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ORIGINAL ARTICLE

Evaluating the effect of the compressed air wheel cleaning in grinding the AISI 4340 steel with CBN and MQL with water

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Abstract

The application of minimum quantity of lubricant (MQL) in grinding process is a challenging task. Once the MQL is considered an environmentally friendly technique, its implementation in grinding process is interesting to achieve cleaner production. On the other hand, its use brings some problems to the process, such as intensification of grinding wheel clogging phenomenon and increase of cutting temperatures, which impairs on the attainment of a good surface quality, together with dimensional and geometrical accuracy. Looking for improving the MQL efficiency in grinding process, two eco-friendly techniques were found: the addition of water in the MQL and the wheel cleaning system with compressed air. The present research seeks to evaluate the improvement of MQL application in grinding using the combination of these techniques. Both techniques MQL + water and wheel cleaning system are innovative, since there are almost no articles in literature citing its use. The experiments were performed in an external cylindrical plunge grinding using a vitrified cubic boron nitrite (CBN) grinding wheel. The workpiece material was a quenched and tempered AISI 4340 steel. The cooling methods employed in the process were a conventional method (flood coolant), MQL + water (1:1, 1:3, 1:5 part of oil per parts of water), MQL + water + cleaning system (1:1, 1:3, 1:5 part of oil per parts of water), and MQL with and without cleaning system. Results were analyzed based on some workpiece parameters (roughness, roundness deviation, and microstructure) and on diametrical wheel wear and grinding power. The addition of water allied to cleaning system with compressed air provided the best results among those using the MQL technique, with results comparable to the conventional cooling method.

Keywords Cylindrical external plunge grinding · Minimum quantity of lubricant with water · Compressed air wheel cleaning

1 Introduction

The grinding process is the most used process to manufacture precision components [1]. This process removes precisely the material, resulting in an excellent dimension and geometry accuracy and a satisfactory surface finish [2]. The process generates a massive quantity of thermal energy, because of its intrinsic input parameters, e. g. high cutting speeds and small chip thickness. Once grinding chips have small thickness, a great deal of energy is transformed into heat, due to

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rubbing and plowing of the area in the vicinity of the chip formation, instead of being used to remove material [3]. This heat has to be managed in a correct way to avoid thermal damages to workpiece and economic inefficiency of process (reduced removal rate and premature grinding wheel wear). According to Webster [4], the heat must be immediately dissipated, to prevent workpiece from reaching high temperatures, which leads to phase transformations, tensile residual stresses, white layer formation, reduced fatigue life, and surface and subsurface cracking. Correct application of cutting fluid is one of the most effective solutions to increase process efficiency. With a proper use of cutting fluid, the heat is dissipated and friction is minimized, what allows the increase of the cutting speed and feed rate [5]. Despite the technological advantages provided by the cutting fluid abundant flow, this method presents serious problems such as high cost to the industry, potential to contaminate the environment, and to cause diseases in the workers. Therefore, the minimum quantity of lubricant technique (a minimum amount of fluid pulverized in a jet of compressed air) arose as an alternative method to lubricate the contact between workpiece and wheel and also to cool the workpiece [5].

Shokrani et al. [6] applied the minimum quantity of lubricant in some machining processes and proved that it enables a profound reduction of costs and it avoids the environmental problems caused by the cutting fluid. The small quantity of lubricant is sufficient to form a lubricant film between the tool and workpiece, what results in a lower friction coefficient and, consequently, in the reduction of the generated heat. Due to the fact that the low amount of cutting fluid used in the process is not reused, there is no necessity of maintenance, circulation, and disposal of fluid together with the associated costs [6].

When MQL is used, the cooling effect is provided by the compressed air. Despite the high forced convection action of the air jet, it is insufficient to remove all the heat generated in the grinding process. The addition of water in the MQL technique emerged to raise the cooling ability of the method. The added water evaporates during the process, draining the overage heat [7]. Also, water has specific heat two times higher than pure oil, thereby, water speeds up the absorption rate [8]. The added water plays three important rolls in the process: carry the lubricant, spread the lubricant, and remove the heat [7]. The oil dilution with water reduces the quantity of lubricant, spread the lubricant homogeneously and efficiently in the cutting zone, by their inertia, and dissipate the heat when the water evaporates.

Despite reducing the MQL lubricity, the addition of water improves grinding results. Investigating water influence in MQL during grinding, Belentani et al. [8] concluded that MQL with addition of water provides better surface roughness, smaller roundness deviation, and lower diametric wheel wear than MQL with pure oil. Mao et al. [9] demonstrated, analyzing cutting forces and temperature, that addition of water in MQL increases cooling effect and decreases the lubricity of the technique.

The phenomenon of wheel clogging, or wheel loading, occurs when the chips generated during the grinding process is not completely removed from the process. The chips remain in the grinding wheel pores and return to the contact zone, what obstructs the cutting fluid penetration and reduces the chip clearance [2].

According to Oliveira et al. [5] the elevated temperature of the grinding process makes the workpiece material more ductile, what facilitates the adherence of generated chips to the abrasive tool. As the cutting surface porosity is fully loaded with the chips, the cutting fluid does not penetrate in the cutting zone. Consequently, the cutting forces and the specific energy and the heat flux to the workpiece increase.

The phenomenon is aggravated when the MQL technique is used. The technique is not able to completely wash the chips from the cutting zone. The chips mingled with the lubricant used in the MQL compound a paste which adheres to the grinding wheel. As a result, the grinding wheel cutting ability is affected, increasing the cutting power, surface roughness, roundness errors, and wheel wear. In addition, the workpiece surface is scratched by the chips (the chips present a higher hardness due to the work hardening) [5].

According to Sinot et al. [1], the solutions to remove the chips adhered in the abrasive tool are to remove the loaded layer to restore the cutting surface by redressing the wheel or to clear the wheel pores with coolant. The frequent redressing consumes the grinding wheel and increases the costs. The cleaning with coolant requires a complex system, containing large pumps, tank and filters and, as the fluid has to be applied with high pressure to remove the chips, the method increases the spindle power in 30 to 50%.

An alternative to solve the problem of the wheel clogging is the grinding wheel cleaning with compressed air. The air injected with high pressure impacts the wheel cutting surface and expels the impurities lodged in the porosity, improving the workpiece quality and reducing the grinding wheel wear [5]. Oliveira et al. [5] investigated the efficiency of the wheel cleaning system with compressed air having as an input parameter of their experiments the angle between the air jet and a line tangent to the wheel diameter. They concluded that the wheel cleaning system with compressed air improved MQL results and, also the best efficiency was achieved with 30° incidence angle of compressed air jet.

Once the efficiency of addition of water technique and wheel cleaning system with compressed air have been proved, the combination of these sustainable technique has potential to provide even better results. Taking this possibility into account, this study aimed to evaluate the improvement provided by this combination, as an attempt to obtain satisfactory results (surface roughness, roundness deviation, grinding wheel wear, grinding power, and microstructural modifications) applying MQL in grinding, thereby contributing to the reduction of cutting fluid use.

2 Material and method

In this section, the materials used in the research and the methodology applied in the trials are presented.

2.1 Workpiece

The samples used in the tests as workpieces were previously machined in a ring shape with an external diameter of 54 mm, internal diameter of 30 mm, and thickness of 4 mm. The ground material was AISI 4340 steel quenched and tempered resulting in hardness of 54 ± 2 HRc. The material is utilized by manufacturers to produce shafts, rods, and crankshafts, components that have to pass by the grinding process.

2.2 Grinding wheel

The cubic boron nitrite (CBN) grinding wheel used in the experimental tests had the following specifications: external diameter of 350 mm, internal diameter of 127 mm, width of 15 mm, abrasive layer thickness of 5 mm, vitrified bonded 14A1 type. The grinding wheel was made by Nikkon Ferramentas de Corte company with the specification SBN 151 Q12 VR2.

2.3 MQL system

The MQL system was composed of a compressor, pressure regulator, dosing valve of cutting fluid, and nozzle projected to use in the grinding process. The equipment allows the regulation of air and lubricant flow individually. The air and lubricant were conducted separately, and in the nozzle, the atomization of the cutting fluid occurred. The fluid utilized in the MQL technique was the synthetic oil ME-2, of the Quimatic company, diluted in water in the following proportions (oil:water): 1:1, 1:3, and 1:5 besides the pure oil. The flow rate of the cutting fluid used in the experiment were 100 ml/h, and the pressure of compressed air was $6{,}5 \times 10^5$ Pa. The equipment used was the ITW *accu-lube* 79053D, made by the ITW *Chemical Products* Ltda.

2.4 Grinding wheel cleaning system

The wheel cleaning system had as duty fluid the air and was basically composed of a compressor, a pressure regulator, and a cleaning nozzle. The grinding wheel cleaning system and the MQL system were independent, avoiding the overcharge of the compressor and variations in the pressure.

The cleaning nozzle was designed to create a uniform jet in all grinding wheel width. The nozzle used in the cleaning system is presented in Fig. 1. The nozzle was placed at a distance of 1 mm from the cutting surface with an incidence angle of 30° from the normal that according to Oliveira's work et al. [4] provided the best efficiency. The air pressure in cleaning system was $7{,}0 \times 10^5$ Pa.

A cylindrical CNC grinding machine, RUAP 515H model of SULMECÂNICA company, was used in the trials.

2.5 Experimental procedure

The input parameters were kept constant, in exception of the cooling method. The cutting speed was 30 m/s, the radial feed rate was 0.50 mm/min, and the workpiece speed was 0.58 m/s (up-grinding). The spark out time was 1.78 s in each grinding cycle and 3.56 s at the end of the experiment. For each sample, 42 cycles occurred, and in each cycle, two feeds of 100 μm and two spark outs occurred. In other words, the wheel fed 100 μm into the workpiece (plunge grinding), stopped its feed during a sparkout time (1,78 s), fed again 100 μm into the workpiece, and stopped again the same sparkout period, before its retraction. As the workpieces had 4-mm width and the grinding wheel has 15-mm width, it was possible to machine two workpieces before the dressing process.

After the grinding of two samples, the wheel profile was printed in a cylindrical AISI 1020 steel workpiece. This workpiece was wider than the grinding wheel allowing the complete printing of the profile. For this process, the conventional cooling and a radial feed rate of 0.25 mm/min were used.

After the printing of the wheel profile, the grinding wheel was dressed using a conglomerate type dresser that consists in diamond particles placed in a metallic body. The dressing

Fig. 1 Cleaning nozzle and the fixing support

depth was 0.002 mm in each pass, and successive passes were performed in order to remove a total 0.120 mm in the grinding wheel diameter.

The workpiece surface roughness was measured using the Surtronic 3+, made by Taylor Hobson company. The measurement was done perpendicularly to grinding marks, using a cutoff of 0.25 mm and a total path of 1.25 mm. The roughness parameter used was the arithmetic average of roughness profile (Ra). For each condition, three workpieces were done. Three measurements were done on each workpiece, what resulted in nine measurements for each condition.

The workpiece roundness was determined using a Talyrond 31C equipment. Three initial contacts were done on the workpiece surface, what results in nine measurements for each condition.

To determine the grinding wheel wear, a Surtronic 3+ equipment was used together with a Taylor Hobson TalyMap software. This equipment provided the wheel profile printed on the workpiece, allowing the measurement of the difference between the worn and not worn wheel. The printed profile and the equipment used are presented in Fig. 2.

The micrograph analyses were done using the optical microscope Olympus BX51M, amplifying the images 1000 times. The samples were prepared previously (cut in a small sample, embedded in a resin, sanded, and polished to create an appropriate reflective surface to the microscope. Moreover, it was chemically attacked with nital 1%).

The grinding power was measured by a data acquisition board and the LabVIEW 7.1 software of National Instruments.

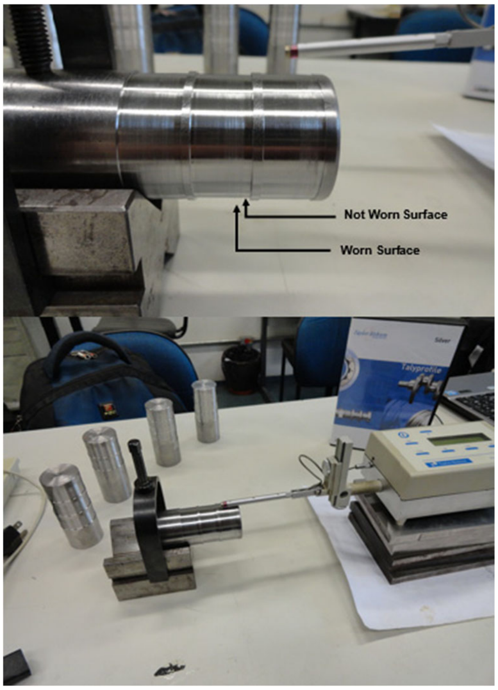

Fig. 2 Printed profile and equipment used

3 Results and discussion

In this section, the experimental results for each grinding conditions are going to be presented and discussed.

3.1 Surface roughness

Figure 3 presents the surface roughness of workpieces machined under different cooling conditions. It is found from Fig. 3 that surface roughness improved when water was added to MQL, indicating that, somehow, water has influenced the grinding process.

MQL with pure oil provided the highest surface roughness as shown in Fig. 3. Having the highest viscosity among tested conditions, pure oil intensified clogging phenomenon, since fluids with high viscosity tend to retain solid particles in suspension, compounding the grout (mixture of oil and chips) that lodges in the wheel porosity. This grout affects the surface quality, because the chips inside it scratch the workpiece surface, worsening surface quality [5]. Also, according to Walker [10], fluids with high viscosity may present problems in spraying correctly the fluid in the MQL. Therefore, even having excellent lubrication, pure oil does not lubricate the process, due to its inefficient penetration in the cutting zone. This deficient lubrication affects the surface roughness too, since this fact leads to abrasive grains plowing and rubbing instead of cutting and sliding [3].

The overall viscosity of the fluid declines with the addition of water in MQL (water is less viscous than oil), and, consequently, the spraying of the liquid inside the air is more efficient, leading to an also more efficient chip removal from the cutting zone. The improvement provided by water addition in MQL can be seen in Fig. 3.

Clearly, oil dilution with water implies in lower cutting fluid lubricant effect; however, the decrement of fluid viscosity provided by water addition improves the penetration of the cutting fluid droplets in cutting zone, resulting in better lubricant effect of the process [7]. In other words, diluting oil with

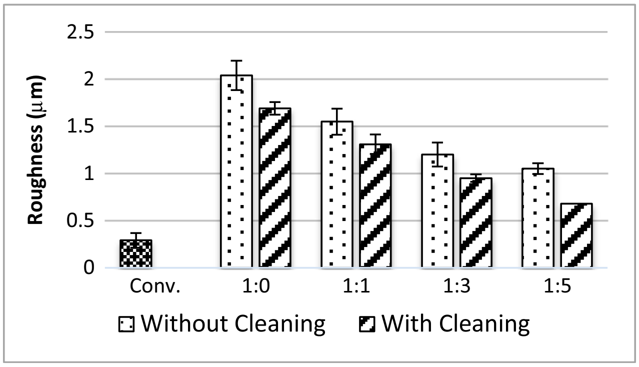

Fig. 3 Roughness profile (Ra) average for each tested condition

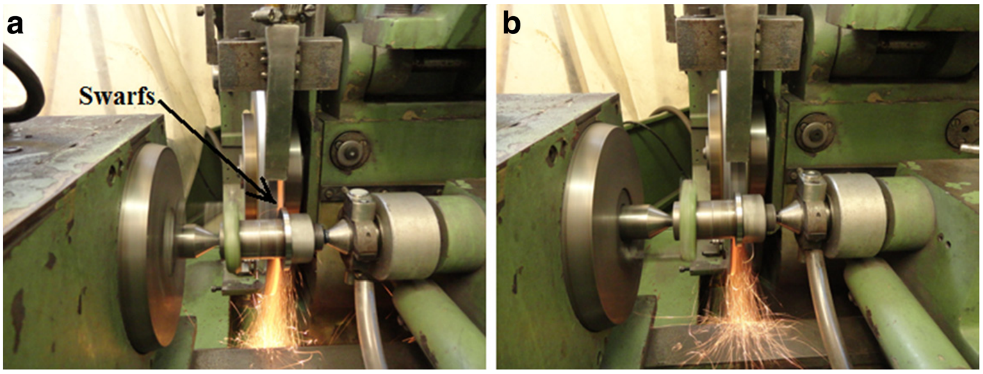

Fig. 4 Grinding operation: **a** without cleaning and **b** with cleaning

water, the cutting fluid lubricant effect decreases; but, on the other hand, the MQL lubricant effect increases.

Therefore, surface roughness decreases with MQL water content due to the better lubrication and cooling effects provided by this system, compared with MQL without water. These effects keep the wheel grains sharp, which contributes to the surface roughness decrease.

Knowing that clogging phenomenon affects the surface roughness, it was expected an improvement in surface roughness when the wheel cleaning system was employed. Figure 3 shows that, as expected, in all conditions with cleaning system, the surface roughness was low. This fact demonstrates the efficiency of wheel cleaning system with compressed air in scaling down clogging phenomenon.

Once the conventional cooling method has sufficient chip removal capability, the occurrence of clogging phenomena is insignificant to affect the surface roughness. As a result, the conventional cooling method provided the lowest surface roughness among tested conditions.

The return of the chips to the cutting zone was visible during grinding under MQL without air cleaning, as it is shown in Fig. 4a. Undoubtedly, in this condition, the incandescent chips generated in the cutting process lodged in the grinding wheel porosity and returned to the cutting zone. As described by Oliveira et al. [5], in the MQL technique, the chips return to the contact zone, blocking the entrance of cutting fluid and impairing the chip removal. Utilizing the wheel cleaning system, this fact did not occur, as observed in Fig. 4b, since the high pressure jet of air expel the chips lodged in wheel porosity.

Figure 5 shows the grinding wheel after the grinding process under MQL without cleaning condition.

It can be seen in Fig. 5 that the used portion of the grinding wheel were covered with metallic chips, and the available porosity was gravely reduced. In this condition, the contact area between the tool and workpiece increased, what affected the cutting ability of the grinding wheel.

The portion of grinding wheel used to machine the workpiece was not notable when the wheel cleaning system was applied, as can be seen in Fig. 6.

The lowest surface roughness obtained when the MQL technique was used occurred in the condition of MQL 1:5 with wheel cleaning. This result indicates that, to use MQL in grinding operation, it is necessary to mix the oil with a large portion of water and to utilize a compressed air jet to clean the wheel.

3.2 Roundness deviation

Figure 7 presents the arithmetic averages of roundness deviation and their standard deviations for each cooling-lubrication condition tested. Since this parameter is strongly connected with the workpiece thermal expansions, the inappropriate heat management compromises the precision of the process, due to the excessive amount of heat extracted through the workpiece [11]. Considering this point, an improvement in the cooling

Fig. 5 The grinding wheel after the grinding process under MQL technique without wheel cleaning system

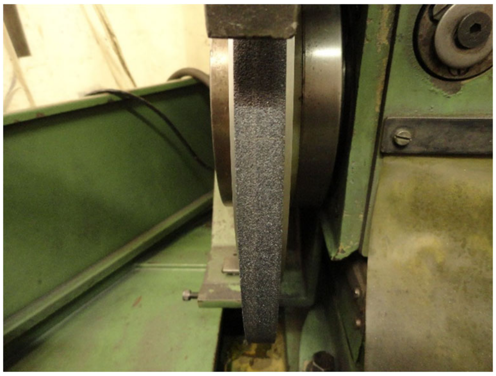

Fig. 6 The grinding wheel after grinding process under MQL technique with wheel cleaning system

capability of the cooling method keeps the process temperature acceptable, avoiding the thermal expansions and improving the roundness deviation. That is exactly what occurs with the addition of water in MQL technique, i.e., water evaporates, due to the high process temperatures, dissipating a great quantity of heat, and, consequently, improving the cooling capability of MQL. Analyzing Fig. 7, it can be seen that the MQL technique with high proportion of water (1:3 and 1:5) and air cleaning presented roundness deviation values very close to the conventional cooling system. Also, it can be seen in Fig. 7 the same pattern showed in Fig. 3, i.e., the output improvement with addition of water.

As already cited, the addition of water in MQL is responsible for boosting the cooling effect of technique and reducing the overall viscosity of the fluid, improving the cutting fluid penetrability, increasing the process lubrication, and reducing the clogging phenomena. These facts contribute positively to roundness results.

As shown in Fig. 7, the worst roundness error was provided by MQL 1:0 without cleaning, it supports the fact that the pure oil does not provide a satisfactory cooling effect.

The chips shown in Fig. 4 were red-hot caused by the process high temperature. The incandescent chips became ductile and adhered to the grinding wheel, aggravating the clogging phenomenon, resulting in what is shown in Fig. 5 [5]. The cleaning jet of air removed the chips lodge in the grinding wheel, what minimized the generate heat and improved the cutting ability of the grinding wheel and, consequently, reduced the roundness errors. Figure 7 shows the improvement caused by the grinding wheel cleaning system. The analyses of Fig. 7 reveal more pronounced improvement when the cleaning system was used in the 1:0 dilution than in the 1:5. This fact is explained by the strong connection between the roundness deviation and the temperature. This result shows that the use of the air cleaning of the wheel is even more important when no water was used in the MQL since, in this condition, the wheel clogging is more severe due to the high temperature of the chips, what make them more ductile and prone to lodge into the wheel pores.

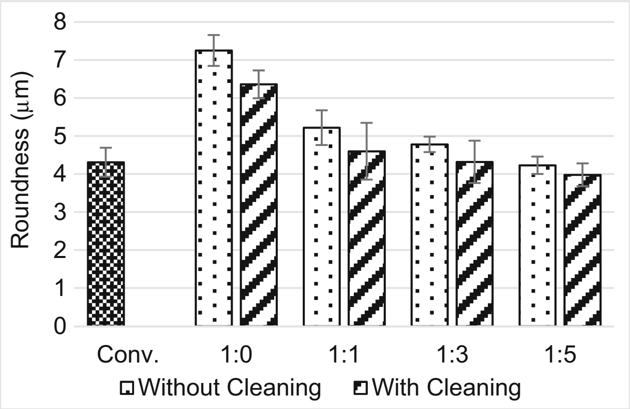

Fig. 7 Average of roundness for each tested condition

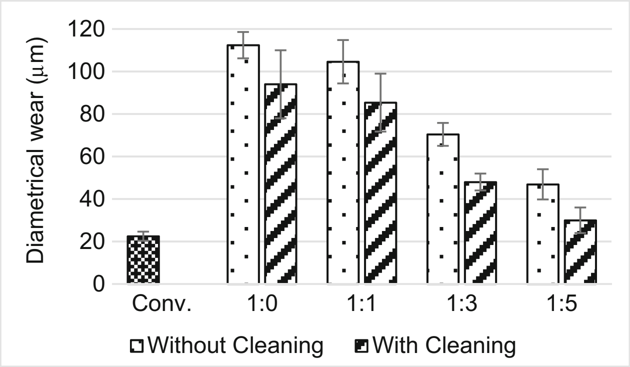

Fig. 8 Diametrical grinding wheel wear average for each tested condition

3.3 Diametrical grinding wheel wear

Figure 8 shows the arithmetic average of diametrical grinding wheel wear and the respective standard deviation for each tested lubricating cooling method.

As shown in Fig. 8, the conventional cooling method provided the lowest diametrical grinding wheel wear of all tested conditions. According to Silva et al. [11], the grinding wheel wear is caused by the friction between the grinding wheel and

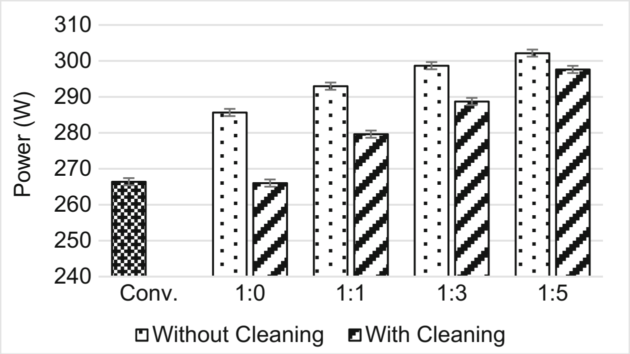

Fig. 9 Grinding power average for each tested condition

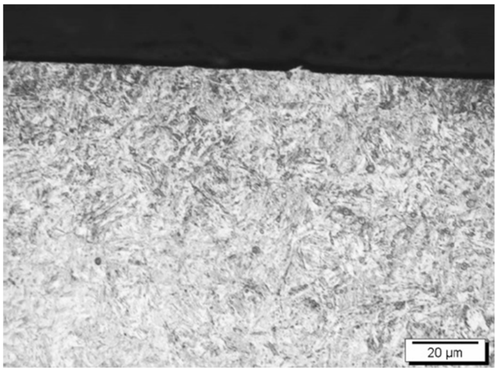

Fig. 10 Microstructure of the machined sample with conventional method

workpiece. According to Belentani et al. [8], the main factors that cause the grinding wheel wear are the thermal degradation and the high mechanical stresses in which the grinding wheel is submitted. The temperature control of the process is vital to keep the hardness of the abrasive grains and the bond strength. With the increase of lubricant and cooling effects, the cutting fluid reduces tool wear, since cutting efforts and strength loss are minimized.

Therefore, cooling and lubricating method applied in the grinding process has to exhibit an excellent combination of lubrication and cooling effects to reduce the friction and dissipate the excess heat. In addition, Rowe [12] concluded that the use of MQL results in an accentuated wheel wear. As shown in Fig. 8, MQL 1:0 without cleaning condition provided the most pronounced wheel wear, which evinces that, despite its high potential of lubrication, the pure oil does not penetrate efficiently in the cutting zone due to its high viscosity index, resulting in a deficient lubrication. Also, utilization of pure oil in MQL results in high temperatures, which triggers bond and abrasive softening.

As mentioned, the addition of water in MQL improves the cooling and lubrication effect of technique, which contributes to avoid tool wear. It can be seen in Fig. 8 that addition of water in the MQL caused a decrease in the wheel wear.

Also, once the clogging phenomenon increases the generated heat and elevates the friction between the tool and workpiece, the phenomenon aggravates the grinding wheel wear [5]. The chips lodged in the porosity extend the contact area between the tool and workpiece what makes the contact more intense, elevating the process temperature and increasing the mechanical solicitation of the wheel material. Using the grinding wheel cleaning with compressed air most of the adhered chips were expulsed, improving the grinding wheel wear. Therefore, it can be seen in the figure that MQL with a large proportion of water in the mixture (1:5) helped by the wheel air cleaning, even not reaching the performance of the conventional cooling system, presented the lowest wheel wear among all the MQL conditions tested.

3.4 Grinding power

The arithmetic average of grinding power and the standard deviation for each tested condition is presented in Fig. 9.

The two lowest grinding powers, presented in Fig. 9, are provided by the MQL 1:0 with wheel cleaning, and the conventional method.

Unlike the previous output parameters, the grinding power increased as the proportion of water increased.

An efficient cooling effect of the cooling and lubricating method keeps the temperature low. Consequently, the workpiece material did not suffer softening by the heat. As the material hardness did not reduce, the grinding wheel is subject to higher stress and the grinding power increased [8]. In short, as the method presents a better cooling effect, the grinding power increased. Therefore, analyzing Fig. 9, the addition of water increases the cooling effect of the MQL technique.

According to Oliveira et al. [5], the lodge chips affect the process efficiency. The phenomenon causes elastic and plastic deformation of the workpiece and a greater friction between the tool and workpiece, increasing the power consumed by the process. As observed in Fig. 9, when the grinding wheel cleaning system was used, the grinding power fell off, demonstrating the efficiency of the tested cleaning system.

Sinot et al. [1] stated that when the wheel cleaning system with cutting fluid was used, the grinding power increased by 30–50% due to the fact that the shock of the air flow with the

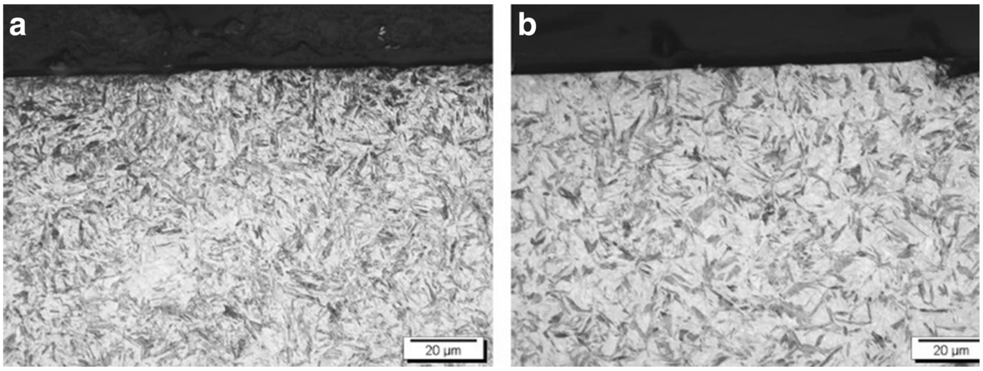

Fig. 11 Microstructure of the machined samples with MQL 1:0 technique: **a** without cleaning and **b** with cleaning

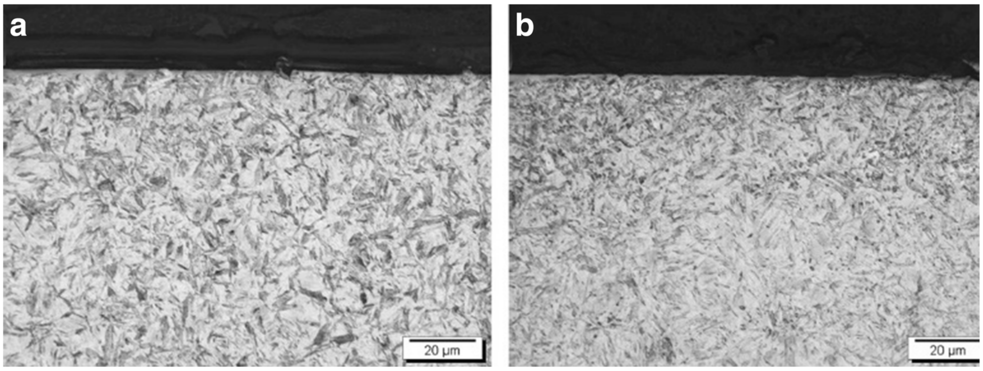

Fig. 12 Microstructure of the machined samples with MQL 1:1 technique: **a** without cleaning and **b** with cleaning

wheel works as a hydraulic break to the wheel. In our work, the use of the wheel cleaning system caused a loss in grinding power, what indicates that the hydraulic break effect was not relevant.

The MQL 1:0 with wheel cleaning condition presented the lowest grinding power due to the fact that the MQL technique makes the fluid to penetrate in the air barrier and create a lubricant film on the grinding wheel cutting surface. The use of pure oil in this condition promoted an efficiency lubricating effect and a limited cooling effect, increasing the temperature and softening the workpiece material. The softening of the material made the chip more ductile stimulating the clogging phenomenon. However, the cleaning system was able to minimize this phenomenon and contributed to reduce the grinding power.

What remains to be explained is the fact that the one of the lowest grinding power occurred when the conventional method was used, despite the fact that it presented the highest cooling effect and, consequently, the softening of the workpiece material did not occur. The best hypothesis to explain this occurrence is the efficiency of the chip removal of this method, what reduced the clogging phenomena. Therefore, the low temperature of the workpiece tended to increase the grinding power and the lack of wheel clogging tended to decrease the grinding power. The results obtained prove that the clogging phenomena have more impact than the workpiece temperature in this parameter.

3.5 Micrographs

To analyze the microstructure integrity, the micrograph analyses with a magnification of 1000 times were done. According to Rowe [12], the material microstructure plays an important role in the mechanical properties of the material. Once the grinding process occurs after the heat treatment, which provides to the workpiece its final mechanical properties, the machining process must not modify the microstructure.

Oliveira et al. [5] explained that the microstructure alteration may occur when the material is exposed to high temperatures. Then, the micrograph is an indirect analysis of the method cooling ability.

After the heat treatment, the microstructure of the workpiece material (AISI 4340 steel quenched and tempered), was tempered martensitic.

Figure 10 presents the microstructure of the machined workpiece under the conventional method condition.

The microstructure presented in Fig. 10 is the same of the material before grinding, i.e., tempered martensitic. No microstructural changes were detected in this figure, what proves that the input parameters were not severe enough to cause any thermal damages when the workpieces were grounded under conventional cooling condition. Figures 11, 12, 13, and 14 present microstructures of the samples machined with MQL 1:0, 1:1, 1:3, and 1:5, respectively.

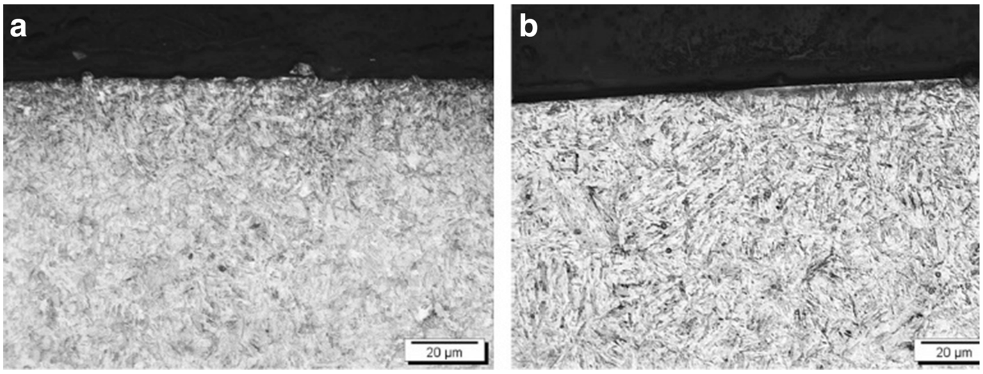

Fig. 13 Microstructure of the machined samples with MQL 1:3 technique: **a** without cleaning and **b** with cleaning

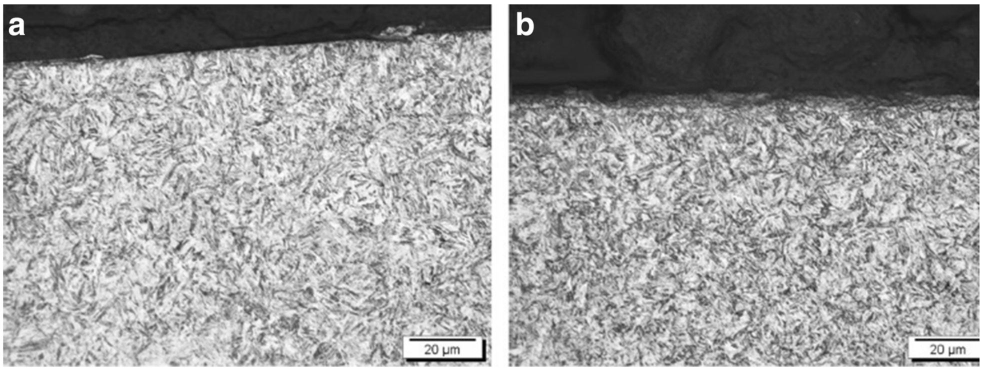

Fig. 14 Microstructure of the machined samples with MQL 1:0 technique: **a** without cleaning and **b** with cleaning.

Analyzing Figs. 11, 12, 13, and 14, it can be seen that all the microstructures presented were homogeneous, at both places: close to the grounded surface and below it (subsurface). No microstructural changes, formation of white and dark layers, and thermal damages occurred during the process.

Based in the micrograph analyses, it can be said that all the tested conditions presented a sufficient cooling ability to avoid thermal damages in the workpiece.

4 Conclusion

The experiments applying the combination of the MQL + water technique and the grinding wheel cleaning system with compressed air in grinding were performed and evaluated. The main conclusions obtained are as follows:

- The dilution of the lubricant in water in the MQL technique increased the cooling ability of the technique and facilitated the fluid atomization. The addition of water provided lower roughness and roundness errors to the workpieces. Also, the grinding wheel wear had decreased as the proportion of water increased.
- The addition of water in the MQL flow caused the increase of the grinding power. The water improved the cooling ability of the fluid and, consequently, the temperature did not provoke the material softening, what kept the stress high.
- The clogging phenomenon is real, and it has a negative impact in the grinding process. The grinding wheel cleaning system with compressed air demonstrated efficiency to remove the lodged chips of the grinding wheel cutting surface, improving substantially the output parameters.
- The wheel cleaning system using a compressed air did not cause the hydraulic brake effect cited in the literature and, consequently, the cutting power obtained with this method was always lower than when it was not used.
- The combination of MQL + water with compressed air wheel cleaning is a promising technology, and it has total potential to be applied in industry, promoting the reduction of costs, being environmental friendly, and avoiding diseases to the workers.

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Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interest.

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