THE MINIMUM QUANTITY OF LUBRICANT TECHNIQUE IN GRINDING OF STEEL USING A WHEEL CLEANING SYSTEM

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ABSTRACT
The application of minimum quantity of lubricant (MQL) for metal cutting 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, the widespread application is hindered mainly due to the high heat generation and the clogging of wheel pores caused by machined chips, harming the final product quality and increasing tool wear. This study sought to improve MQL use in grinding. Thus, besides the conventional MQL injected at the wheel/workpiece interface, a compressed air jet was also added, in order to clean the clogged wheel pores from the mixture of MQL oil and machined chips. Experiments were conducted using external cylindrical plunge grinding on AISI 4340 quenched and tempered steel, and a vitrified cubic boron nitrite (CBN) wheel. The lubri-refrigeration methods employed were the conventional with abundant flow, conventional MQL (both without any cleaning air jets) and MQL with the cleaning jet, directed at the surface at different angles of incidence. The main goal of these experiments was to verify the viability of replacing traditional abundance flow with MQL with wheel cleaning. The analyses were conducted by measuring the following output variables of the process: workpiece surface roughness, roundness, diametrical wear of the wheel. Results show the possibility of implementing the cleaning jet technique as a technological improvement of the minimum quantity of and 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 to obtain improved surface quality and accurate workpiece shape, as well as to reduce wear wheel and to prevent thermal damage, when compared to the other lubri-refrigeration methods tested (without cleaning jet).
KEY WORDS: external plunge grinding, MQL, minimum quantity of lubricant, wheel cleaning, CBN.

1.- INTRODUCTION
Abrasive processes are used in the production of higher quality components in terms of shape, integrity and surface finishing [1]. State that grinding is an abrasive machining process in which material is removed through interaction between the abrasive and the workpiece. In this typical finishing process, possible problems generated in previous processes can be corrected. Therefore, [2] conclude that, since grinding is usually the final operation in a given surface, errors could prove expensive.
Describe grinding as an energetically intense machining process, a great amount of energy is required per unit of removed material compared to other processes. As a result of the combination of countless high-speed cutting edges, a great 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 grinding wheel life [1]. Also underscore that during the material removal process, the heat will induce thermal distortions in both machine and workpiece, thus limiting the precision. However, if lubricants, such as cutting fluids, are used, the heat can be reduced by decreasing friction. Thus, the forces and the residual stresses in the workpiece will be minimized [3].

However, when abrasive tools are used, a reduction in the use of cutting fluids impairs one of functions, i.e. the cleaning of the wheel pores (filled up with machined chips), favoring the tendency for clogging, which consequently decreases cutting potential [4]. Weel clogging increases the forces involved, accelerates degradation of wheel surface and gives rise to high surface roughness on ground surfaces [6]. Since MQL uses low oil flow, efficient removal of the machined chips from the cutting zone is not achieved, because they tend to mix with the MQL fluid and create a grout which adheres to the surface of the cutting tool, thus clogging its pores.

Analyzing this context, this work demonstrates a technological improvement of the MQL technique, by adding a wheel cleaning system to the conventional MQL. The results obtained proved very satisfactory, even exceeding those achieved in conventional lubri-refrigeration. This fact enables to replace the abundant use of cutting fluids with this new technique, generating several benefits to industries through a reduction in excessive expenses with handling and disposal of cutting fluids, while reducing environmental and health impacts, thus contributing towards sustainable technological development.

2.- PROBLEMS WITH CUTTING FLUIDS

The state that cutting fluids are used in machining of materials, aiming for the reduction of friction, which is always present on the contact between workpiece and tool (lubrication), and also the minimization of generated heat in the cutting region through refrigeration [6].

Cutting fluids also hinder corrosion of the workpiece and machine tool, while helping to transport the chips away from the cutting zone, thus cleaning the wheel [7].

Once used, cutting fluids contain tiny particles of materials, such as small abrasive particles from the wheel, chips and other impurities. As a result, after some time, all the fluid needs to be changed and disposed due to contamination.

Despite the technological advantages cutting fluids promote, their negative effects have been questioned, since it can give rise to both environmental aggression and health-related problems [8]. Thus, Companies are being forced to program less toxic refrigeration strategies in machining processes.

Strategies for promoting a reduction in cutting fluid use is to optimize fluid flow, which occurs with the use of the minimum quantity of lubricant [9].

3.- THE MINIMUM QUANTITY OF LUBRICANT TECHNIQUE

The minimum quantity of lubricant (MQL) is defined as an aspersion of small droplets of oil in a compressed air jet, directed to the cutting region, avoiding the huge flows of conventional cutting fluid application techniques. Since the air jet carries the oil droplets directly to the cutting area, it provides efficient lubrication. Conventional

cutting fluids, due to the use of additives and the low jet pressure, are not able to enter the cutting zone directly, making MQL more efficient in this aspect [10].
One of the advantages of MQL is the fact that at the end of grinding, chips, workpiece and tool have less fluid residue, making cleaning easier and more economical. Furthermore, during grinding, since the workpiece is not fully covered with fluid, it can be easily observed through visual contact. On the minimum quantity of lubricant, a low oil flow is used, approximately $2.0.10^{-9}$ to $2.7.10^{-8}$ m^3/s (nearly one thousand times less that in conventional processes) at a pressure of $4.0.10^4$ to $6.0.10^4$ Pa [11]. A major challenge for the minimum quantity of lubricant technique is in refrigeration, with its problems in situations when high refrigeration rates are needed. Moreover, the lower fluid flow entails less removal of chips from the cutting zone, bringing about conditions for wheel clogging [12].

4.- PHENOMENON OF WHEEL CLOGGING

When energy at the wheel/workpiece interface generates a rise in temperature, there is greater tendency towards lodging of metal particles in the pores of the abrasive tool. That will lead to an even higher increase in local temperature, which may cause thermal damage, such as workpiece surface burn, while also impairing the workpiece finishing and increasing wheel wear.
The wheel clogging phenomenon as follows: when the chips generated in the grinding process are not fully removed from the cutting zone by the cutting fluid, they lodge in wheel pores, impairing the entrance of the cutting fluid in the cutting zone and thus further hampering the cleaning. These lodged chips affect the process efficiency and quality due to the increase of the contribution of elastic and plastic deformations in total grinding energy. Thus, the initial energy of the process will rise as the heat in the cutting zone [13].
Certain alloys are characterized as being hard to grind because they easily clog the wheel pores when metal particles are compressed and also adhered to the spaces between grains. With high chip removal rates, the phenomenon is further accentuated; also, some wheels are more or less passive to clogging. These same authors also describe two ways to avoid clogging: using a wheel with an open structure, which will have fewer grains (and thus less capacity to obtain good workpiece quality), increasing the probability of fracturing the bond; or dressing it frequently, which increases the costs involved in the process [14].

5.- PERSPECTIVES OF JETS OF COMPRESSED AIR FOR CLEANING

Who conducted experiments in groove grinding, the compressed air jet is an alternative for reducing clogging, because the air impacts on the wheel surface and removes a great part of the impurities that adhere to it (see Fig. 1). Thus, the lower the air pressure, the lower the cleaning effect will be. These same authors concluded that an increase in cutting depth is achieved by reducing tool wear, and furthermore, it is possible to obtain better geometric tolerances and shape surface quality, i.e., better surface roughness values and overall finishing, when cleaning jets were used [8].

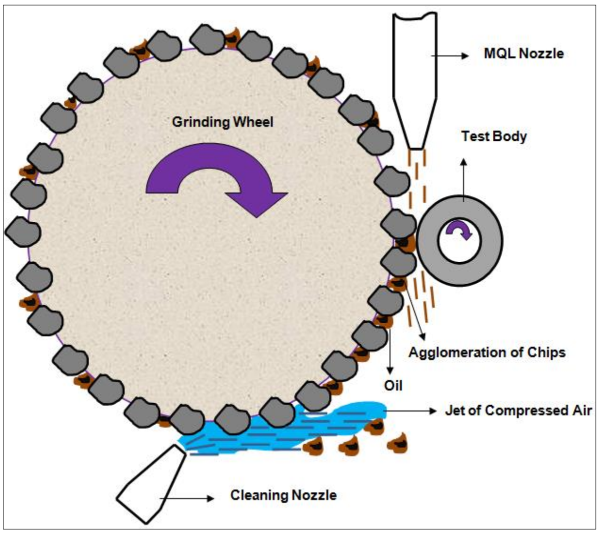

Fig. 1. Effect of the compressed air jet in wheel cleaning.

6.- EXPERIMENTAL PROCEDURE

The grinding experiments were conducted on a cylindrical CNC grinding machine equipped.
The ground material was AISI 4340 steel with hardness of 54 ± 2 HRc. 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 an outer diameter of 350 mm, an inner diameter of 127 mm, a width of 20 mm and an abrasive material thickness of 5 mm.
The MQL equipment is made of a compressor, pressure regulator, air flow gauge and mixing nozzle. This equipment uses a pulsating system for oil supply, which allows the regulation of the flows of compressed air and lubricant separately. The compressed air 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 lubri-refrigeration were used: conventional (abundant flow), conventional MQL, and MQL + cleaning system, using distinct jet angles of incidence on the wheel surface. Four angles of incidence were defined for the cleaning jet: 30^0, 60^0, normal and tangential to the wheel.
Besides the variation in lubri-refrigeration conditions, the wheel infeed velocity was also varied (three different values). The output parameters measured were workpiece quality (surface roughness and roundness), wheel wear, acoustic emission generated by the process.
Measurement of surface roughness was carried out using Ra, with a surface roughness meter (Taylor Hobson Surtronic3+). The results shown are averages of readings in different positions, for each of the 3 workpieces used, for each lubri-refrigeration condition. The number of surface roughness readings was such to guarantee 95% confidence that the sample average represented the average of the population.

Roundness errors measurements were obtained in all experiments, with 5 measurements at different positions of the ground workpieces, carried out on a Taylor Hobson Talyrond 31C.
Measurement of wheel wear was done using a cylindrical AISI 1020 steel workpiece used for printing the wheel profile. This measurement was possible due to non-utilization of total wheel width (15 mm against 4 mm for the workpiece). Thus, the profile produced in the wheel after the experiment, enabled to print wheel wear on this soft steel cylinder. The diametrical wheel wear was measured using a surface roughness meter software (Taylor Hobson TalyMap) for profile projection and measurement. Five measurements were made on each piece, and each experiment.
The machined parameters and the experimental setup data are:
Grinding mode: external cylindrical plunge grinding, grinding wheel SNB151Q12VR2 (vitrified cubic boron nitride wheel). Grinder speed (Vc) - Vc = 30 m /s, infeed velocity (Vf) - Vft = 0.25 mm/min; 0.50 mm/min and 0.75 mm/min, angular speed of the piece (ωw) ωw = 204 rpm. Cutting depths (ae) - ae = 1.2; 2.5; 3.7 μm.
Lubri-refrigeration conditions - conventional (abundant flow), conventional MQL and MQL with wheel cleaning, at four angles using compressed air jets with the following incidence angles: 30^0, 60^0, tangential and normal. Conventional cutting fluid - semi-synthetic vegetable oil based emulsion at 2.5% concentration, MQL cutting fluid - 100% vegetable, biodegradable, oil flow in MQL - $2.7.10^{-8}$ m3/s, air pressure in MQL $6.0.10^5$ Pa, air flow in cleaning system - $8.0.10^{-3}$ m^3/s, air pressure in cleaning system $7.0.10^5$ Pa, workpiece material - AISI 4340 steel, quenched and annealed (54 ± 2 HRc), dresser - multigranular fliese, dressing depth (ad), sparkout time (ts), dressing speed (vd) - ad = 0.02 mm, ts = 3s and 600 mm/min

7.- RESULTS AND DISCUSSION

This section will present the experimental results of the output variables for each grinding condition. The condition used as a reference for discussions was the conventional lubri-refrigeration system, because it is the most broadly used in industry. The results for those variables analyzed are shown in bar graphs, containing the average of measurements with their respective confidence intervals calculated at 95%, according to Student's distribution.
Average surface roughness (Ra) and roundness as results of infeed velocity are shown in Figures 2 and 3, respectively.
Before beginning the analysis of these figures, it is important to mention that described porosity as the measurement of spacing between abrasive grains, a local effect in the wheel structure, which enables fluid flow and the lodging of machined chips. 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 lubri-refrigeration method (abundant flow). Higher temperatures in the cutting zone, when using MQL, increased chip ductility and made them adhere to the wheel, clogging the pores and thus hampering workpiece quality;
- When the compressed air jet was used to clean the wheel, workpiece surface roughness and roundness error values fell substantially, when compared to the MQL (without the cleaning jet), becoming smaller or equal to those obtained with abundant

flow (conventional lubri-refrigeration). This proves that the worse workpiece quality, when changing from conventional lubri-refrigeration method for conventional MQL (without cleaning) was caused by the clogging of wheel pores by machined chips;

- The 30º angle of incidence of the compressed air jet was the condition that achieved the greatest efficiency in wheel cleaning, thus generating the lowest workpiece surface roughness and roundness error values.

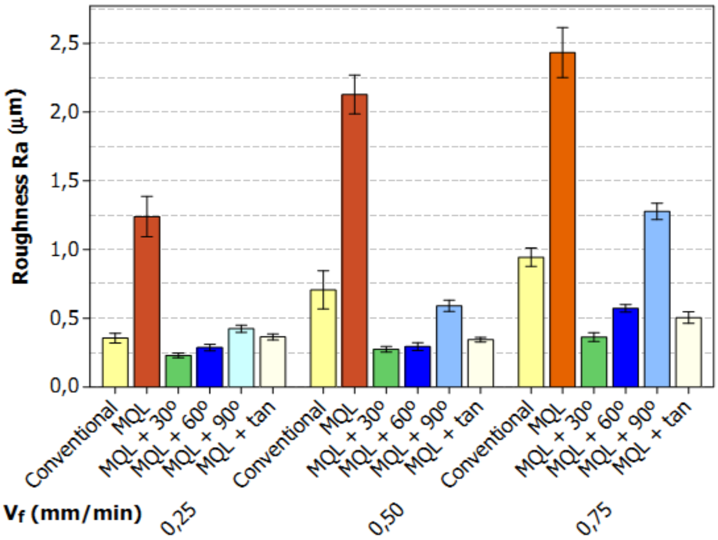

Fig. 2 – Average surface roughness (Ra) results for each plunge speed and lubri-refrigeration condition.

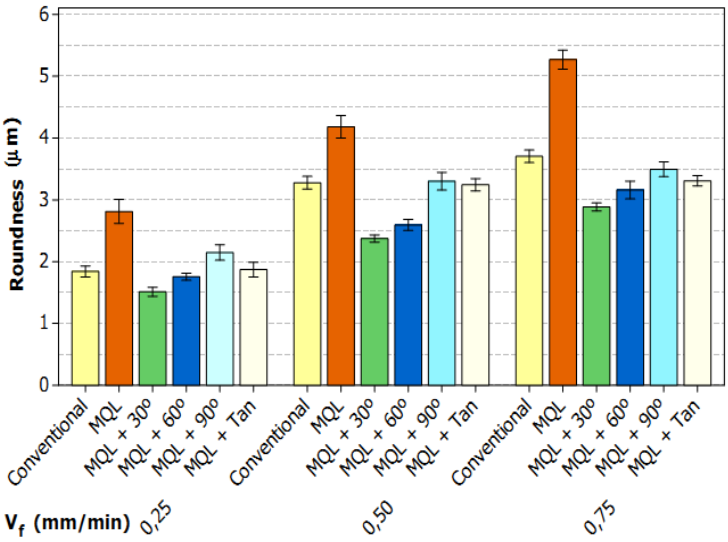

Fig. 3 – Roundness error results for each plunge speed and lubri-refrigeration condition.

In Figure 4, for the three infeed velocities, MQL with cleaning jet (at 30 degrees) was the condition that presented the lowest diametrical wheel wear values. 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 were also those which provided higher diametrical wheel wear (Fig. 4), higher surface roughness (Fig. 2) and higher roundness error values (Fig. 3) (MQL without cleaning and MQL with an air jet normal to the wheel). The increase in cutting forces caused by the friction of lodged chips and the workpiece makes exceed the cohesion force of abrasive grains in wheel, thus accelerating wear.

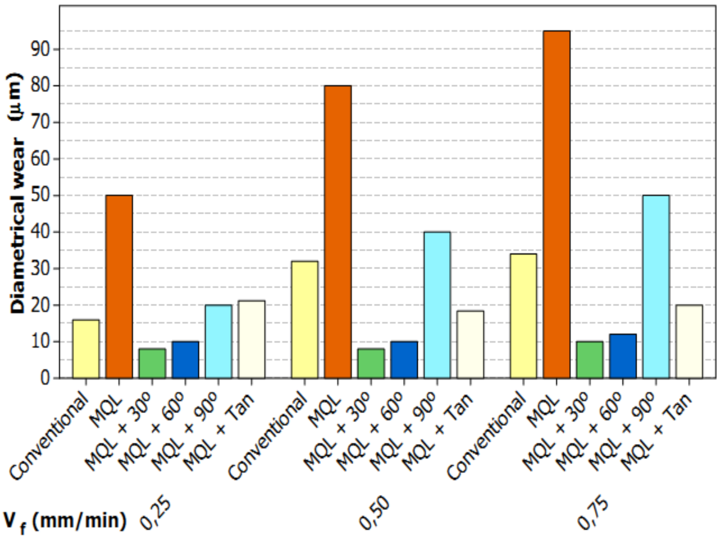

Fig. 4 – Diametrical wheel wear (µm) results for each plunge speed and lubri-refrigeration condition.

8.- CONCLUSIONS

After analyzing the results, it can be concluded that:

- The use of the MQL lubri-refrigeration technique associated 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 variables, when compared to conventional lubri-refrigeration and especially conventional MQL (without cleaning jet).
- The clogging of the wheel pores by machined chips was the responsible for increase of the acoustic emission signals, workpiece surface roughness and roundness errors, and diametrical wheel wear.

With the increase of the infeed speed, the superior performance of this condition was maintained, indicating that the use of MQL along with a compressed air jet (placed with an adequate incidence angle), makes possible the increase of the grinding conditions, reducing the grinding time, without harming the workpiece quality.

- The drastic reduction of the fluid flow, associated with the better results of surface roughness and roundness errors of the workpiece, and the decrease of the wheel wear caused by the use of MQL with cleaning jet indicate that the improvement of the lubri-refrigeration conditions in grinding operations may reduce the environment and health hazards, contributing to a cleaner, faster and more cost-effective manufacturing process.

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