INFLUENCE OF OPTIMIZED LUBRICATION-COOLING AND MINIMUM QUANTITY LUBRICATION ON THE QUALITY OF HARDENED STEEL PARTS

Manoel Cleber de Sampaio Alves, manoel@itapeva.unesp.br
Marcos Tadeu Tiburcio Gonçalves, tadeu@itapeva.unesp.br
Alexandre Jorge Duarte de Souza, alexandre@itapeva.unesp.br
Luis Fernando Frezzatti Santiago, frezzatti@yahoo.com.br
Francisco Mateus Faria de Almeida Varasquim, mateus1985@uol.com.br
UNESP- São Paulo State University-Faculty of Industrial Wood Engineeering, Rua Geraldo Alckmin 519, Itapeva 18409-010 , SP, Brazil.

Eduardo Carlos Bianchi, bianchi@feb.unesp.br
Paulo Roberto de Aguiar, aguiarpr@feb.unesp.br
UNESP- São Paulo State University-Faculty of Engineering of Bauru-FEB, Av. Eng. Luiz Edmundo C. Coube 14-01, Bauru 17033-360, SP, Brazil

Abstract. *Grinding gives workpieces their final finish, minimizing surface roughnesses and irregularities through interactions between the abrasive grains of a tool (grinding wheel) and the workpiece to be ground. The worldwide tendency is to produce ever more sophisticated parts with very strict geometrical, dimensional and surface finish tolerances, at low costs and without polluting the environment. However, several machining processes, including grinding, use cutting fluids to lubricate and cool the workpiece. In these manufacturing processes, if lubrication and cooling are not satisfactory, the high temperatures that are generated may damage the resulting workpiece in several ways. The objective of this work was to evaluate the quality of ground workpieces using three cutting fluid application methods in the external plunge cylindrical grinding of ABNT 4340 steel with two types of cutting fluid that are less harmful to the environment and to human health, and a superabrasive CBN tool with a low concentration of abrasives. The three lubrication/cooling techniques used here were the minimum quantity lubrication (MQL) method, the optimized lubrication/cooling method (OM), and the conventional lubrication/cooling method (CM), using new nozzle designs for industrial settings. An analysis of these methods is made using different cutting fluid volumes and flow rates on the quality of workpieces produced with hardened steel in cylindrical plunge grinding with superabrasive CBN grinding wheels. The quality of the workpieces was analyzed based on an evaluation of process output variables such as the behavior of the surface roughness, roundness errors, scanning electron microscopy (SEM) analyses and microhardness. The analysis of the various forms of cutting fluid application identified cooling conditions that favor the reduction of cutting fluid volume and shorter grinding times without impairing the geometrical and dimensional parameters, surface finish and surface integrity of the workpieces. Among the various forms of cutting fluid application, optimized application at higher speeds showed the best performance, confirming the efficiency of the new nozzle concept employed in this study. The optimized and MQL processes were successful in maintaining the hardness and surface integrity of the ground workpieces. The only exception was the use of MQL with a flow rate of 40ml/h, which caused cracking and quenching of the workpiece surface. Low-concentration CBN wheels, which are less expensive and subject to less wear, produce good results when associated with more efficient cutting fluid application techniques..*

Keywords*: Sanding, Eucalyptus grandis, Roughness, Sanding force, Sanding pressure*

1. INTRODUCTION

Grinding is considered one of the most complex machining processes due to the large number of variables it involves. This process gives the workpiece its final finish, minimizing surface roughness and unevenness.

The worldwide tendency is to produce ever more sophisticated parts with very strict geometrical, dimensional and surface finish tolerances, at low costs and without polluting the environment. However, several machining processes, including grinding, use cutting fluids to lubricate and cool the workpiece. In these manufacturing processes, if lubrication and cooling are not satisfactory, the high temperatures that are generated may damage the resulting workpiece in several ways. The various types of damage are: surface burn, microstructural changes, residual stresses, shape errors, and even deterioration of the final quality of the workpiece (MALKIN, 1989; GUO,1999)

Cutting fluids are frequently discarded into the environment, a practice that is inappropriate in Earth's current situation and considering today's restrictive environmental regulations and man's growing environmental awareness. Moreover, the relative cost of cutting fluid increases continually due to its high consumption and the treatment it must undergo prior to disposal in order to meet environmental regulations. Large volumes of cutting fluids are needed to meet the requirements of growing industrial productivity and of machining processes (WEBSTER, 1999).

Furthermore, many cutting fluids impair the health of machine operators who work with these fluids. However, this problem is being diminished through the use of vegetal-based cutting fluids that are less harmful to human health.

Thus, the overall use of cutting fluids tends to decline over time, making it necessary to engage in research on the subject in order to reduce the participation of these fluids in productive processes, and hence, in the environment. To this end, more in-depth analyses are needed about the consequences of this type of alteration on the final state of machined components.

Lubrication and cooling depend on the effective delivery of fluid at the workpiece-tool interface, and high volumes are not necessary since part of the fluid does not actually penetrate the cutting region. However, the type of nozzle and its position strongly affect the cutting process (WEBSTER, 1995). Application nozzles designed to avoid turbulence present the best effect, since they tend to approach the films of fluid forming inside the nozzle.

In view of the above, it is evidently important to evaluate the quality of workpieces produced by more efficient cutting fluid application methods. The present research involved the use of three methods for applying cutting fluid in order to evaluate workpiece wear (the conventional method, the optimized method – also called Webster's method, and the minimum quantity lubrication – MQL method), using new designs for nozzles and CBN wheels with low abrasive concentrations.

Cutting fluids causing low environmental and health impacts were used in this research. Based on the quality of the ground workpieces attained with these fluids, the use of cutting fluids with these characteristics may increase, contributing significantly to the process and to society as a whole.

Another noteworthy aspect of this work is the use of innovative concepts with regard to the lubrication methods used in the grinding process, which can be extended to other processes that also use cutting fluids. The lubrication/cooling methods currently in use (conventional, minimum quantity lubrication, and optimized) are aimed at meeting real conditions in industry in the machining of large regions. It was therefore necessary to study and design suitable lubricant dispensing nozzles based on new nozzle shapes not commercially available.

Another objective was to innovate with regard to the quantity of abrasive material in the grinding wheel. One of the reasons that hinder the wider use of CBN grinding wheels is the fact that they are much more expensive than conventional wheels, and their cost depends on the quantity of CBN grains they contain. In this research, a CBN grinding wheel with a 15% volume concentration of abrasive grains was used, seeking a more economic alternative for the fabrication of ground workpieces.

The objective of this work was to evaluate the quality of ground workpieces using three cutting fluid application methods in the external plunge cylindrical grinding of AISI 4340 steel with two types of cutting fluid that are less harmful to the environment and to human health, and a superabrasive CBN tool with a low concentration of abrasives. The three lubrication/cooling techniques used here were the minimum quantity lubrication (MQL) method, the optimized lubrication/cooling method (OM), and the conventional lubrication/cooling method (CM), using new nozzle designs for industrial settings. Efforts focused on finding a compromise between quality, cost, and environmental concerns applied to more efficient lubrication/cooling systems through innovative nozzles designed for industrial use. The influence on quality was evaluated based on analyses of *the surface roughness, roundness errors, scanning electron microscopy (SEM) analyses and microhardness*.

2. METHODOLOGY

In this research, three distinct cutting fluid application techniques were used, i.e., the conventional method (CM) using two circular nozzles; the minimum quantity lubrication (MQL) method, using a nozzle designed for this type of application; and the optimized method (OM), using a new nozzle designed specifically to cover the entire grinding surface.

A RUAP 515 H-CNC grinding wheel (SULMECÂNICA, Cachoerinha, RS, Brazil) was used, equipped with a computer numerical control (CNC) (FAGOR AUTOMATION DO BRASIL, São Paulo, SP, Brazil). Fifty workpieces were ground, 15 using MQL, 25 using the OM, 5 using the CM, and 5 dry (without lubricant/coolant).

Test Specimens: The test specimens were made of quenched and annealed ABNT 4340 steel. This material is widely used in the manufacture of parts that require a good combination of strength and toughness, with relatively uniform values throughout the section.

Cutting Fluids: Vegetable oil emulsion (based on synthetic esters), specification DMS 3200 F-1 Lot 0193/06-S manufactured by Shell do Brasil S.A., used in the conventional and optimized lubricant dispensing methods. A 5% concentration, pH 9, was used. The cutting fluid used for the MQL method was Accu-Lube LB 1000 Lot 39540 manufactured by ITW Chemical Products Ltda. The fluid was controlled microbiologically using ADEP 30 triazine bactericide.

Cutting Tool: The tests were carried out with a superabrasive CBN (cubic boron nitride) grinding wheel manufactured with vitrified binder and a 15% volume concentration of CBN, having the following characteristics: 350 x 20 - 5 x 127 – SNB151Q12VR2 – lot 7936, with an open structure of fine hard grains.

Conventional lubrication/cooling (CM): Characterized by the application of cutting fluid under low pressure, low velocity, and high flow rate. The nozzle used in this system consists of two misting nipples, each 6.3 mm in diameter, for the outlet of fluid (Fig 1).

Figure 1 View of the Conventional nozzle.

Minimum quantity lubrication (MQL): Characterized by a spray of cutting fluid and compressed air. The system consists basically of a compressor, pressure regulator, airflow meter, doser, and nozzle designed for the use of MQL in grinding (Fig 2). The MQL system allows for the lubricant/air volume to be finely regulated.

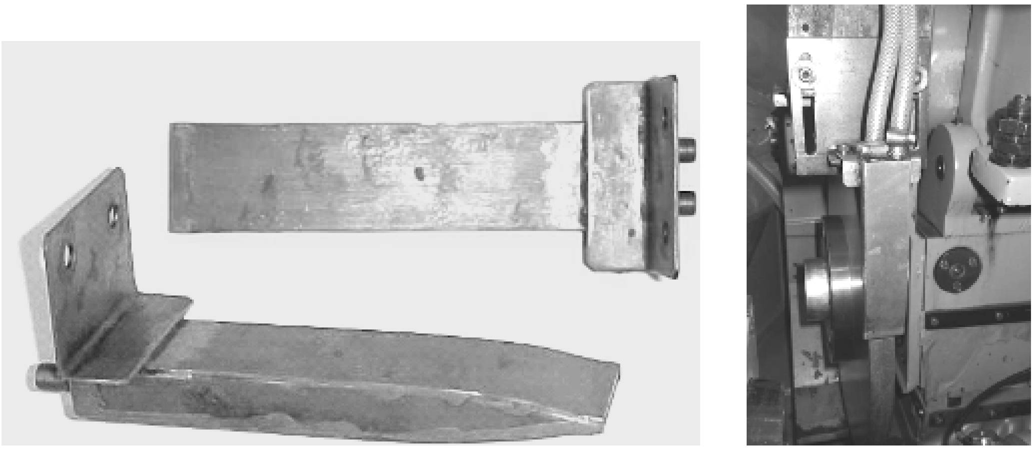

Figure 2 View of the MQL nozzle.

Optimized system (OM): Characterized by high cutting fluid flow rate and pressure. The system consists basically of an optimized nozzle designed from an MQL nozzle. A rectangular tube made of galvanized ABNT 1010 sheet steel, which was shaped by fitting two U-channels into each other, was inserted into and welded to the nozzle outlet. Fig 3 illustrates the design of the optimized nozzle fabricated and used in this study.

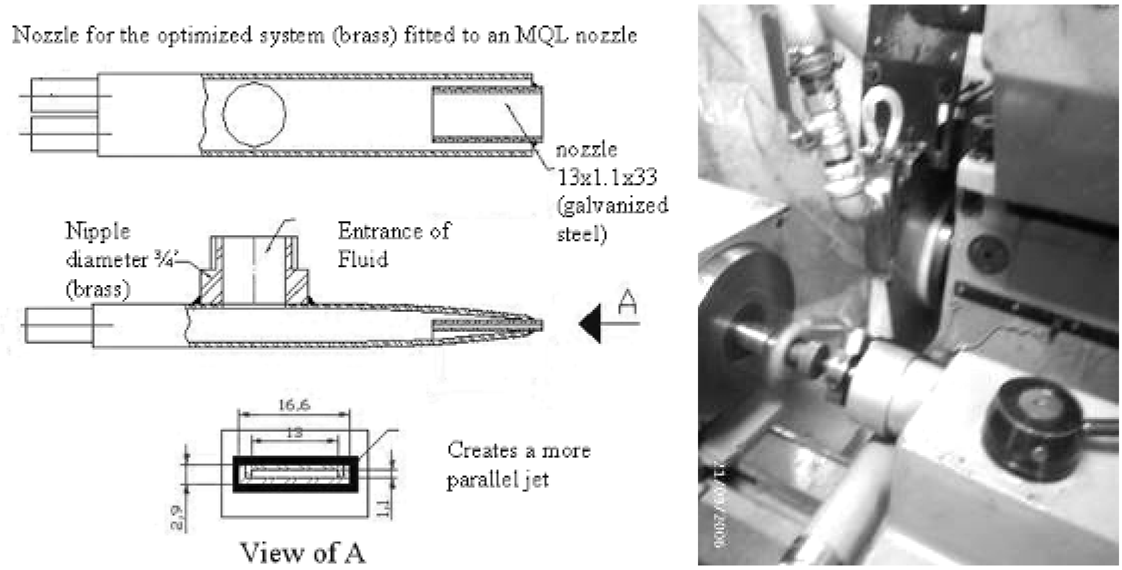

Figure 3 Design of the optimized nozzle and view of the jet it produces

The machining conditions used in the tests were as follows: Plunge velocity (V_f) of 1 mm/min; Cutting speed (V_s) of 30 m/s; Workpiece rotation (ω_w) of 204 rpm; Penetration depth (a) of 0.1 mm; Spark-out time (t_s) of 8 seconds; Grinding width of 12 mm; Grinding cycles of 100; Maximum equivalent cutting thickness (h_{eq}) of 0.065 µm; Minimum equivalent cutting thickness (h_{eq}) of 0.047 µm; fleece dresser.

Table 1 list the cutting fluid velocities and flow rates in the optimized, MQL and conventional conditions, respectively. It should be noted that the concentration of fluid used in the optimized and conventional techniques was kept constant at 5%.

Table 1 – Speeds and flow rates used in the optimized, MQL and conventional methods.

Condition	**Total cutting fluid flow (l/min)**	**Cutting fluid flow velocity, V_j (m/s)**
Optimized 30m/s	26.3	30
Optimized 27m/s	23.7	27
Optimized 25m/s	21.9	25
Optimized 20m/s	17.5	20
Optimized 15m/s	13.2	15
Minimum Quantity Lubricant (MQL)	**Total cutting fluid flow (l/min)**	**Compressed air exit velocity V_i, (m/s)**
MQL 40ml/h	0.00067	30
MQL 60ml/h	0.00100	30
MQL 80ml/h	0.00133	30
Conventional application	**Total cutting fluid flow (l/min)**	**Cutting fluid flow velocity, V_j, (m/s)**
Conventional	20	5.3

Roughness: The mean roughness of the workpieces, represented by the parameter R_a, was measured with a Taylor Hobson SURTRONIC *3+* roughness meter. Measurements were taken perpendicular to the grinding surface. The cut-off was 0.8 mm and the filter was a 2CR with phase correction. The diamond tip of the profilometer had a radius of 0.2 µm.

Scanning electron microscopy (SEM): a ZEISS DSM 960 scanning electron microscope was used with 2000 X magnification, applying the electron scattering technique, which offers a better view of the profile of the structures on the analyzed surface.

Roundness errors: These errors were measured with a Taylor Hobson TALYROND 31C roundness measuring instrument using TR31 software installed in a microcomputer coupled to the roundness meter.

Residual stress: This stress was measured with a Siemens D5000 diffractometer with cobalt target X-ray tubes and a Rigaku D/Max-2000 diffractometer with chromium target X-ray tubes. The multiple exposure method ($sen^2\psi$) of X-ray diffraction was used.

Scanning electron microscopy (SEM): a ZEISS DSM 960 scanning electron microscope was used with 2000 X magnification, applying the electron scattering technique, which offers a better view of the profile of the structures on the analyzed surface.

Microhardness: Microhardness was measured with a BUEHLER 1600-6300 microhardness tester, applying a load of 200g for 40s.

3. RESULTS AND DISCUSSION

3.1. Influence of the cutting fluid dispensing methods on the roughness:

The importance of analyzing this variable lies in the fact that the surface finish strongly affects the fatigue strength of manufactured components subjected to fatigue loads. The roughness of a workpiece is directly related to lubrication and depends principally on the size of the abrasive grains in the grind wheel, the dressing conditions, the rate of removal, spark-out time and lubrication/cooling conditions (MALKIN, 1989).

Figure 4 shows the mean roughnesses of the five repetitions carried out for each of the MQL, OM and CM conditions employed here.

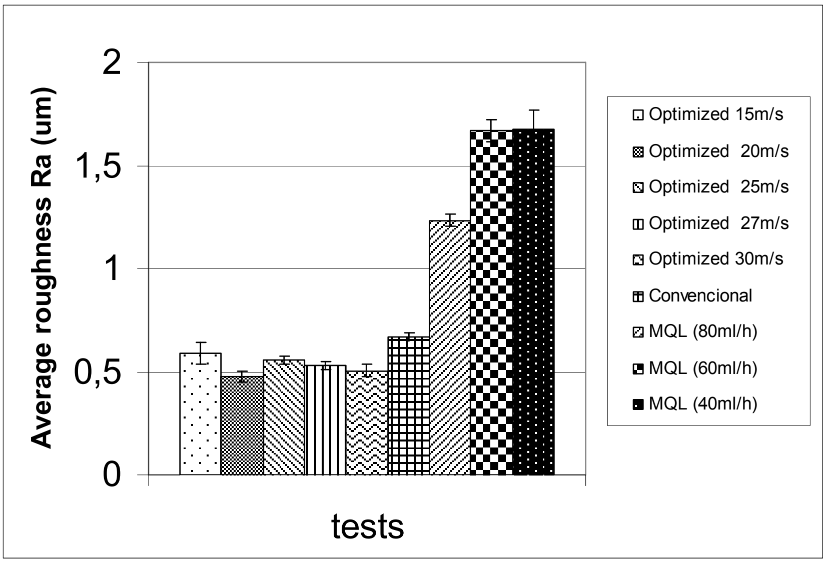

Figure 4 Analysis of the effect of the cutting fluid dispensing methods on roughness

An analysis of the results indicates that the roughness values were generally lower in optimized lubrication/cooling, followed by the conventional method and lastly by MQL. The lowest roughness values obtained with MQL were obtained using a lubricant flow of 80ml/h, thus confirming that the larger amount of fluid lead to lower roughness values due to the greater lubrication it provided.

The conventional lubrication/cooling method resulted in lower roughness values than the MQL technique, but the values obtained with a lubricant flow of 80ml/h are lower roughness values than those of the majority of industrial applications.

The best optimized situation (fluid flow velocity of 20m/s) with respect to he mean roughness, R_a, of the workpiece was 71.7% lower than the best MQL condition (Q=80ml/h) and 47% lower than the conventional cutting fluid dispensing method.

The lowest values attained with the optimized method were obtained at higher cutting fluid flow rates, thus confirming that a larger quantity of fluid allowed for lower roughness values due to the greater lubrication it provided. Higher cutting fluid flow rates allow for more rapid chip removal, contributing to a better finish. The differences in roughness between the optimized conditions were minor, but showed a tendency for better quality at higher cutting fluid flow rates.

The results differ from results obtained by Silva et al (2006). Silva et al. (2006) showed the effectiveness of the MQL technique in the external cylindrical grinding process by comparing with the conventional cooling method. The surface roughness values were significantly decreased with the use of MQL method.

3.2. Influence of the cutting fluid dispensing methods on the roundness errors:

Figure 5 depicts the results of roundness errors in the five repetitions carried out for each of the MQL, OM and CM conditions.

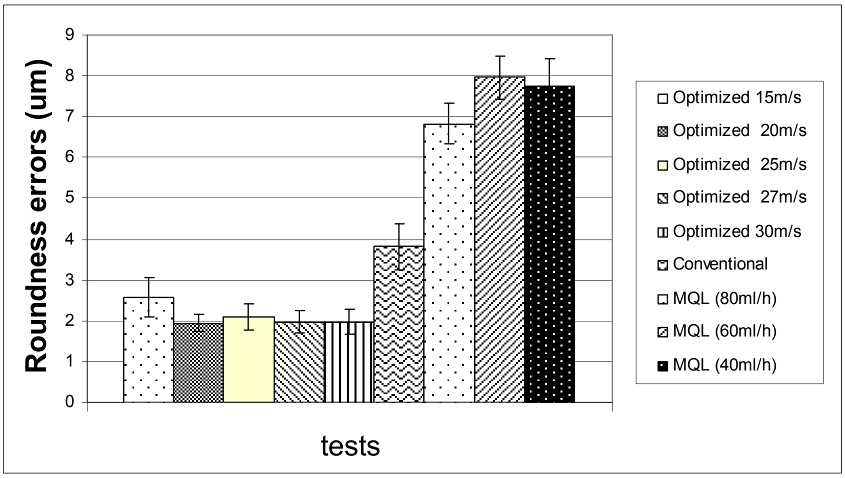

Figure 5 – Analysis of the effect of the cutting fluid dispensing methods on roundness errors

An analysis of the roundness results indicates that, in general, the values did not show significant differences in each of the conditions using the optimized technique. Moreover, the optimized technique showed better roundness results than did the conventional and MQL methods.

The amount of cutting fluid in the MQL technique proved of fundamental importance to roundness errors.

The optimized condition with a fluid flow rate of 30m/s presented lower roundness errors than the other conditions and than the other lubrication/cooling techniques. The mean roundness error for this condition was 2μm, and was 70.5% lower than the best MQL condition obtained with a flow rate of 80ml/h.

The highest roundness error was 7.9 μm obtained in the MQL condition with a lubricant flow rate of 60ml/h.

As for the flow rates used in the optimized lubrication/cooling method, a tendency was found for roundness to improve in response to higher cutting fluid flow rates.

Another relevant factor, according to Kohli et al. (1995), is the fact that the thermal conductivity of CBN grains enables less heat to be directed to the workpiece, thus facilitating its dimensional control and ensuring the surface integrity of the machined component.

3.3. Influence of the cutting fluid dispensing methods on the microhardness:

Figure 6 illustrates the mean Vickers microhardness results obtained for each of the MQL, OM and CM conditions. This figure also shows the mean Vickers microhardness obtained in the burn test of a turned workpiece.

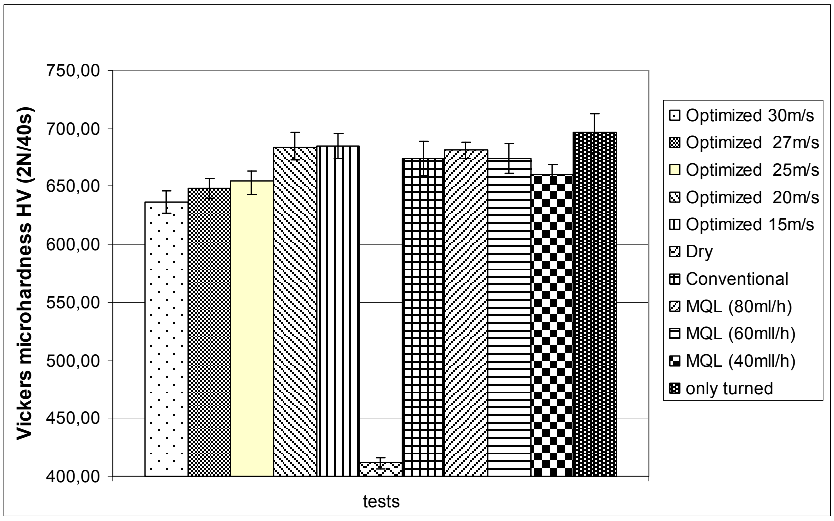

Figure 6 – Mean Vickers microhardness values attained with the MQL, OM and CM techniques; burn test on turned workpiece

The highest mean variation in hardness in relation to the original (turned) workpiece was found in the MQL condition with a fluid flow rate of 40m/s, which presented 5.1% lower hardness, on average, than the turned workpiece. This was the worst (lowest hardness) condition with respect to the Vickers microhardness output variable for the MQL condition. The best MQL condition was attained with the flow rate of 80ml/h, which presented a 2.15% lower hardness than the turned workpiece.

The analysis of the microhardnesses obtained with the MQL, CM and OM techniques led to the conclusion that, regardless of the efficiency of the lubrication/cooling method employed, there is a slight loss of surface hardness. It was also concluded that the highest cutting fluid flow rate (80ml/h) in the MQL technique leads to lower loss of hardness. However, generally speaking, none of the techniques proved more efficient than the others in general terms.

The Vickers microhardness for the best optimized condition was practically the same as that attained with the best MQL condition, with a difference of less than 1%.

Similar results were observed by Nguyen et al. (2003). The result showed that the hardness of the component ground with MQL method was more or less the same as that ground with conventional method.

3.4. Influence of the cutting fluid dispensing methods analysed by microstructural analysis:

The surface integrity of a workpiece is an extremely important factor, and damage of the surface of a material may affect it significantly, causing degradation of the properties of wear, corrosion resistance, crack nucleation and propagation, and acceleration of the components fatigue process. The surface integrity of the workpiece is affected principally by the temperature produced by the grinding process, which may lead to its thermal damage.

The conventional method lubricated and cooled the workpiece efficiently, without allowing it to sustain damage. The same holds true to optimized lubrication/cooling. In addition, the contact time of the abrasive grains and the cooling time are very short, thus not leading to significant differences at the subsurface.

The MQL conditions of 80ml/h and 60ml/h did not lead to substantial subsurface alterations of the microstructure when using the MQL technique.

Nguyen et al. (2003) suggests that the improvement of lubrication by a small amount of oil in the air stream could significantly reduce the thermal impact on the workpiece. This was observed for MQL method with a flow rate of 60 and 80 ml / h.

The microstructure depicted in Fig 7 corresponds to the MQL condition of 40ml/h. In this condition it was possible to detect significant subsurface changes in the microstructure, such as cracks and surface burn.

An analysis of the microstructure indicated that the various conditions tested in this study using the optimized and conventional lubrication/cooling techniques showed satisfactory results. In other words, no significant microstructural changes or surface damage of the workpiece were found after grinding, thus improving the component's properties of corrosion resistance and abrasive strength and enhancing its fatigue strength. The only exception was the situation in which a cutting fluid flow rate of 40ml/h was used with the MQL technique, which showed the presence of cracking and surface hardening, albeit without visually detectable burn.

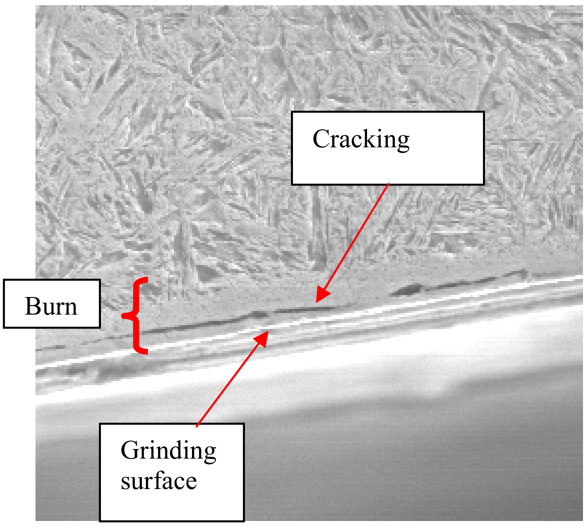

Figure 7 Micrograph of a test specimen subjected to MQL with cutting fluid flow of 40ml/h (2000 X magnification)

4. CONCLUSIONS

• This study indicated that it is possible to use CBN grinding wheels with smaller quantities of abrasive grains associated to more efficient forms of applying cutting fluids, without impairing the properties of the machined components, contributing to reduce the costs of the grinding process.

• The analysis of the overall results indicates that the MQL proved feasible as an alternative substitute of the conventional lubrication/cooling method, depending on the desired degree of precision of the component, providing ecological and economic advantages.

• The optimized technique was found to be essential to produce more precise workpieces than those produced with the other two techniques, and therefore offers an option to obtain higher quality components without changing grinding wheels, cutting fluid, and dressing and cutting conditions.

• Higher flow volumes and cutting fluid application velocities lead to better results for the machined material, producing lower roughnesses and smaller roundness errors.

• Cutting fluids that are less harmful to the environment and to human health, such as the ones used in this research, proved feasible for use in grinding processes, without impairing the quality of the workpieces, thus contributing to reduce impacts on health and nature.

• With regard to the surface integrity of workpieces, the SEM images and microhardness values revealed that the properties of the material did not change in any of the optimized and conventional conditions due to the lubricating efficiency of these methods.

• In the case of the MQL technique, the fluid flow rates of 80ml/h and 60ml/h did not produce any detectable thermal effects. However, the MQL condition with a flow rate of 40ml/h led to appearance of cracking and surface hardening due mainly to the smaller amount of lubricant delivered, causing greater generation of heat due to the attrition between grain and workpiece.

• All the variables analyzed here were significantly reduced with the application of the optimized technique due to the good lubrication and cooling it provided, and due to the efficiency of the innovative nozzle model employed.

• Although a hard open-structured CBN grinding wheel with a low concentration of CBN grains (15% in volume) and fine grain size (100 to 200 mesh) was used, the results of the MQL technique were satisfactory, since they fell within acceptable limits for grinding.

• It was found that a cutting jet velocity close to the cutting velocity led to the best results, since in this condition breaks the aerodynamic barrier around the grinding wheel, favoring the entrance of fluid and providing more efficient chip removal, thus reducing its effects on the workpiece. Nevertheless, there is still need for more in-depth studies at higher jet velocities in relation to the cutting velocity.

• It was concluded that the use of the MQL technique is viable using a grinding wheel with a low concentration of abrasive grains (15%) in situations where the roughness and roundness specifications are not as stringent as in the machining of shaft bearing seats, shafts and holes for gears, etc., which represent a large part of industrial grinding applications.

5. ACKNOWLEDGEMENTS

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