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Improving minimum quantity lubrication in CBN grinding using compressed air wheel cleaning

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A B S T R A C T

The application of minimum quantity lubrication (MQL) in grinding has emerged as an alternative for reducing the abundant flow of cutting fluids, thus achieving cleaner production. Although considered an innovative technique in grinding operations, its widespread application is hindered due primarily to the high heat generation and wheel pore clogging caused by machined chips, harming the final product quality and increasing tool wear on the machine. This study sought to improve MQL use in grinding. In addition to the conventional MQL injected at the wheel/workpiece interface, a compressed air jet was used to clean the mixture of MQL oil and machined chips from clogged wheel pores. Experiments were conducted using external cylindrical plunge grinding on AISI 4340 quenched and tempered steel, and a vitrified cubic boron nitrite (CBN) wheel. The cooling-lubrication methods employed were the conventional flood coolant application, MQL (without cleaning), and MQL with a cleaning jet directed at the wheel surface at different angles of incidence. The main goal of these experiments was to verify the viability of replacing the traditional abundant flow of cutting fluid with MQL and wheel cleaning. The analyses were conducted by measuring the following output variables of the process: workpiece surface roughness and roundness errors, diametrical wheel wear, acoustic emission generated by the process, and metallographic images of the ground surface and subsurface. Results show the positive effects of implementing the cleaning jet technique as a technological improvement of minimum quantity lubrication in grinding in order to reduce the usage of cutting fluids. The MQL technique with cleaning compressed air jet, for a specific angle of incidence (30°), proved to be extremely efficient in the improvement of the surface quality and accurate workpiece shape; it also reduced wheel wear when compared to the other cooling-lubrication methods that were tested (without a cleaning jet).

1. Introduction

Alagumurthi et al. (2007) describe grinding as an energy-intense machining process. A great amount of energy is required per unit of removed material compared to other processes, like hard turning. As a result of the combination of countless high-speed cutting edges, a large amount of energy is consumed, and this energy dissipates in the form of heat. The heat generated in the contact area between the wheel and the workpiece is the main cause for the deterioration of the metallurgical properties, surface quality, and dimensional accuracy of the part, not to mention the shortening of the grinding wheel life. Guo et al. (2007) also underscored that during the material removal process, the generated heat will induce thermal distortions in both the machine and workpiece, limiting the precision. However, if cooling lubricants, such as cutting fluids, are used, the heat can be reduced by decreasing friction. Thus, the forces and the residual stresses on the workpiece will be minimized.

Due to an increasing desire to reduce the human health and environmental impacts of the manufacturing processes, as well as the costs associated with cutting fluids, alternative cooling-lubrication techniques have emerged. According to Dudzinski et al. (2004), minimum quantity lubrication (MQL) is among these alternatives since dry grinding does not provide satisfactory results due to the excessive heat generation. This technique (MQL) uses an aspersion of oil droplets (lubricant with very low flow rate) in a

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compressed air jet (coolant), reducing the usage of conventional cutting fluids.

Sadeghi et al. (2009) showed that, when abrasive tools are used, a reduction in the use of cutting fluid impairs the cleaning of the wheel pores (filled with machined chips), favoring the tendency for clogging, which consequently decreases cutting potential. According to Di Ilio and Paoletti (2000), wheel clogging increases grinding forces, accelerates wheel wear, and causes high surface roughness on ground parts. However, the efficient removal of the machined chips from the cutting zone is not achieved when MQL is used, because they tend to mix with the low amount of MQL fluid and create a grout, which adheres to the surface of the cutting tool, thus clogging its pores.

Analyzing these conditions, this work demonstrates a technological improvement of the MQL technique that is achieved through adding a compressed air wheel cleaning system. The results obtained are very satisfactory, even exceeding the results for conventional flood coolant applications. Therefore, this work shows that it is possible to replace the use of abundant cutting fluids with this new technique, generating several benefits to industries through a reduction in expenses, improved handling, and the disposal of cutting fluids while reducing environmental and human health impacts, contributing to sustainable technological development.

2. Problems with cutting fluids

Pawlak et al. (2004) stated that cutting fluids are used in the machining of materials to reduce friction (lubrication) and heat generation. Another function of cutting fluids is heat dissipation from the cutting zone (cooling). Stanford et al. (2007) affirmed that cutting fluids also hinder the corrosion of both the workpiece and machine tool while helping to remove chips from the cutting zone, thus promoting wheel cleaning. However, once they are used, cutting fluids contain tiny particles of materials, such as small abrasive particles from the wheel, chips, and other impurities. Moreover, water-soluble fluids are susceptible to the attack and growth of microorganisms, such as bacteria, fungi, and molds, which lead to technical and hygienic problems. A wide range of organic cutting fluid components can function as nutrients and energy sources for microorganisms. The degradation of fluid components leads to changes in the chemical composition, which alters the technical properties of the fluid, such as a decrease in pH or reduction in corrosion prevention capacity. Problems arising from degradation include increased tool wear and inadequate workpieces (Brinksmeier et al., 2010). As a result, after a specified time of use, the fluids need to be changed and disposed of due to contamination. However, if this disposal is done improperly, it is harmful to the environment.

Dhar et al. (2007) state that, despite the technological advantages cutting fluids promote, their negative effects have been questioned since they can be both environmentally aggressive and cause health-related problems. The pollutants generated as a result of grinding are known to be potentially toxic to humans. High peripheral speeds of the rotating tools and the supply of high pressure cooling lubricants enables the occurrence of aerosols, which may condense on the skin or may be inhaled (Brinksmeier et al., 2010). Thus, Sokovic and Mijanovic (2001) reported that companies are being forced to use less toxic refrigeration strategies in machining processes. Tawakoli et al. (2007) stated that one of the strategies for promoting a reduction in cutting fluid is to optimize fluid flow, which occurs with the use of a minimum quantity of lubrication.

Based in the negative and positive effects of the cutting fluids in metal cutting, especially in grinding processes, the decision about the use (or not) of cutting fluids should be carried out in a multidimensional manner with productivity, economy, and ecology as central parameters. MQL use is an alternative to flood coolant application during this decision. Other alternatives were tested by Pusavec et al. (2010). These authors made a comparison of flood coolant application, high-pressure jet-assisted machining, and cryogenic cooling, taking into account the energy use, the global warming potential, the use of water, and the solid residues of these cooling techniques, what they called Life Cycle Assessment (LCA). LCA assessments were focused on one machine tool (a turning lathe) over a one-year production period. They assumed that the production and the quality of the process did not vary based on the cooling/lubrication fluids (CLF). In other words, LCA was performed strictly for the production and delivery of the CLF into the cutting zone while the machining process performance was assumed to be the same. This assumption was limited to CLF environmental and health influence comparisons. The authors' primary conclusion was that switching from oil-based CLFs to cryogenic machining is a move toward more sustainable machining. Transitioning from oil-based to cryogenic CLFs resulted in a significant reduction in solid waste, water usage, global warming potential, and acidification and an increase in energy use for CLF production.

3. The minimum quantity lubrication

Minimum quantity lubrication (MQL) is a technique that uses a spray of small oil droplets in a compressed air jet. The lubricant is sprayed directly into the cutting zone, avoiding the huge flows of conventional flood coolant methods. According to Obikawa et al. (2006), since the air jet carries the oil droplets directly in the cutting area, it provides efficient lubrication. When conventional flood coolant is used, specific procedures have to be taken in order to allow the fluid to penetrate the cutting zone efficiently. Morgan et al. (2008) developed experiments and simulations to establish the achievable useful flow rate in grinding operations. This parameter was estimated based on the wheel surface porosity, wheel speed, and coolant jet speed. The authors concluded that: (i) useful flow usually occupies less than the pore space at the wheel surface; (ii) achievable useful flow can be estimated as approximately 50% of the surface pore space; (iii) high porosity wheels tend to allow a higher useful flow rate than low porosity wheels; (iv) the jet flow rate needs to be of four times larger than the achievable useful flow rate; and (v) the jet speed should be approximately 80–100% of the wheel speed to match the achievable useful flow rate.

One of the advantages of MQL is the fact that after grinding runs, chips, workpieces and tools have less impregnated fluid, making cleaning easier and cheaper. Furthermore, during grinding runs, since the workpiece is not fully covered with fluid, visual monitoring is possible. Attanasio et al. (2006) stated that with the minimum quantity lubrication method, a low oil flow rate of approximately 7.2–97.2 ml/h (2.0×10^{-9} to 2.7×10^{-8} m^3/s) is used (nearly 1000 times less than for conventional flood coolant application) at a pressure of $(4.0–6.0) \times 10^4$ Pa.

Hafenbraedl and Malkin (2001) also remarked that, although MQL promotes efficient lubrication and a reduction in specific grinding energy, when compared to processes using soluble oils with abundant flow (flood coolant) in non-severe machining situations, the workpiece surface roughness values that are achieved are not good relative to flood coolant application. Brinksmeier and Brockhoff (1996) affirmed that a major challenge in the minimum quantity lubrication technique is cooling, mainly when high heat removal is needed. Moreover, the lower fluid flow entails less removal of chips from the cutting zone, bringing about conditions for wheel clogging.

Recently, Hadad et al. (2012) compared different coolant-lubrication conditions in grinding AISI 52100 steels. The authors concluded, based on temperature response curves, that, despite the good lubrication of MQL grinding, it could not meet the cooling requirements comparing to flood coolant grinding. However, special additives can enhance the tribological properties of base fluids, decreasing the grinding forces and lowering heat generation in the grinding zone.

From a thorough study conducted by Tawakoli et al. (2011), important conclusions can be drawn concerning MQL grinding with CBN wheels. The authors evaluated the following output variables: grinding forces, specific grinding energy, surface roughness, wear mechanisms, chip and surface morphology, and the determination of the grinding burn threshold. CBN wheels have less tendency toward chip loading over conventional wheels. Also, with porous and coarse-grained CBN wheels, grinding is less sensitive to the coolant-lubricant type in terms of their output variables. From an overall perspective, CBN and porous wheels presented enhanced performance when grinding oils were used.

4. Phenomenon of wheel clogging

The hot chips generated in grinding have a high tendency toward lodging the pores of the abrasive tool. Cameron et al. (2010) explain the wheel clogging phenomenon as follows: when the chips generated in the grinding process are not fully removed from the cutting zone using cutting fluid, they lodge in wheel pores, impairing the entrance of the cutting fluid in the cutting zone and further hampering cooling and lubrication. These lodged chips affect the process efficiency and quality due to the increased contribution of elastic and plastic deformation in total grinding energy, which further increase the generated heat. In other words, the lodged chips will increase the sideflow plowing contribution to the total specific energy, and the heat generated in the cutting zone will increase, increasing the heat flux to the workpiece.

When conventional MQL system is used, the removal of the grinding chips from the cutting zone is difficult, and they mingle with the MQL oil and lodge in the wheel pores. During grinding, the amount of chips keeps increasing until contact (and thus friction) occurs between the workpiece and the lodged chips. This causes elastic and plastic deformation of the workpiece, as well as greater friction, which will increase cutting power, surface roughness and roundness errors of the workpiece, and wheel wear. Additionally, the workpiece will be scratched by the chips, impairing surface roughness.

According to Sinot et al. (2006), certain alloys are characterized as being hard to grind because they easily clog the wheel pores when metal particles are compressed, and they adhered to the spaces between the metal grains. With high chip removal rates, the phenomenon is further accentuated. These same authors also describe two ways to avoid clogging: using a wheel with an open structure, which will have fewer grains (and less capacity to obtain good workpiece quality) and an increasing probability of fracturing the bond or dressing the wheel frequently, which increases the costs involved in the process.

Fig. 1 shows an amplified view of a clogged wheel surface (100× magnification). In this figure, the grayish grout on the wheel surface, characterizing a mingling of MQL oil and machined chips, can be seen with the naked eye. This grout is full of small, shiny, white particles, which can be identified as the lodged chips.

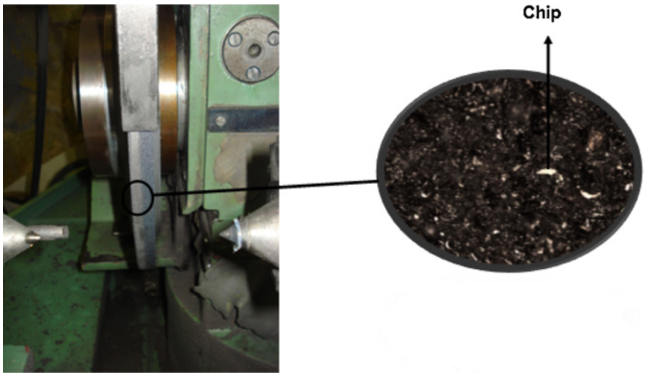

Fig. 1. Paste of oil and chips, with chips adhered.

5. Perspectives of compressed air for wheel cleaning

According to Lee et al. (2002), who conducted experiments in groove grinding, the compressed air jet is a tool that can be used to reduce clogging because the air impacts the wheel surface and removes a large number of the impurities that adhere to it (see Fig. 2). Consequently, a decrease in the wheel wear rate and an improvement in form accuracy can be achieved by using a high pressure air jet. The use of a compressed air cleaning system along with the traditional MQL cooling-lubrication equipment is expected to promote an effect similar to the one seen by these authors. The experiments of this work seek to verify the efficiency of this procedure.

6. Experimental procedure

The grinding experiments were conducted on a cylindrical CNC grinding machine. The ground material was AISI 4340 steel with a hardness of 54 ± 2 HR_C. The workpieces were ring-shaped, with outer diameters of 54 mm, internal diameters of 30 mm, and thicknesses of 4 mm. The grinding method employed was external plunge cylindrical grinding. A vitrified CBN wheel was used, with outer diameter of 350 mm, inner diameter of 127 mm, width of 20 mm, and abrasive material thickness of 5 mm. The wheel was dressed before every experiment in accordance with the conditions shown in Table 1.

The MQL equipment is made of a compressor, pressure regulator, air flow gauge, and mixing nozzle. This equipment used a pulsating system for oil supply, which allowed the separate regulation of compressed air and lubricant flows. The compressed air

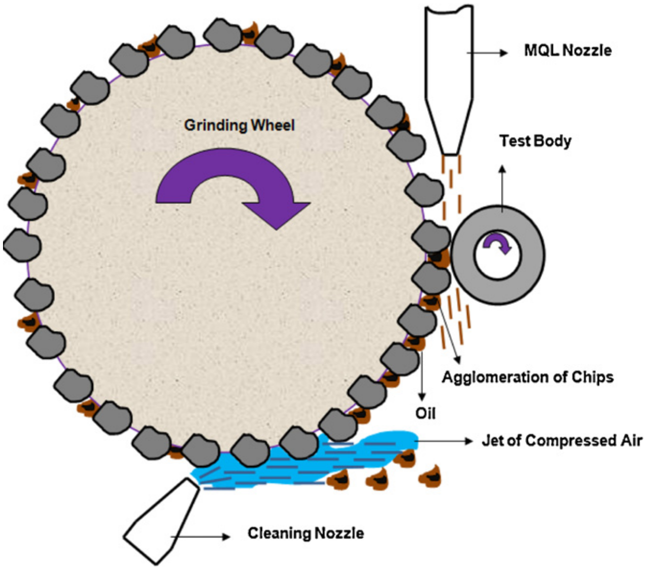

Fig. 2. Effect of the compressed air jet in wheel cleaning.

Table 1
Grinding conditions.

Grinding mode	External cylindrical plunge grinding
Grinding wheel	SNB151Q12VR2 (vitrified cubic boron nitride wheel)
Wheel speed (v_s – m/s)	30 (low for CBN wheels, but limited by the grinding machine)
Radial feed rate v_f – mm/min (specific material removal rate – mm^3/s)	0.25 (0.71); 0.50 (1.41) and 0.75 (2.12)
Work speed (v_w)	$v_w = 0.58$ m/s
Effective depth of cut (a_e)	$a_e = 1.2 \times 10^{-3}$; 2.5×10^{-3}; 3.7×10^{-3} mm/rev
Cooling-lubrication conditions	Conventional (flood coolant) conventional MQL and MQL with wheel cleaning, at four angles using compressed air jets with the following incidence angles: 30°, 60°, tangential and normal
Conventional cutting fluid	Semi-synthetic vegetable oil based emulsion at 2.5% concentration
MQL cutting fluid	100% vegetable, biodegradable, viscosity of 70 centistokes (25 °C)
Oil flow in MQL	2.7×10^{-8} m^3/s
Air pressure in MQL	6.0×10^5 Pa
Air flow in cleaning system	8.0×10^{-3} m^3/s
Velocity of compressed air in cleaning system	470 m/s
Air pressure in cleaning system	7.0×10^5 Pa
Workpiece material	AISI 4340 steel, quenched and annealed (54 ± 2 HRc)
Dresser	Diamond cluster called "block grit" by Marinescu et al. (2004) – area of 15 mm × 8 mm × 10 mm
Dressing depth (a_d)	$a_d = 0.02$ mm
Sparkout time (t_s)	$t_s = 3$ s
Dressing speed (v_d)	600 mm/min

flow was monitored with the aid of a turbine flow meter. The wheel cleaning system is comprised of a compressor, compressed air flow and pressure meter, flow distributor, and nozzle. The nozzle was attached at a distance of 1 mm from the wheel surface.

Three workpieces were ground in each experiment. Chip volume removed at each experiment was 3900 mm^3. Three different types of cooling-lubrication systems were used: conventional flood coolant application, conventional MQL, and MQL+ a cleaning system that used distinct jet angles of incidence on the wheel surface. Based on the work by Cameron et al. (2010), four angles of incidence were defined for the cleaning jet: 30°, 60°, normal, and tangential to the wheel, as shown in Fig. 3.

Besides the variation in cooling-lubrication conditions, the wheel radial feed rate was also varied (three different values). The output parameters measured were workpiece quality (surface roughness and roundness), wheel wear, and acoustic emission generated by the process, as well as microhardness and metallographic images of the ground surface and subsurface in order to identify the presence of thermal damage.

The surface roughness was measured using R_a on a surface roughness meter (Taylor Hobson Surtronic^{3+}). The results shown are averages of readings in different positions for each of the three workpieces used and for each cooling-lubrication condition. The number of surface roughness readings guaranteed a 95% confidence that the sample average represented the average of the population. Roundness error measurements were obtained in all experiments through five measurements at different positions of the ground workpieces carried out on a Taylor Hobson Talyrond 31C.The measurement of wheel wear was carried out using a cylindrical AISI 1020 steel workpiece that is used for printing the wheel profile. This measurement was possible due to the non-utilization of the total wheel width (20 mm of wheel width against 4 mm of workpiece width). Thus, the profile produced in the wheel during the experiment was printed on the soft steel cylinder. The diametrical wheel wear was measured using surface roughness meter software (Taylor Hobson TalyMap) for profile projection and measurement. Five measurements were taken for each piece and each experiment.

Acoustic emission (RMS) data generated by the process was gathered by a sensor placed on the machine tailstock, transmitted to an A/D board, and then read in a computer, using the National Instruments LabVIEW. The RMS was obtained using a time constant of 1 ms and the A/D board was set to sample the signal using a sampling rate of 4 KHz. The metallographic analyses were conducted using an optic microscope with 500× magnification on sanded and polished samples, with the last polishing conducted using an abrasive solution paste containing 3 μm particles. Nital was applied at a 2% in-volume solution rate.

Microhardness measurements were converted to the Rockwell C scale since it is widely used. Three measurement lines were made: at 20 μm from the surface; 50 μm from the surface, and at 5 mm from the surface. For measuring microhardness, a Buehler 1600-6300 testing machine was used. It allowed readings in Knoop (HK) and Rockwell C (HR$_C$) scales, and this conversion follows the criteria established by the ASTM E140 standard. Three force values were originally tested (100, 200 and 300 gf) to define the best one for the experiments. The force of 100 g provided the best relationship between the diagonals, obeying the ASTM E384 standards, which establish a minimum distance between the indentations. The machined parameters and the experimental setup data are summarized in Table 1.

7. Results and discussion

This section, the experimental results of the output variables for each grinding condition will be presented. The conventional cooling-lubrication system (flood coolant application) was used as a reference because it is the most widely used in industry. The results for the analyzed variables are illustrated in bar graphs containing their average measurements and respective confidence intervals calculated at 95%, according to Student's distribution.

Fig. 4 shows pictures of the wheel surface (100× magnification) at the end of the experiments for each cooling-lubrication method tested and in the most severe conditions of the experiment, where $v_f = 0.75$ mm/min and $a_e = 3.7$ μm.

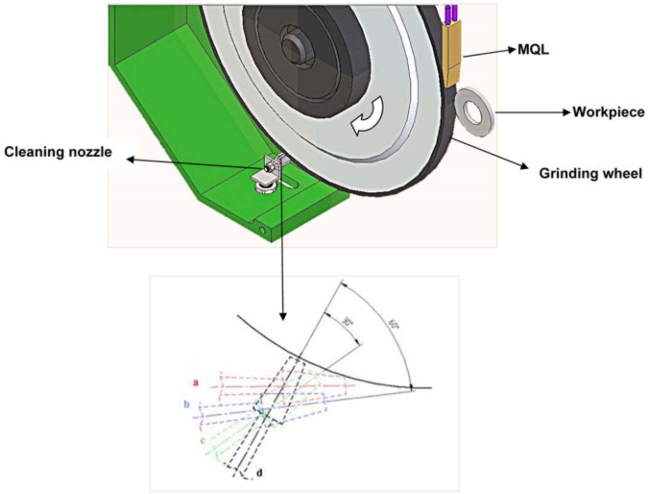

Fig. 3. Positioning of the cleaning nozzle: (a) tangential; (b) 60°; (c) 30°, (d) normal.

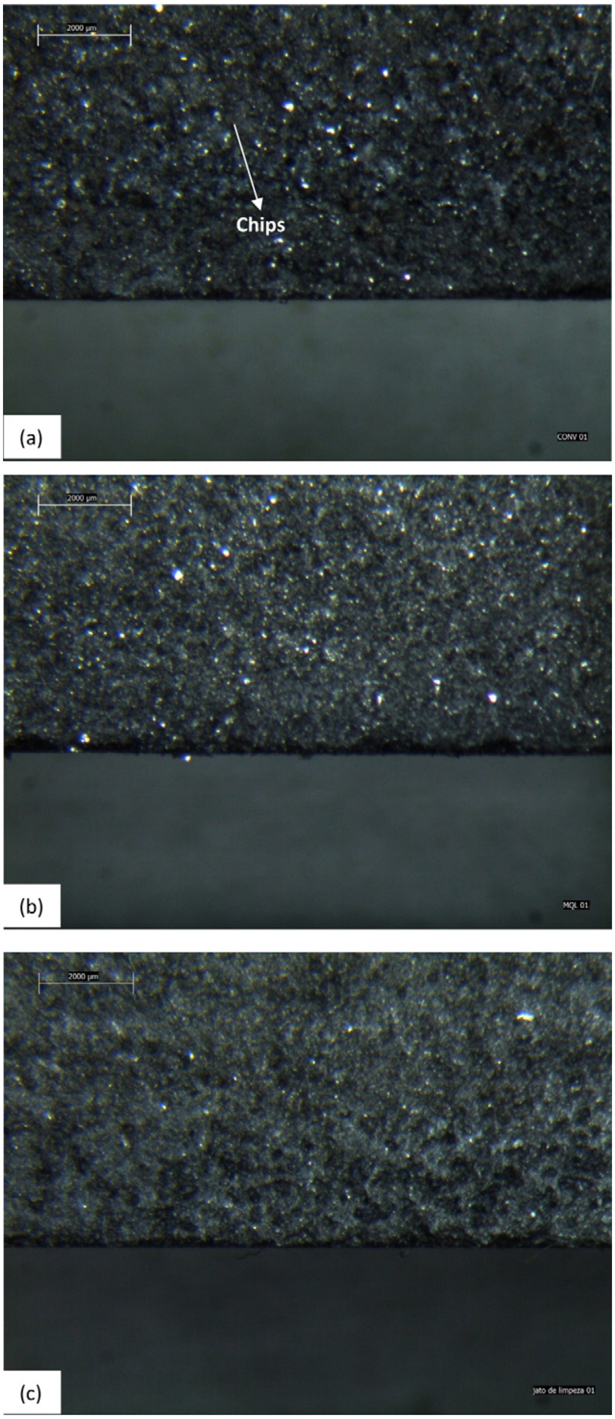

Fig. 4. Wheel surface after machining: (a) conventional flood coolant; (b) conventional MQL and (c) MQL+ cleaning (30°).

An analysis of Fig. 4 shows that when the wheel cleaning jet was added to the traditional MQL, fewer chips adhered to the wheel surface, which reduced the scratching of the workpiece surface and improved the wheel performance, proving the efficiency of this technique in removing the lodged chips. Average surface roughness (R_a) and roundness as results of the radial feed rate are shown in Figs. 5 and 6, respectively.

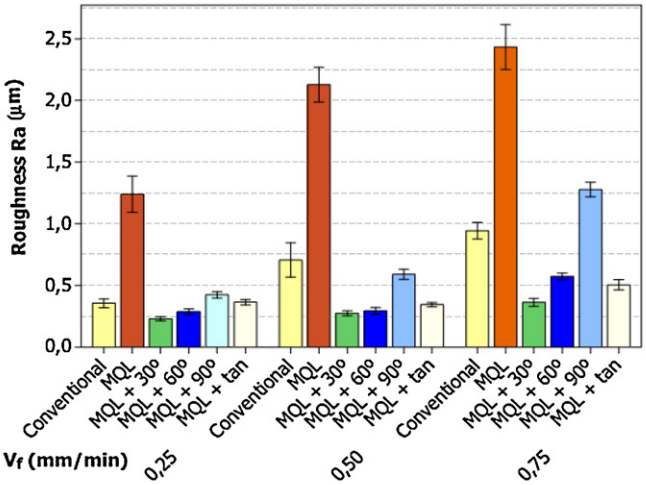

Fig. 5. Surface roughness (R_a) against radial feedrate and cooling-lubrication condition.

Webster and Tricard (2004) described porosity, a local effect in the wheel structure that enables fluid flow and the lodging of machined chips, as the measurement of spacing between abrasive grains. When the cleaning jet is used, the quantity of chips left in the pores is reduced, further improving the results because there is less probability for them to indirectly scratch or deform the ground surface. Some points need to be underscored in these figures:

- MQL without wheel cleaning provided much higher workpiece surface roughness and roundness errors than the conventional flood coolant application. Higher temperatures in the cutting zone from MQL increased chip ductility and made the chips adhere to the wheel, clogging the pores and hampering workpiece quality. This result agrees with Tawakoli et al. (2007), who demonstrated that the cooling-lubrication method with flood coolant is more efficient than conventional MQL in cleaning the wheel.
- When the compressed air jet was used to clean the wheel, workpiece surface roughness and roundness error values fell substantially, compared to MQL (without the cleaning jet), becoming smaller or equal to those obtained with the flood coolant application. This proves that the worse workpiece quality, when changing from conventional flood coolant application to MQL without wheel cleaning, was caused by machined chips clogging the wheel pores.
- The 30° angle of incidence of the compressed air jet was the condition that achieved the greatest efficiency in wheel cleaning, generating the lowest workpiece roughness and roundness

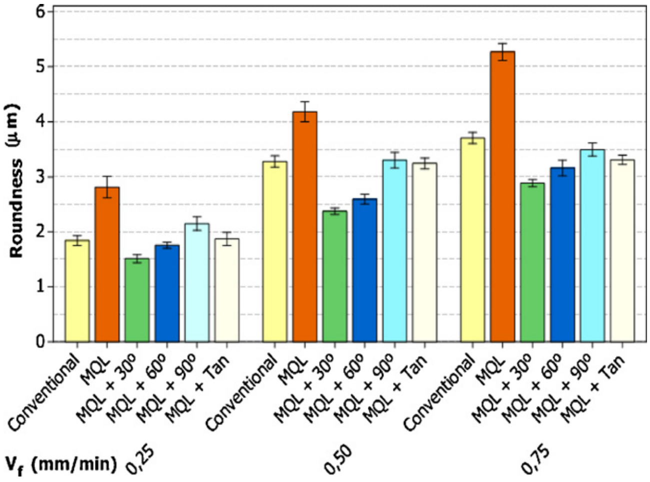

Fig. 6. Roundness error results for each plunge speed and cooling-lubrication condition.

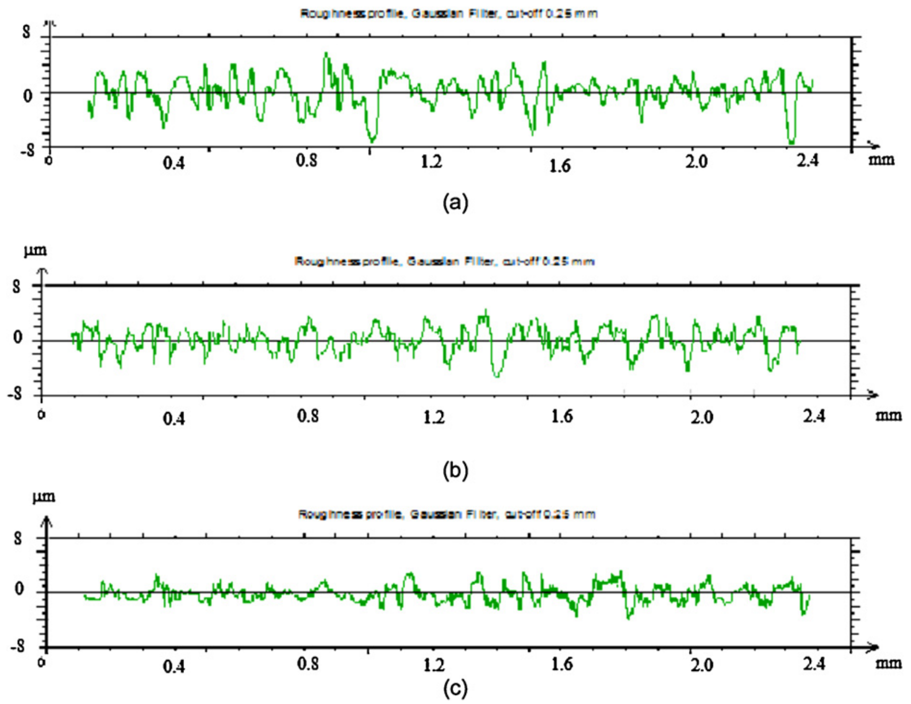

Fig. 7. Surface roughness profiles (R_a) for the most severe machining conditions (v_f = 0.75 mm/min and a_e = 3.7 µm): (a) conventional MQL; (b) conventional flood coolant application and (c) MQL+ cleaning jet (30°).

error values. The wheel cleaning in this condition was better than when the conventional flood coolant application was used, as shown in Fig. 4 and proven by Fig. 7. The surface roughness profile obtained in the workpieces ground using the conventional MQL technique (Fig. 7a) presented a higher range of peaks, which leads to higher average arithmetic roughness values. Since the wheel surface had a higher quantity of chips adhered to its pores (Fig. 4b), it caused more scratches to the workpiece and, consequently, made surface roughness worse. For the wheel cleaning condition, Fig. 4c shows that the amount of chips is lower in relation to the conventional MQL and flood coolant methods and, consequently, roughness peaks (Fig. 7c) were smaller, which led to the lowest surface roughness values among the three conditions, since less scratching between adhered chips and workpiece occurred.

According to Shaw (1996), increasing the radial feed rate deteriorates the surface finish because the equivalent chip thickness and, simultaneously, specific material removal rate increase. However, it can be seen in Fig. 5 that the surface roughness obtained using v_f = 0.75 mm/min and MQL+ air cleaning was similar to that obtained with v_f = 0.25 mm/min and flood coolant application. This result proves that the clogging phenomenon has such an importance to surface finish that, when minimized, it can compensate a large increase in the radial feed rate (three times the increase in this example).

In the most efficient conditions of wheel cleaning, surface roughness values were lower than 0.8 R_a (µm), which is usually a limit value for grinding operations. However, for the most efficient cleaning condition (MQL+ 30° cleaning jet) surface roughness values were lower than 0.3 µm. Moreover, during this condition, the maximum value for roundness errors was 3 µm, which is a very good result for grinding operations.

In Fig. 8, for the three radial feed rates, MQL with the cleaning jet (at 30°) was the condition that presented the lowest volumetric loss of wheel material. It is interesting to observe that the compressed air jet did not remove wheel particles. On the contrary, it preserved the wheel against more accentuated wear. The presence of lodged chips in the wheel pores was the reason for the wheel wear, since the conditions of greater amount of chips on the wheel surface (Fig. 4) were also those which provided higher volumetric loss of wheel material (Fig. 8), higher surface roughness (Fig. 5) and higher roundness error values (Fig. 6) (MQL without cleaning and MQL with an air jet normal to the wheel). Due to the increase in cutting forces caused by sideflow plowing and the friction between the lodged chips and the workpiece, cutting forces exceeded the cohesive force of the abrasive grains in wheel, thus accelerating wear.

Fig. 8 also shows that, with an increase in the material removal rate (and the consequent increase in equivalent chip thickness), the volumetric wheel wear was also high, which agrees with the findings from Choi et al. (2008).

Another measured output variable was the acoustic emission generated by the process. Wang et al. (2001) stated that this variable is related to the grinding process condition and to the surface

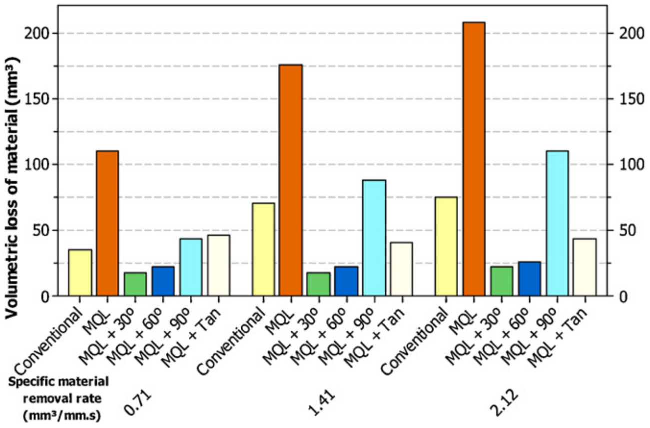

Fig. 8. Volumetric loss of wheel material results for each experiment.

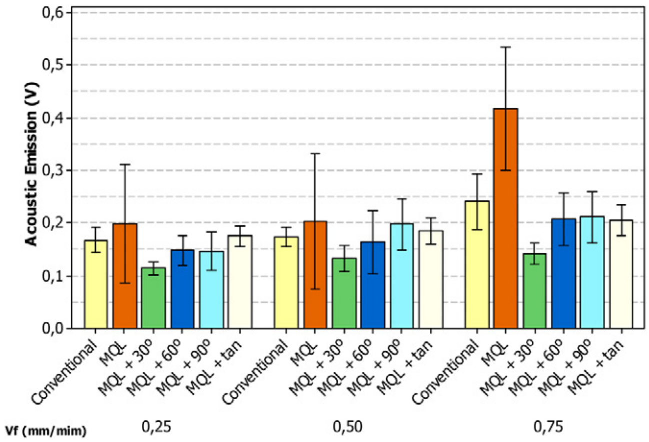

Fig. 9. RMS acoustic emission (V) results for each plunge speed and cooling-lubrication condition.

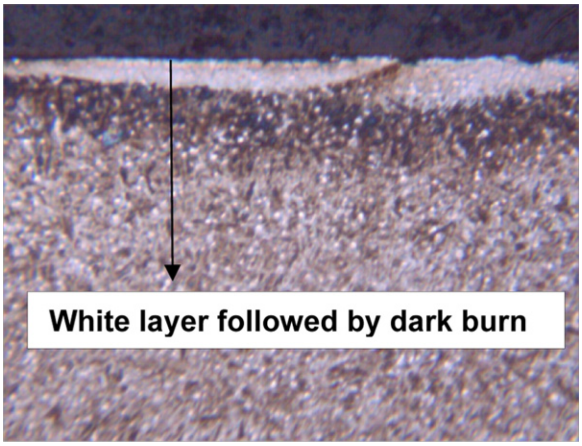

Fig. 10. Grinding burns (AISI 52100 steel presenting burns after grinding with a conventional abrasive – 1000×).

conditions of the wheel and workpiece. All the physical phenomena occurring in the process (friction, plastic and elastic deformation, and chip removal) generate acoustic emission. Fig. 9 shows the acoustic emission results (RMS) for all the experiments. This figure illustrates that the acoustic emission results follow the results obtained for roundness and wheel wear, i.e., the highest values of AE were obtained in the experiments using MQL (without wheel cleaning), the lowest AE values occurring for MQL with cleaning a jet at 30°. The experiments with conventional cooling-lubrication and MQL with a cleaning jet at other incidence angles generated intermediary values. In other words, the condition with the lowest wheel clogging generated the lowest AE values, and the condition with the highest wheel clogging generated the highest AE values. The reason was the scratching of the adhered chips against the workpiece, which generated acoustic emission signals. Therefore, the scratching of the chips adhered to the wheel against the workpiece was the cause for the increase of AE, workpiece surface roughness and roundness errors, and diametrical wheel wear. Fig. 9 also shows that when wheel air cleaning was used, the AE values were either equal to or lower than the values obtained using the flood coolant application. This result proves that the way the signals were sampled was suitable to avoid all the acoustic emission noise that could be caused by the air injection.

The workpiece surface integrity is extremely important as it determines the functional behavior of the component. It defines load ability, resistance to wear, fatigue life, and the reliable function of the part. Damage caused to the material surface may affect it significantly, causing alterations in wear resistance and the nucleation and propagation of cracks, which accelerate fatigue failure. The workpiece surface integrity is primarily affected by the high heat generated in the grinding process, which can thermally damage the workpieces.

When the workpiece surface being ground is exposed to high temperatures for a sufficient period of time, microstructural alterations may occur. In this aspect, the cooling-lubrication conditions combined with the physical and mechanical properties of the wheel (primarily its thermal conductivity) play a fundamental role in controlling temperatures and dissipating heat. According to Marinescu et al. (2004), grinding temperatures may not be high enough to cause visible burning; however, in severe conditions, the grinding temperatures may exceed the material tempering temperature, causing a reduction in the ground workpiece surface hardness (softening). When metallography is conducted, the region affected by this new tempering is darker. The affected region is treated as dark burn, as workpiece or oxidation burn. The depth of this softened layer is not greater than 100 μm.

Also, according to Marinescu et al. (2004), when temperatures are higher than the austenitizing temperature of the material during grinding, rapid cooling can promote new quenching on the ground surface. This requenched layer, commonly called a rehardening burn, has little thickness, and it is followed by a region with reduced hardness and a dark burn. Due to the light coloration seen in the microscope, the term used for this occurrence is white layer. This occurrence can induce microstructural transformations on the material surface (the formation of untempered martensite), causing the loss of mechanical characteristics like fatigue strength (Silva et al., 2007). The white layer followed by a dark burn can be seen in Fig. 10.

Malkin and Guo (2007) concluded that, the more efficient the cooling-lubrication, the lower the incidence of damage to material integrity.

In order to verify possible microstructural alterations, metallographic analyses were conducted (500× magnification) in cross sections of the workpieces. Figs. 11–13 show the metallographic images of workpieces obtained in the following cooling-lubrication conditions: conventional; conventional MQL, and MQL a with cleaning jet at 30°, for the three radial feed rates employed.

Comparing the surfaces of ground pieces (Figs. 11–13), it can be seen that the microstructure was unaltered in the regions close to the ground surface. No microstructural transformations, such as those seen in Fig. 10, occurred. In other words, grinding did not cause any formation of white or dark layers in any of the surfaces.

After analyzing the metallographic images, it can be seen that all the proposed cooling-lubrication conditions minimized the increase in temperatures to a point that they impeded microstructural alterations. That was possible due to the use of a CBN wheel and also due to the use of low wheel speed, which yields low grinding power and low heat flux to the workpiece. According to Marinescu et al. (2007), CBN wheels have high thermal conductivity (up to 1300° W/m K), which contributes to heat dissipation in the cutting zone and, consequently, to a reduction in thermal damage. Therefore, the high conductivity of the CBN wheel used in the experiments stimulated heat removal, eliminating the occurrence of microstructural alterations and ensuring surface integrity during the process.

Measurements of microhardness complement the metallography results, proving the exemption of softening through a quantitative variable. Figs. 14–16 show the microhardness results obtained for the surfaces of the ground pieces in the following cooling-lubrication conditions: flood coolant; conventional MQL, and MQL with a cleaning jet at 30°, respectively.

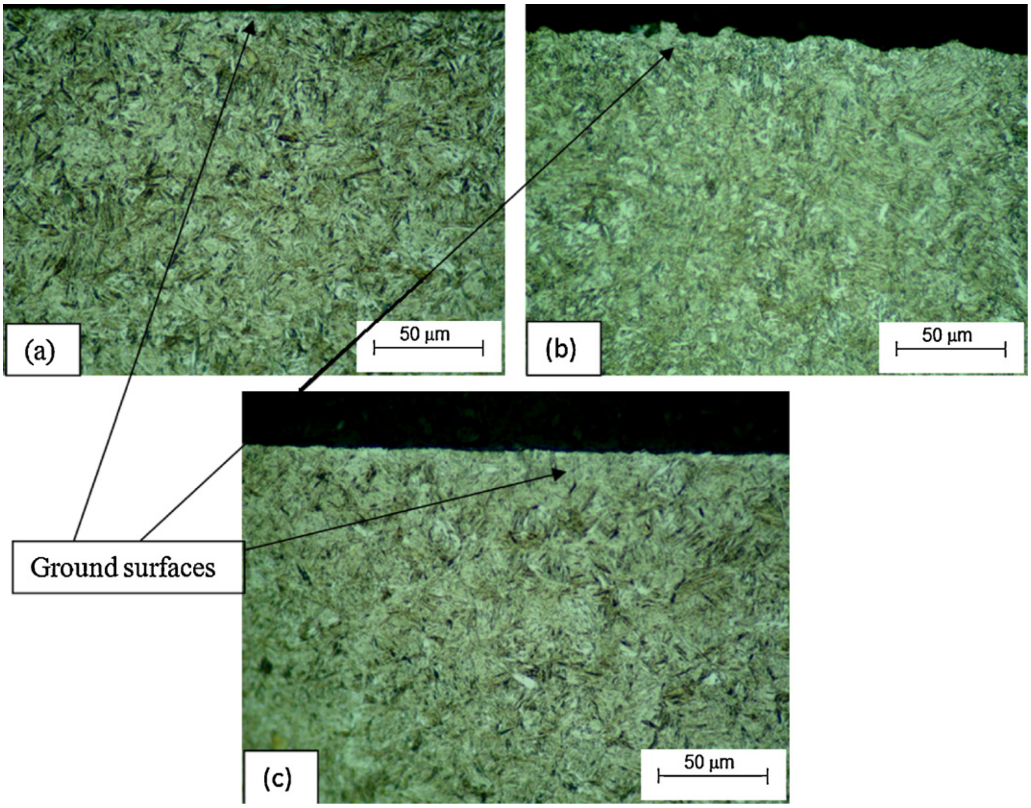

Fig. 11. Metallographic images of the ground pieces with $v_f = 0.25$ mm/min: (a) conventional; (b) conventional MQL and (c) MQL with cleaning jet at 30°.

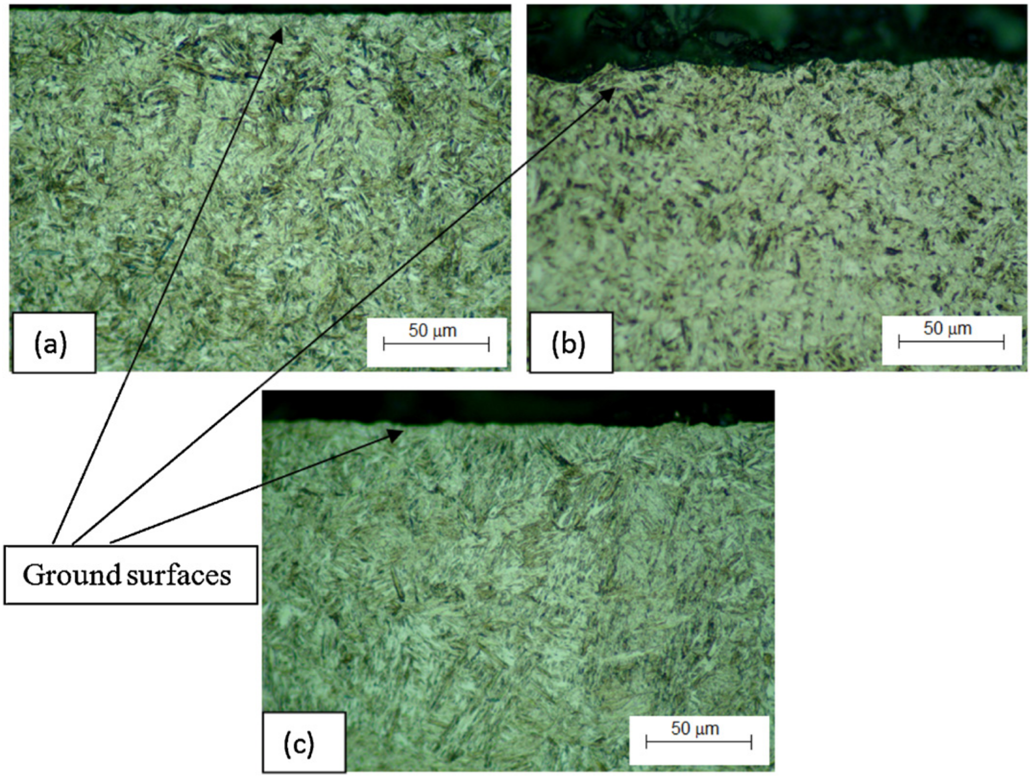

Fig. 12. Metallographic images of the ground pieces with $v_f = 0.50$ mm/min: (a) conventional; (b) conventional MQL and (c) MQL with cleaning jet at 30°.

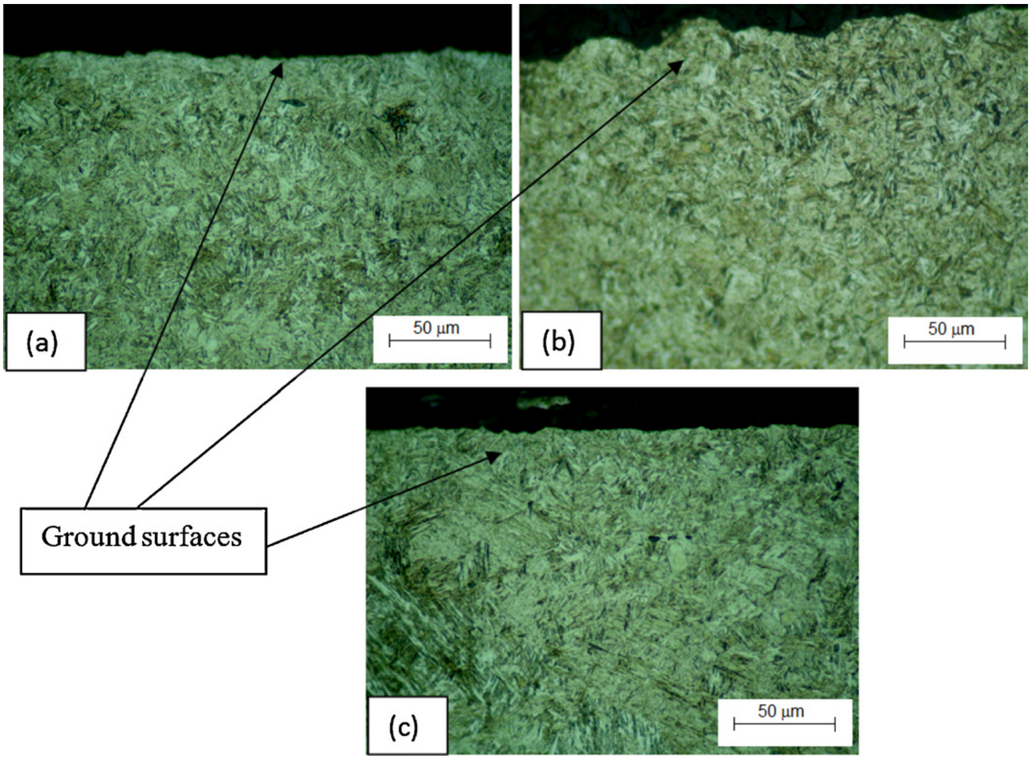

Fig. 13. Metallographic images of the ground pieces with $v_f = 0.75$ mm/min: (a) conventional; (b) conventional MQL and (c) MQL with cleaning jet at 30°.

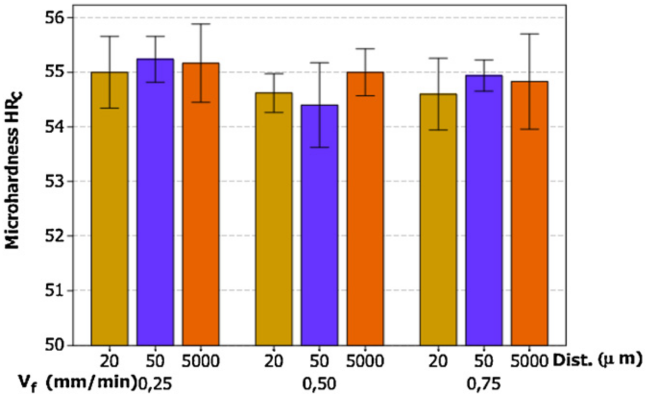

Fig. 14. Microhardness results for flood coolant application.

The analysis of these figures permits the conclusion that in the cooling-lubrication conditions tested, there was no loss of hardness due to grinding temperatures. The CBN wheel provided great heat dissipation in the cutting region, reducing process temperatures and eliminating thermal damage. It can be observed that, even when using conventional MQL, the high thermal conductivity of the CBN wheel provided enough heat dissipation to avoid surface softening.

Fig. 16 shows that when the workpieces were ground with the highest radial feed rate, the average values of microhardness were a little lower than the values obtained with the other radial feed rates. However, due to the high dispersion of the values, it cannot be confirmed that the value of the feed rate caused a decrease in the workpiece's microhardness.

It is important to state that the heat flowing through the chip when MQL was used was enough to make it more ductile and facilitate its adhesion on the wheel pores and surface, but the heat

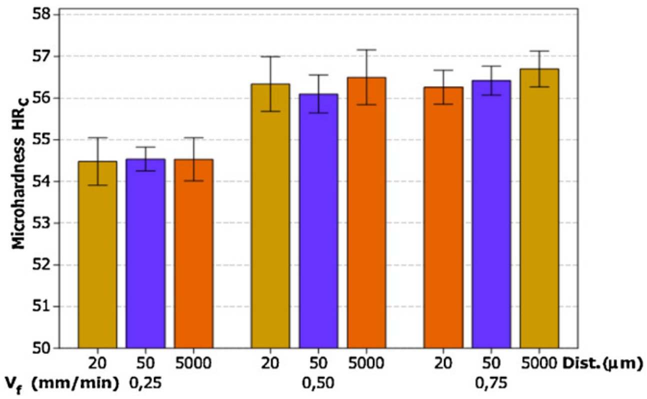

Fig. 15. Microhardness results for conventional MQL cooling-lubrication.

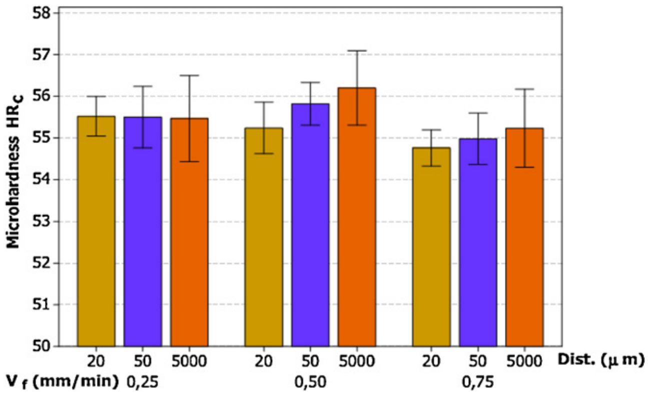

Fig. 16. Microhardness results for MQL cooling-lubrication with cleaning jet at 30°.

flowing through the workpiece was not enough to cause thermal damage to it.

8. Conclusions

Based on the results described in this paper, it can be concluded that, under conditions similar to those used here:

- The use of the MQL cooling-lubrication technique combined with a compressed air jet for cleaning the wheel surface, with the nozzle placed with an incidence angle of 30°, provided efficient wheel cleaning and, thus, better results in almost all analyzed process outputs, compared to conventional flood coolant and, especially, conventional MQL (without a cleaning jet).
- The clogging of the wheel pores from machined chips was responsible for the increase in the acoustic emission signals, workpiece surface roughness and roundness errors, and volumetric wheel wear.
- With the increase in the radial feed rate, the superior performance of the cooling-lubrication condition with MQL plus compressed air with an incidence angle of 30° was maintained, indicating that the use of MQL along with a compressed air jet (placed at an optimal angle of incidence) makes it possible to increase the specific material removal rate, reducing the grinding time without harming the workpiece quality.
- The drastic reduction of the fluid flow, associated with better results in the surface roughness and roundness errors of the workpiece and the decrease in the wheel wear caused by the use of MQL with a cleaning jet indicate that the improvement of the cooling-lubrication conditions in grinding operations may reduce environment and health hazards, contributing to a cleaner, faster, and more cost-effective manufacturing process.

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