

José Augusto Camargo Alves
jaugusto@feb.unesp.br

Ulysses de Barros Fernandes
ulyssesbfernandes@yahoo.com.br

Carlos Elias da Silva Júnior
cesilvaj@gmail.com

Eduardo Carlos Bianchi
Senior Member, ABCM
bianchi@feb.unesp.br

Paulo Roberto de Aguiar
aguiarpr@feb.unesp.br
São Paulo State University - UNESP
Bauru School of Engineering
Department of Mechanical Engineering
Caixa Postal 473
17033-360 Bauru, SP, Brazil

Eraldo Jannone da Silva
eraldojs@sc.usp.br
University of São Paulo - USP
School of Engineering - São Carlos
13566-590 São Carlos, SP, Brazil

Application of the Minimum Quantity Lubrication (MQL) Technique in the Plunge Cylindrical Grinding Operation

Precision cylindrical grinding is used extensively in the manufacture of precision components in the metal-mechanical industry in general. Modern CNC grinding machines have improved this process with respect to the positioning and rigidity of the machine-workpiece-tool system, allowing the production of high precision parts with low dimensional tolerances. Besides the difficulties inherent to the process, awareness has grown in recent years regarding the environmental issues of cutting fluids. As a response, the industry has begun to seek alternative lubrication and cooling methods. Among the various existing techniques, Minimum Quantity Lubrication (MQL) has been considered as an alternative. This technique can be understood as a combination of conventional lubrication and cooling methods and dry machining, in which a small quantity of lubricating oil mixed with compressed air flow is delivered in the wheel-workpiece interface. The MQL technique is already widely employed in machining processes with tools of defined geometry (e.g. turning), in which produces very satisfactory results. However, the MQL technique has been little explored in grinding processes (non-defined tool geometry), in which the really effective heat removal methods are required due to the frictional heat generation in the grinding zone. Consequently, the aim of this study was to evaluate the plunge cylindrical internal grinding operation when using the MQL technique and the conventional cooling method. Roughness and roundness were the output parameters. As a result, it was found that the best values of roughness Ra were obtained with the conventional lubrication method. The MQL technique applied as proposed was not able to flush the chips away from the grinding zone, leading to the highest Ra values. No significant differences were detected among the cooling methods when analyzing the roundness results. The workpiece fixture method selected was responsible for the overall unsatisfactory results.

Keywords: cylindrical grinding, minimum quantity lubrication (MQL), spray nozzle, CBN superabrasives

Introduction

The industrial metal and mechanical sector must continually seek feasible alternatives for manufacturing processes that allow good quality products to be manufactured within a satisfactory time frame (Novaski & Dörr, 1999).

Standing out in this context is the grinding process, which is characterized by the good surface, dimensional and geometrical finish that it can confer to the workpiece. In most of the cases, those characteristics are difficult to achieve through other machining operations. Nevertheless, improving the grinding process is crucial, since it is employed as a final stage of production, and at this point the workpiece added value is already very high (Hassui & Diniz, 2003). Therefore, it is important to monitor the entire process, accurately correlating all the input parameters and output variables in order to ensure that analogous and convergent results are achieved. Enhancing the grinding process implies not only on selecting the most appropriate wheel type and cutting conditions according to the material to be ground, but also the most effective lubricant and cooling method and the fluid type in order to reduce the heat generation due abrasive friction and the thermal damage. The cutting fluids are responsible for reducing friction heat and flushing the chips out of the grinding zone.

Adopting such procedures enables high material removal rates, producing workpieces of high dimensional and geometric quality, increasing the abrasive tool life in service (Sales et al., 1999; Webster et al., 1995).

However, according to Schmidt & Dyck (2003), from the environmental standpoint, the use of lubricating oils in the grinding process must be reconsidered as in the end of their service life they

have been found to transform themselves into a waste difficult to dispose. In the past, this type of waste was dumped into rivers and lakes, causing severe environmental damage. Over the last few decades, aiming to stop those harmful practices, environmental laws strictly enforced and certifications such as the ISO 14001 standard have been implemented, increasing the commitment with the environment preservation.

The costs associated to conventional cooling methods have driven the search for feasible alternative production processes, creating new technologies that can minimize or even prevent the production of environmentally harmful wastes (Silva et al., 2004).

According to Klocke et al. (2000), the Minimum Quantity Lubrication (MQL) technique can be understood as a small quantity of lubricating oil mixed with compressed air flow resulting in moisture that is delivered in the wheel-workpiece interface. According to Klocke et al. (2000), the improved lubricant characteristics of the oil are responsible for reducing the friction and as consequence the heat generation. It maintains the workpiece temperature range below a certain limit not thermally damaging it.

Heisel et al. (1998) and Klocke et al. (2000) listed the MQL advantages when compared to the conventional cutting fluid application technique, as follows:

- reduced quantity of cutting fluid is used, not being necessary the installation of additional recirculation cutting fluid system;
- avoidance of recycling and filtering systems;
- less maintenance of the fluid;
- drier workpieces;
- reduced volume of lubricant impregnated with the chips;
- reduced amount of biocides and fungicides are needed.

Based on that scenario that researchers concentrated their efforts on dry machining and developed the Minimum Quantity Lubrication

(MQL) technique for machining processes (Tawakoli, 2003), including internal plunge grinding (Hafenbraedl & Malkin, 2000).

However, the good performance of the grinding process is also associated with the abrasive tool. In this segment, CBN (Cubic Boron Nitride) grains have been more widely used due to their excellent performance in grinding hardened steels, ensuring the improved fatigue resistance of machined workpieces, increasing productivity and reducing the energy consumption (Chen et al., 2000). In the MQL technique, according to Heisel et al. (1998), the compressed air mixed with a small amount of oil is responsible for cooling and lubricating the tool-workpiece interface, thus preventing excessive friction. While conventional lubrication processes use up to 45-50 liters of fluid per minute (2,700-3,000 L/h), the maximum oil flow in the MQL technique does not exceed 100 ml per hour (approximately 0.004% of lubricant consumption when compared to the conventional technique).

The aim of this study was to evaluate the plunge cylindrical internal grinding operation when using the MQL technique and the conventional cooling method. Roughness and roundness were the output parameters.

Materials and Methods

The internal grinding operations were conducted in a NC-cylindrical grinder manufactured by Sulmecânica, model RUAP 515 H-CNC, on which were installed the accessories required for carrying out the tests, such as: the pneumatic internal grinding head (max spindle speed = 45,000 rpm) and the MQL application system. The spray nozzle used in the MQL cooling technique is shown in Figure 1. The conventional cooling nozzle under operations is presented in Figure 2.

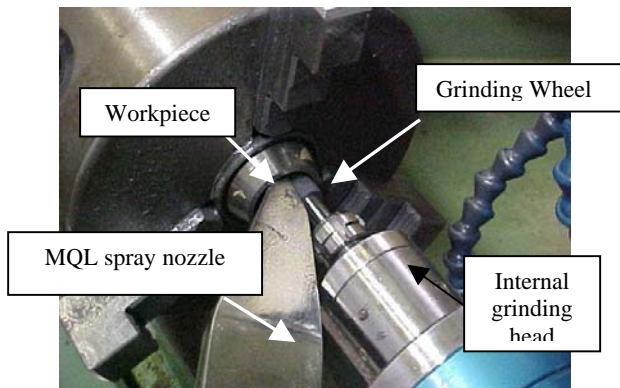


Figure 1. Position of the MQL spray nozzle in the cutting region.

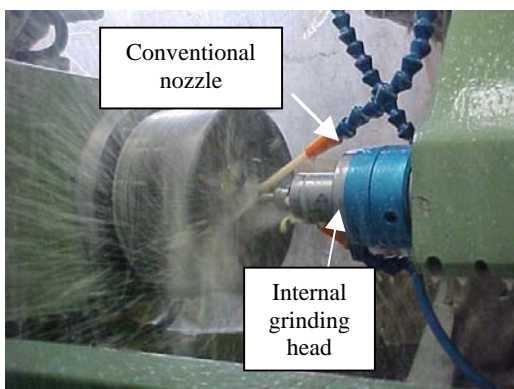


Figure 2. Conventional cooling system under operation.

Care was taken to keep the output velocities of the fluid (conventional cooling system) and the MQL mist constant at around 30m/s, thus attaining to the unitary relationship between the grinding wheel’s peripheral speed and jet velocity. The cutting fluid application method and conditions according to the test classification are presented in the Tab. 1:

Table 1. Test classification according to the cutting fluid method and flow rate.

Test	Application Method	Flow rate		
		[l/min]	Air[m ³ /h]	Oil [ml/h]
1	Conventional	13		
2	MQL		30	48
3	MQL		30	60
4	MQL		30	80

The material ground was the SAE 52100 steel (quenched and tempered). The test specimens have an average hardness of 60 HRC. The internal grinding diameter was equal to 24.4 mm. The tests were carried out with a super abrasive grinding wheel with CBN grains and vitrified bond, having a diameter of 16 mm and cutting width of 15 mm, specification SNB151Q12VR2. The dressing operation was kept constant, using a multigranular dresser with dressing infeed equal to 2 µm and traverse rate equal to 15 mm/min. The test conditions for each cycle were: cutting speed (v_s) = 31.4 m/s, plunge speed (v_r) = 1.00 mm/min, depth of cut = 8 µm. In total, 60 cycles per grinding test were performed. Five repetitions were performed for each test described in Tab. 1.

The output evaluation parameters were the roughness and roundness. The roughness values were measured in a 20 cycle’s interval, evaluating that parameter throughout the process. A Hank Taylor Robson®, model Surtronic 3+ rugosimeter was used for the measurements (cut-off = 0.8 mm and filter = 2CR corrected phase and tip of the diamond stylus had a radius of 0.2 µm). The roundness deviations were measured using a TALYROND 31 C (Taylor Robson®).

Results and Discussion

The plotted roughness and roundness results represent the average value and standard deviation calculated considering the five repetitions of each test condition mentioned in Tab. 1.

Roughness

Figures 3 to 6 present the roughness values expressed in microns (µm) as a function of the lubrication and cooling conditions applied.

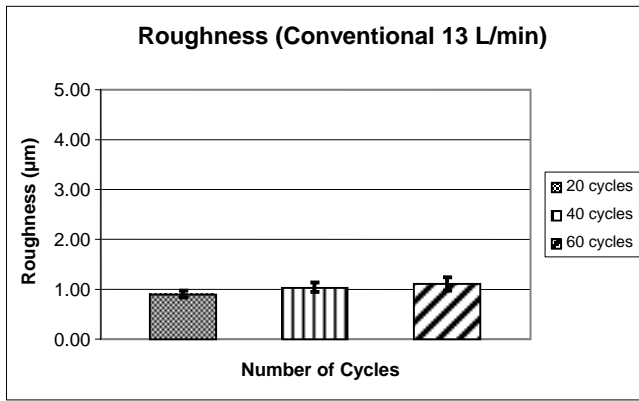


Figure 3. Roughness values measured every 20 grinding cycles using the conventional method (10 ml/min).

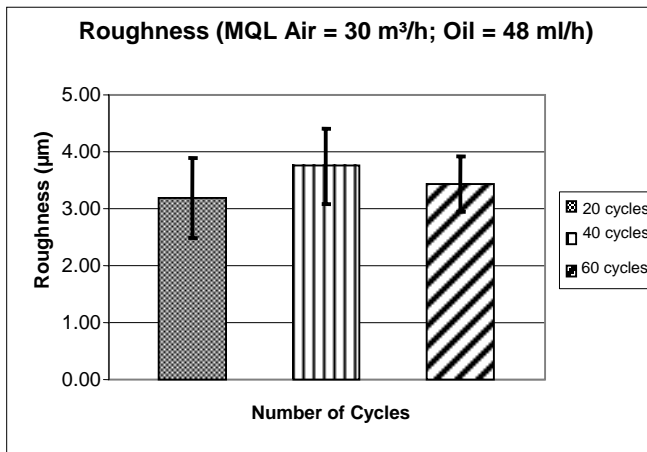


Figure 4. Roughness values measured every 20 grinding cycles using the MQL technique (air flow = 30 m³/h; oil flow = 48 ml/h).

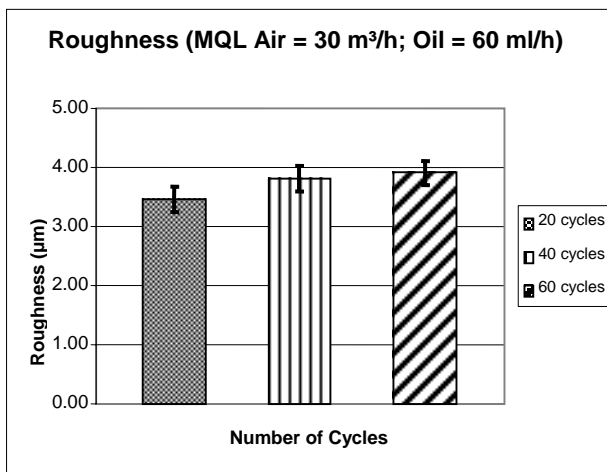


Figure 5. Roughness values measured every 20 grinding cycles using the MQL technique (air flow = 30 m³/h; oil flow = 60 ml/h).

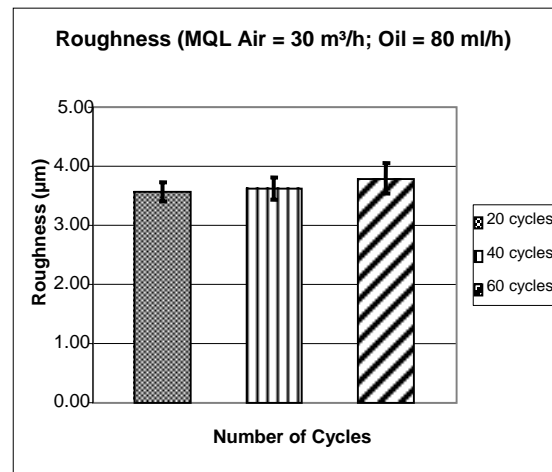


Figure 6. Roughness values measured every 20 grinding cycles using the MQL technique (air flow = 30 m³/h; oil flow = 80 ml/h).

An analysis of Figs. 3, 4, 5 and 6 indicates that the conventional cooling method (Figure 3) was responsible for ensuring roughness values well below those obtained with the MQL technique. In Fig. 3, the number of grinding cycles did not interfere on the roughness values (no statistical difference among cycles), remaining practically constant in the range of 1.00 μm .

Figures 4, 5 and 6 show that the oil flow rates employed in the MQL technique did not affect roughness, which remained approximately equal to 3.5 μm . Similarly to the conventional method, the grinding cycles did not interfere in the roughness values, which were all located within the same range.

The roughness values attained by the conventional cooling method were lower than those obtained by the MQL technique. This is explained by the fact that in the plunge cylindrical grinding operation, the removal of the chips from the grinding zone is very difficult because of the operation configuration. However, when using the conventional method, the abundant flow of cutting fluid is responsible for removing those chips from the internal diameter of the workpiece. In the MQL technique, on the other hand, the intense compressed air flow did not have enough energy to remove the chips from the grinding region. Moreover, the small amount of atomized oil became mixed with the chips, creating slurry between the grinding wheel and the workpiece. That compromised the workpiece ground quality, increasing the surface roughness values obtained through this technique. Those values were found to exceed the acceptable limits for the grinding process, which, according to Diniz et al. (2000), should range from 0.2 to 1.6 μm .

The small amount of removed material during the tests was not sufficient enough to evaluate the roughness behavior as a function of removed material.

Roundness Deviations

Figure 7 presents the roundness values expressed in microns (μm) as a function of the lubrication and cooling conditions applied.

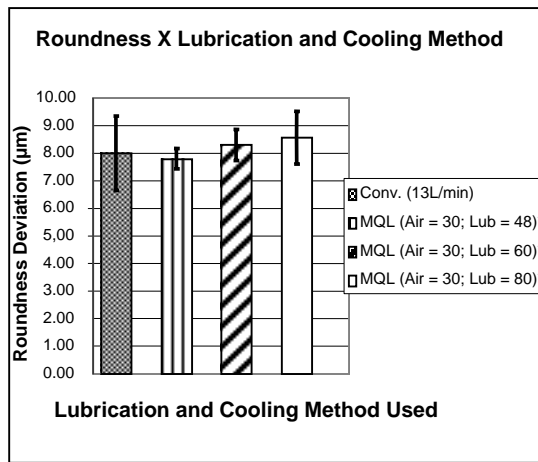


Figure 7. Roundness deviations as a function of the lubrication and cooling method employed. (* The air flow is expressed in m³/hour and the lubricant in ml/hour).

The roundness deviations showed in Figure 6 indicate that no significant differences were detected among the cooling methods. A slight tendency for increasing roundness deviations proportional to the increase in the oil flow rate (MQL technique) was detected. Although, it could not be statistically confirmed based on the observed results.

Contrary to initial assumption, those high values were found to be attributable to the fixture mode. The adopted workpiece clamping method produced intense radial loads subjecting the parts, from that very instant, to a large portion of the deviations measured later. That assumption was confirmed by the presence of three large lobes, corresponding to the three jaws, on the surface of most workpieces ground.

Conclusions

The authors concluded that:

- The small amount of removed material during the tests was not sufficient enough to evaluate the roughness (R_a) behavior as a function of the volume of removed material.
- The best roughness (R_a) values were obtained with the conventional cooling method.
- Application of the MQL technique caused the formation of slurry (a mixture of oil and chips) which was retained in the grinding zone, compromising the internal surface of the workpiece and thereby increasing its roughness.
- When analyzing the roundness deviation, significant differences were not detected among the cooling methods.

- The high values of roundness deviations probably resulted from the fact that the workpiece was clamped by jaws using a chuck.
- Wheel wear was not detected during the tests to measure the volume of removed material.
- Under the tested conditions, the MQL technique was not suitable. However, this technique requires further investigation, involving other parameters that may render its application viable.

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