition of water in the cutting oil used in the MQL technique can have facilitated the penetration of the fluid between abrasive grain and workpiece in comparison to the conventional MQL method, improving surface roughness. However, with an increase in water volume (from 1:1 to 1:5), the lubrication characteristics were reduced and surface roughness increased.

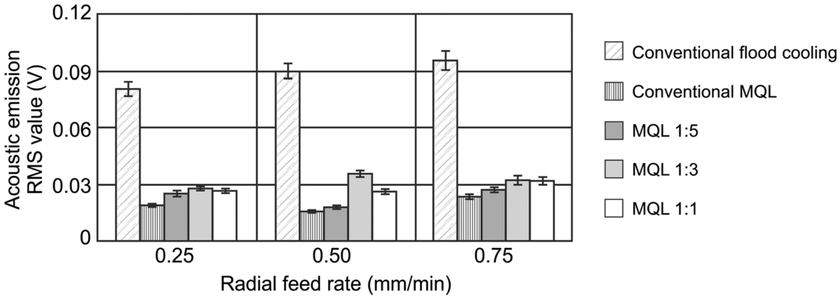
Additionally, the application of conventional flood cooling played an important role in removing chips adhered to the abrasive layer. These can scratch the workpiece and damage the surface, increasing its roughness. Regarding to this, MQL systems were less effective. Although the addition of water made it easier to the fluid to penetrate in the wheel pores and remove the chips, the reduction of the lubricating effect was predominant and surface roughness achieved higher values in these cases. It is worth remembering that the bond material corresponds to a resin, which limits the volume of pores and the space between abrasive grains. This makes it more difficult to bring the fluid to the cutting zone.

Another reason for the reduced roughness values obtained by applying conventional flood cooling corresponds to the wear of the abrasive grains. Such cooling lubrication method did not extract the heat in an effective way when compared to MQL with water. In the latter case, higher pressures increase the kinetic energy of the fluid in direct contact with the wheel, increasing the convection coefficient and potentializing the heat transfer [24]. Thus, thermal effects predominated when applying conventional flood cooling and due to diffusion and abrasion mechanisms, the diamond grains became flat (Fig. 5a) and the grain protrusion decreased, reducing the single-grain chip thickness and, as a consequence, surface roughness. Such phenomenon is supported by Malkin and Guo [25], who affirm that surface roughness can be empirically related to the uncut chip thickness, which in turn depends on the depth of cut of a single grain. Associated with this, an increase in the contact area between grain and material occurs. Thereby, not only cutting forces per abrasive grain can be increased, but also the thermal load. Both of these effects weakened the grinding wheel bond material (resin), which released sets of abrasive grains, causing high diametral wheel wear (Figs. 6a and 7).

When using MQL with oil and water, this effect was less significant because of the more effective heat extraction. Therefore, the resin bond kept the grains longer (Fig. 6c–e). Taking into account the smaller effect of thermal loads in this case, grain fracture predominated (Fig. 5b) and a reduced diametral wheel wear was observed with the increase in water volume (Fig. 7). With new sharp edges, the diamond grinding wheel became more aggressive, as grain protrusion was higher, and surface roughness increased (Fig. 4).

The difficulties associated with the penetration of the fluid in the cutting region during the application of conventional MQL (pure oil and high viscosity) damaged the roughness, as already explained, and increased grain wear, as well as bond wear and clogging (Fig. 6b), due to the higher thermal loads. This led to even higher values of diametral wheel wear, as demonstrated in Fig. 7.

Fig. 8 Acoustic emission RMS values during grinding ceramic workpieces with different feed rates and cooling lubrication methods



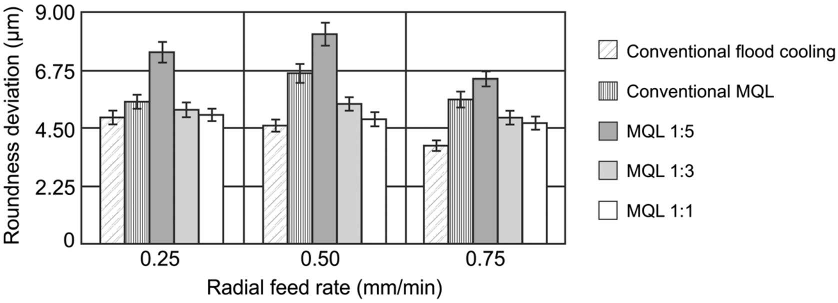


Fig. 9 Roundness deviation after grinding ceramic workpieces with different feed rates and cooling lubrication methods

For the experiments with the application of MQL with oil and water, the increase in feed rate caused an increase in wheel wear, explained by the higher mechanical loads exerted on the grains, which leads to the occurrence of grain fracture, reinforcing the already described wear mechanism. Otherwise, for the experiments carried out with conventional flood cooling and conventional MQL, higher feed rates caused a reduction of wheel wear. In the latter cases, the increase of mechanical load and resultant grain fracture contribute to the generation of new sharp edges, which reduce the forces per grain and the release of sets of abrasive grains from the wheel bond.

According to Fig. 8, which shows RMS values of acoustic emission for different cooling lubrication techniques, the application of conventional flood cooling led to the highest value, while the use of MQL with or without water presented smaller values and did not show significant differences or any clear trend between them. In this regard, it cannot be concluded in this case that acoustic emission is related to the loss of abrasive grains, clogging of the grinding wheel, or aggressive material removal, as MQL demonstrated high diametral wheel wear and conventional flood cooling contributed to the cleaning of the wheel and to the reduction of roughness values. However, the application of conventional flood cooling led to a flatter grain during the process due to the wear mechanisms related to the low heat extraction capacity of this method. This greater contact area between abrasive grain and workpiece surface caused high acoustic emission RMS values. This explanation is reinforced by the increase in the RMS with higher feed rates, which increase chip thickness.

Roundness deviation also corresponds to a relevant parameter when cylindrical plunge grinding is investigated. Several causes can be responsible for such geometric error: elastic deflection of the tool–workpiece–machine system, irregular grinding wheel profile, and irregular material removal. On the one hand, elastic deflection can be recovered by the application of an appropriate spark out time and an adequate dressing process can avoid irregular wheel profile. On the other hand, reduction of irregular material removal depends on process conditions. As spark out and

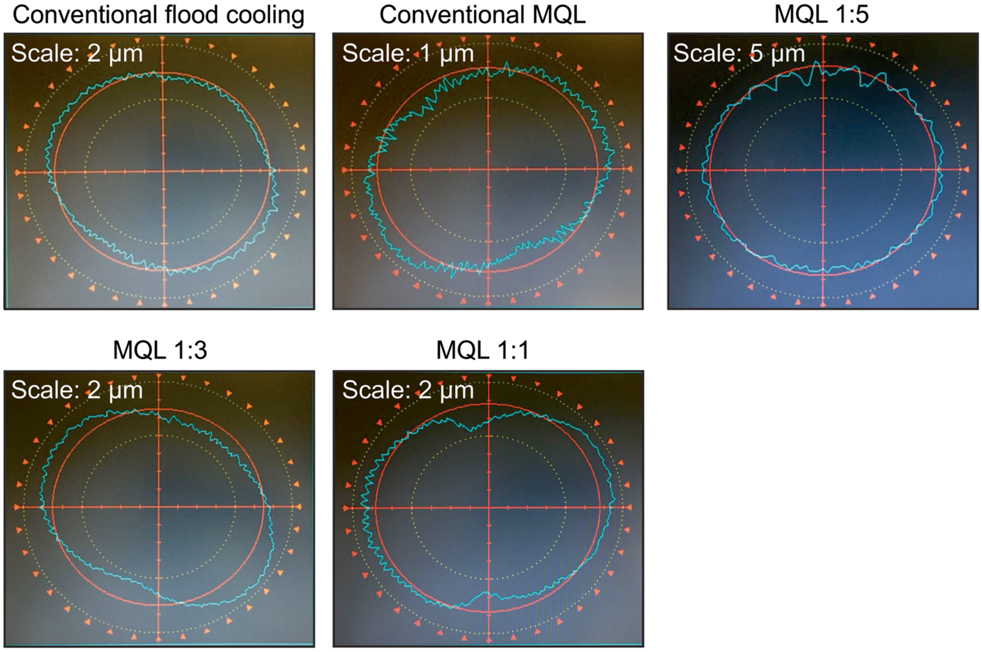


Fig. 10 Representative roundness profiles after grinding ceramic workpieces with different cooling lubrication methods (radial feed rate of 0.25 mm/min)

dressing were used in all cases, in the present investigation, roundness deviation can be associated with irregular material removal. Bearing this in mind, roundness deviation presented approximately the same behavior of surface roughness for most cutting fluid application methods (Fig. 9), which is also related to the penetration of fluid in the cutting region and removal of adhered chips from the abrasive layer. However, MQL with 1:5 oil/water proportion did not follow the same trend probably because of the increase in the total normal force during grinding. The predominance of grain fracture in this case (as already discussed) decreases the grain protrusion and increases the number of active cutting edges. This causes a reduction of the force per abrasive grain, but an increase in the total force in the process.

Figure 10 demonstrates representative roundness profiles obtained after grinding with a radial feed rate of 0.25 mm/min. It can be observed that irregularities in the workpiece ground with MQL 1:5 oil/water proportion have higher frequencies and amplitudes, which can have been caused by the vibrations related to the higher total force.

4 Conclusions

From the results obtained after grinding alumina workpieces with different cutting fluid application methods, the following conclusions can be drawn:

- Regarding workpiece quality, lubricating effect and effective penetration of fluid in the cutting zone are considered the most relevant factors. The lowest surface roughness value (≅ 0.60 μm) was obtained with the application of conventional flood cooling, followed by MQL 1:1 (≅ 0.80 μm).
- MQL 1:5 provided the smallest diametral wheel wear due to the more efficient cooling effect, being grain fracture the main wear mechanism in comparison to bond wear and the resulting loss of sets of grains. Considering this, the reduction of oil volume is possible if the reduction of grinding wheel wear is a priority.
- RMS values of acoustic emission signal were not sensitive to variations in roughness or wheel wear. However, a relation could be found between them and the abrasive grain–workpiece contact area.
- Roundness deviation followed the same trend presented by surface roughness (lowest value for the application of conventional flood cooling), except for MQL 1:5. The latter case presented the highest deviation value due to the increase in grinding force related to the wear mechanism obtained by applying such cooling lubrication technique.

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