INFLUENCE OF METHODS OF LUBRICATION IN THE CYLINDRICAL PLUNGE GRINDING PROCESS USING SUPERABRASIVES GRINDING WHEEL

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Abstract. *The quality of machined components is currently of high interest, for the market demands mechanical components of increasingly high performance, not only from the standpoint of functionality but also from that of safety. Components produced through operations involving the removal of material display surface irregularities resulting not only from the action of the tool itself, but also from other factors that contribute to their superficial texture. This texture can exert a decisive influence on the application and performance of the machined component. This article analyzes the behavior of the MQL technique and compares it with the conventional cooling method. To this end, an optimized fluid application method was devised using a specially created nozzle through which a minimum amount of oil is sprayed in a compressed air flow, thus meeting environmental requirements. This paper, therefore, explores and discusses the concept of the minimum quantity of lubricant (MQL) in the grinding process. The performance of the MQL technique in the grinding process was evaluated based on an analysis of the surface integrity (roughness, residual stress, microstructure and microhardness). The results presented here are expected to lead to technological and ecological gains in the grinding process using MQL.*

***Keywords**: Surface integrity, minimum quantity lubricant (MQL), nozzle and grinding.*

1. INTRODUCTION

In recent years, energy consumption, air pollution and industrial waste have been the focus of special attention on the part of public authorities. The environment has become one of the most important subjects within the context of modern life, for its degradation directly impacts humanity. Driven by pressure from environmental agencies, politicians have drawn up increasingly strict legislation aimed at protecting the environment and preserving natural energy resources. These combined factors have led the industrial sector, research centers and universities to seek alternative production processes, creating technologies that minimize or avoid the production of environmentally aggressive residues.

Emulsion-based cooling fluids for machining are still widely used in large quantities in industrial metal-mechanical processes, generating high consumption and disposal costs and harming the environment. The growing need for environmentally friendly production techniques and the rapidly rising cost involved in the disposal of cutting fluid justify the demand for an alternative to the grinding process with fluid. In the last decade, however, the goal of research has been to restrict to the barest minimum the use of cooling and/or lubricating fluids in metal-mechanical production processes. According to Sahm and Schneider (1996), dry machining and Minimum Quantity Lubricant (MQL) machining have caught the attention of researchers and technicians in the field of machining as an alternative to traditional fluids. The drastic reduction or even the complete elimination of this fluid can undoubtedly lead to higher temperatures in the process, causing reduced cutting tool output, loss of dimensional and geometrical precision of the work pieces and variations in the machine's thermal behavior. When abrasive tools are used, a reduction in cutting fluid may render it difficult to keep the grinding wheel's pores clean, favoring the tendency for clogging and thus strongly contributing to the aforementioned negative factors.

Confirming the trend for environmental concerns triggered by the use of cutting fluids in machining processes, as reported by several researchers and machine tool manufacturers, strong emphasis today focuses on environmentally friendly technologies aimed at preserving the environment and at conforming to the ISO 14000 standard. On the other hand, despite persistent attempts to completely eliminate cutting fluids, in many cases cooling is still essential to the economically viable service life of tools and the surface qualities required. This is particularly true when strict tolerances and highly exact dimensions and shapes are required, or when the machining of critical difficult-to-cut materials is involved. Minimum quantity lubricant, in these cases, is an interesting alternative because it combines the functionality of cooling with an extremely low consumption of lubricant (usually < 80 ml/h). According to Klocke and Eisenblätter (1997), the minimization of cutting fluid has taken on increasing relevance over the last decade.

The grinding process requires a considerable amount of energy per volume unit to remove material. During the process, this energy is transformed into heat, which concentrates in the cutting region. High temperatures can cause several types of thermal damage to the work piece, such as superficial burning, microstructural modifications, and surface and subsurface heating of the piece, which allows for superficial tempering and re-quenching of a material (in tempered steel machining) with the formation of nonsoftened martensite, generating undesirable residual tensile stresses and thus reducing the ultimate fatigue strength of the machined component. Moreover, uncontrolled thermal expansion and contraction of the piece during grinding contribute to errors in the dimension and shape of the final component, these phenomena leading mainly to errors in circularity. The grinding rates utilized today are limited by the maximum temperatures permissible in the grinding process. To Malkin (1989), when these temperatures are exceeded, they may lead to deterioration of the part's end quality. Thus, the sources giving rise to residual stress on the machined surface can be phase transformation, thermal stress due to irregular heating and cooling of the surface layer, and mechanical strain.

This project aims to evaluate the performance of the minimum quantity lubricant (MQL) technology compared with conventional cooling, applied in minute flow rates as an environmentally correct alternative to the cutting fluid utilized in plunge cylindrical grinding. The small amount of lubricant is pulverized in a compressed air flow, reducing the undesirable effects involved in supplying lubrication and cooling. The evaluation of the MQL technique in the grinding process consisted of analyzing the surface integrity (roughness, residual stress, microstructure and microhardness).

2. THE GRINDING PROCESS

Grinding has long been considered one of the most important manufacturing processes, whose purpose is to improve the surface finish and ensure the integrity of finished pieces (Vieira et al., 1999). This high precision process is very important, since the loss of a workpiece at this stage is unacceptable because, in this stage, the material's added value is high due to the various processes that preceded grinding.

Grinding, according to Diniz et al. (2000), is a machining process which is used to attain tight dimensional tolerances of IT4 to IT6 and compatible geometrical tolerances, and low roughness (Ra) values of 0.1 to 0.6 µm. This process subjects the cutting region to high temperatures, which may lead to major problems for the workpieces, including burn, microstructural damage and undesirable residual stresses.

With regard to the composition of the cutting fluid, Jahanmir and Strakna (1993) state that, in response to pressures from environmental protection and health agencies, manufacturers have focused their efforts on developing products that are less harmful to the health of machine tool workers and less damaging to the environment.

According to Novaski and Rios (2002), the cost of fluids has increased due to their high consumption and frequent disposal. This goes against today's policies of environmental preservation, thus highlighting to the need for systems to be developed that are compatible with environmental and human health concerns.

Figure 1 indicates that the external plunge cylindrical grinding operation consists, basically, of the total depth of the plunge corresponding to the end of the grinding cycle, with a tool cutting speed, Vs, plunge velocity, Vf, workpiece rotation, nw, flow rate of fluid from the nozzle to the cutting region, Vj (which will have four variations in this study), tool diameter, ds, and workpiece diameter, dw. The external plunge cylindrical grinding operation is therefore characterized by the correlation between these and other parameters. The same figure also gives a schematic diagram of some of the output variables of the process, such as tangential cutting force, Ftc, and normal cutting force, Fn.

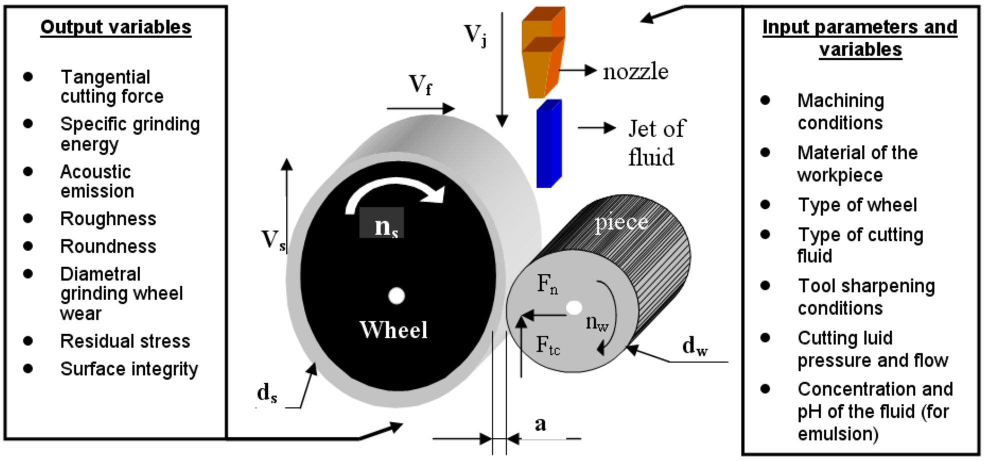


Figure 1 – Parameters and variables involved in external plunge cylindrical grinding (adapted from Malkin,1989)

2.1. Variables analyzed in the grinding process

2.2.1. Roundness errors

A workpiece is never perfectly cylindrical, according to Shaw (1994), because all workpieces contain circularity errors. Jedrzejewski & Modrzycki (1997) describe circularity errors as any divergence between the manufactured part and the part theoretically required with a specified tolerance.

The heat generated in grinding is most intense at the point of contact between the grinding wheel and the workpiece, penetrating toward the latter's center. The more difficult it is for the fluid to penetrate the cutting region, the greater will be the heat in the workpiece, facilitating the formation of thermal dilations and deformations which lead to roundness errors. Moreover, the vibration of the machine and the cutting parameters employed also affect this variable (Malkin, 1989).

The high frictions generated during grinding, especially at the workpiece-grinding wheel interface, can be considered an extremely important factor in the appearance of roundness errors. To reduce these frictions, a fluid with good lubricating and cooling capacity is recommended in order to improve the final quality of the ground workpiece (Minke, 1999).

2.1.2. Residual stresses

According Malkin (1989), cylindrical grinding generates residual stresses in the surroundings of the surface of the finished workpiece, and these stresses may impair the mechanical behavior of the material. Residual tensile stresses are created mainly by stresses introduced by the thermal gain and deformations associated with grinding temperatures, which cause the gradient to occur from the workpiece surface inward. Compressive stresses, on the other hand, are generated predominantly by mechanical interactions between the grinding wheel's abrasive grains and the workpiece.

Residual stresses resulting from grinding are generated by three basic effects: thermal expansion and contraction of the material during grinding, phase transformations due to the high temperatures produced in machining, and plastic strains caused by the grinding wheel's abrasive grains (Weingaertner et al., 2001).

Weingaertner et al. (2001) state that in the grinding process, while the grinding wheel is removing material, the outer layers of the workpiece dilate more than the inner ones because they are at a higher temperature, leading to the formation of residual compressive stresses on the surface of the workpiece. On the other hand, when the action of the grinding wheel stops (the moment when cooling of the workpiece takes place), the external layer should contract more, which is not allowed by the internal layers. Thus, residual tensile stresses emerge on the surface during cooling. However, for mechanical equilibrium to occur, residual compressive stresses appear in the layers close to the core.

2.1.3. Microstructural analysis

Microstructural analyses of machined materials are important because they reveal the structural characteristics of workpieces, indicating possible microstructural changes, the appearance of microcracks or even macrocracks, both types of cracking damaging to the final ground part. One of the main causes of both microstructural changes and cracking is the rise in temperature at the grinding wheel-workpiece interface. One of the most common ways of visualizing the final behavior of microstructure and verifying the integrity of the machined component is by using a scanning electron microscope (SEM).

To Goldstein et al. (1992), SEM is a highly versatile device which allows for various types of analyses of microstructural elements, such as precipitates, phases, defects, etc. The principal advantages of SEM over optical microscopy are its resolution and its depth of focus, for scanning electron microscopes have a resolution of about 0.003 µm, while that of an optical microscope is 0.1 µm.

3. EXPERIMENTAL PROCEDURE

The material used in these tests was hardened ABNT 4340 steel. Classified as quenching steel, it is employed in the manufacture of pieces that require a good combination of mechanical strength and toughness.

The tests were carried out with aluminum oxide (Al2O3) grinding wheels (355.6 x 25.4 x 127mm - FE 38A60KV). The dressing operation was kept constant, using a multigranular fliese-type dresser that did not influence the output variables of the process.

A series of preliminary tests were carried out to determine the best lubricant and compressed air flow, as well as the best choice of the various types of lubricants using the MQL technology. Seven types of lubricants were subjected to preliminary testing. The LB 1000 lubricant supplied by the MQL equipment manufacturer presented the best performance; therefore, all the results reported here involve this type of lubricant.

The equipment used to control the minimum quantity lubricant (MQL) was Accu-lube, which uses an oil supply pulse system and allows the air and lubricant flows to be adjusted separately. The creation of the nozzle allowed for a compressed air flow close to that of the grinding wheel's peripheral velocity (30m/s). This velocity is required to enable the mixture (lubricant plus compressed air) to penetrate the region of contact between the tool and the piece, favoring lubrication and cooling of the process. The lubricant flow used here was 40 ml/h. A flow meter and a pressure regulator equipped with a filter were purchased to take precision measurements of the compressed air flow at the aforementioned speed. The MQL system consists of a compressor, a pressure regulator, a rotameter, a doser and a spray nozzle. Figure 2 shows the nozzle developed and utilized in the testing of the MQL technique in the grinding process. The nozzle was placed at a distance of about 35mm from the grinding wheel-piece interface.

The main input parameters [grinding wheel cutting velocity (Vs), plunge velocity (Vf), peripheral velocity of the piece (Vw), grinding depth (a) and spark out time (ts)] were selected based on preliminary testing. The cutting conditions selected after testing preliminary to the definitive tests were: Vs = 30 m/s; Vf = 1 mm/min; Vw = 20m/min (average velocity); a = 0.1 mm and ts = 10s. These parameters were kept constant throughout the tests.

A synthetic emulsion in a 5% concentration was used in the conventional cooling condition. The maximum flow supplied by the pump and by the machine's original nozzle was 8.4 l/min.

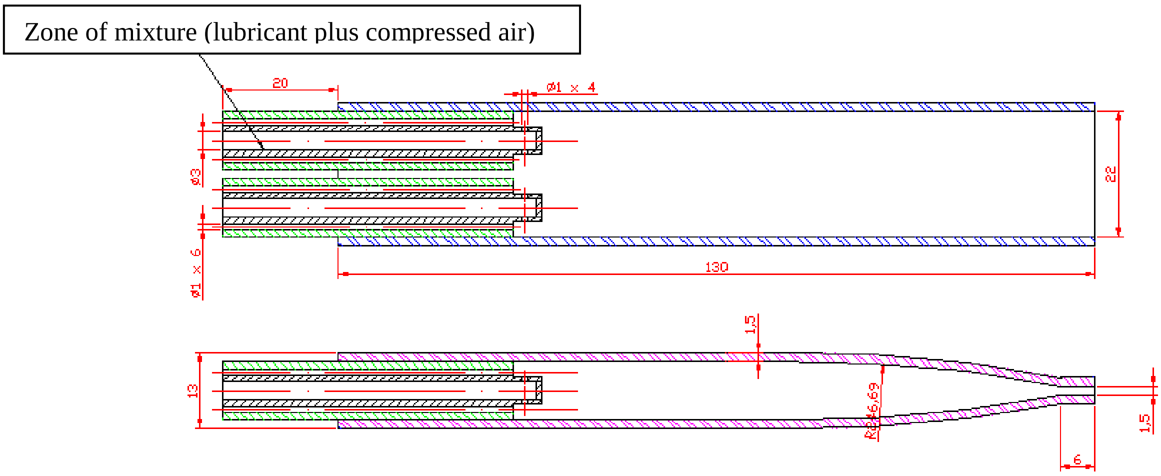


Figure 2. Design of the nozzle used in the MQL tests.

The surface roughness was measured by adjusting the profilometer to a cut-off length of 0.8mm. At the end of each test, the average roughness values, R_a, were measured at three different points approximately 120° equidistant from each other. Scanning electron microscopy (SEM) was used to analyze possible damage caused by thermal and mechanical forces on the material's surface. The scanning electron microscope is a highly versatile device which allows for a variety of analyses. The main advantages of the SEM in relation to an optical microscope are its resolution and focus depth. The nominal values of residual stress were determined based on the method of multiple exposition ($\text{sen}^2\Psi$), following the SAE J784a code. In this procedure, the normal residual stress and the residual shear stress are evaluated by adjusting (d) *versus* ($\text{sen}^2\Psi$) curves for an elliptically shaped curve, where (d) is the interplanar distance of the analyzed crystallographic plane and (Ψ) is the angle of the sample's slope. For experimental reasons, we chose on to analyze the (211) plane of the ferrite and martensite using the values of modulus of elasticity and Poisson's coefficient. Cobalt radiation was employed to determine the residual stress, with a scanning angle (2θ) varying from 47 to 63 degrees, in 0.1 degree steps and an exposure time of 2 seconds. The sample's slope angles varied from -60 to 60 degrees, with measurements taken at 10 degree intervals.

4. RESULTS AND DISCUSSION

The results described below refer to the best cutting, lubrication and cooling conditions found in the plunge cylindrical grinding of hardened ABNT 4340 steel for the parameters evaluated here.

4.1. Roughness

It is well known that the surface finish can significantly affect the mechanical strength of components when they are subjected to fatigue cycles. Figure 3 compares the mean values of the Ra parameter (µm) with the Al2O3 grinding wheel under conventional cooling against those obtained with the MQL technique. The values were obtained after three 30-cycle plunge grinding stages. The depth for each cycle was 100µm. Six Ra measurements were taken in three different positions approximately 120° equidistant from each other.

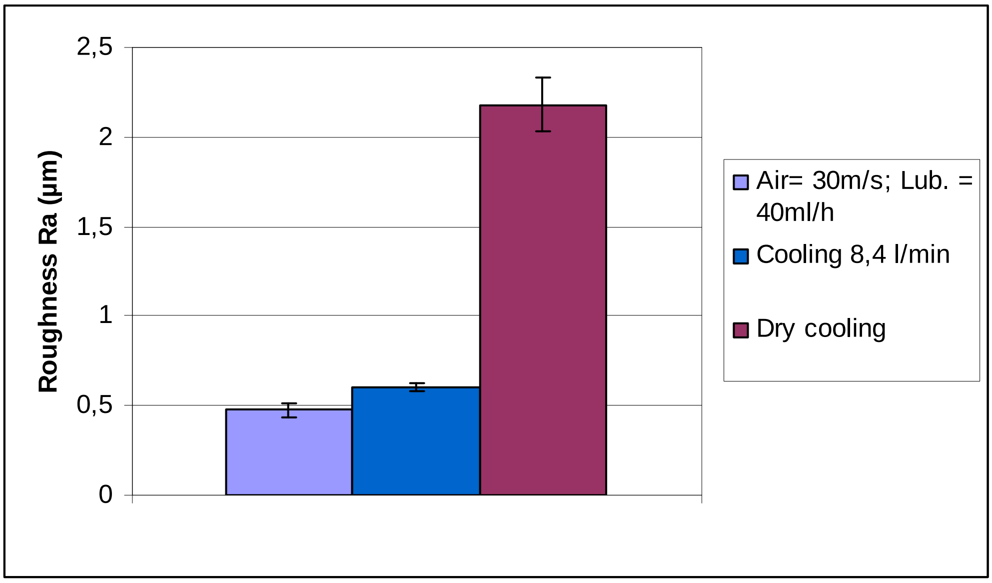


Figure 3. Roughness after 90 cycles with the Al2O3 grinding wheel (Vs = 30m/s; Vf = 1mm/min; ts = 10s; a = 100µm)

An analysis of the results obtained with the conventional cutting fluid application system and with the MQL technique indicates that the application of cutting fluid by the MQL technique led to a result superior to that of the conventional system due to the more efficient penetration of the fluid into the cutting region. The MQL technique led to lower roughness values, probably because of the more effective lubrication and cooling of the abrasive grains at the work-tool interface. Efficient lubrication allows the chips to slide more easily over the tool's surface, resulting in a better surface finish.

4.2. Residual Stress

Based on a pre-analysis of the dry condition during the tests, we also decided to measure the residual stress under the dry condition in order to compare the behavior of the residual stress under the 3 grinding conditions (conventional, MQL and dry cooling). The values were obtained after three 30-cycle stages, each cycle of 100µm.

Figure 4 shows the values of residual stress for the samples ground by aluminum oxide wheels with MQL, conventional cooling and dry cooling. To identify how the grinding process affected the residual stress, the residual stress was also measured after turning followed by heat treatment.

As indicated in the bibliographic review, grinding can lead to microstructural transformations due to high temperatures and displacement of the austenite in relation to the carbon, which helps diffusion. This may cause tensile or compressive stresses, depending on the material that is being ground and on the machining conditions.

According to Malkin (1989), residual stresses can be caused by three factors: influence of thermal dilation, influence of microstructural transformations in the piece, and mechanical influence. Thermal dilations in grinding are proportional to the temperatures generated in the process. The temperature in external layers is high, gradually decreasing in the internal layers in the direction of the core. In grinding, when the source of heat is active, the external layers dilate more than the internal ones, leading to residual compressive stresses on the surface. When the heat source is no longer active (cooling), the external layer should contract more, which is not permitted by the lower layers. The mechanical influence derives from the penetration of the abrasive grain into the piece.

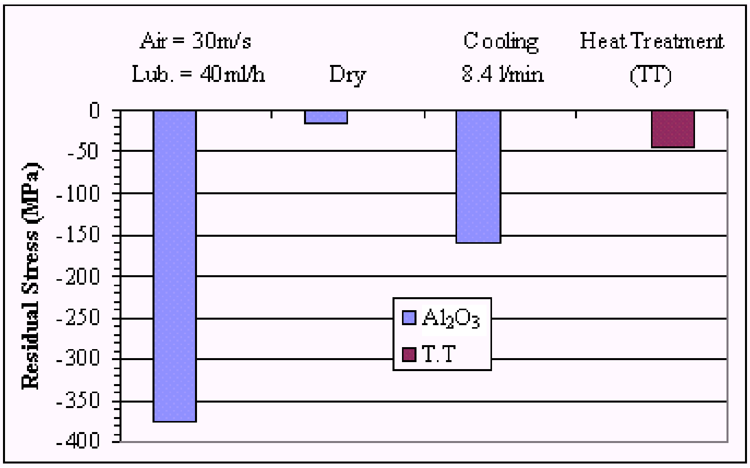


Figure 4 - Comparative results of residual stress at a depth of approximately 10µm below the surface after 90 cycles (Vs = 30m/s; Vf = 1mm/min; a = 100µm and ts = 10s)

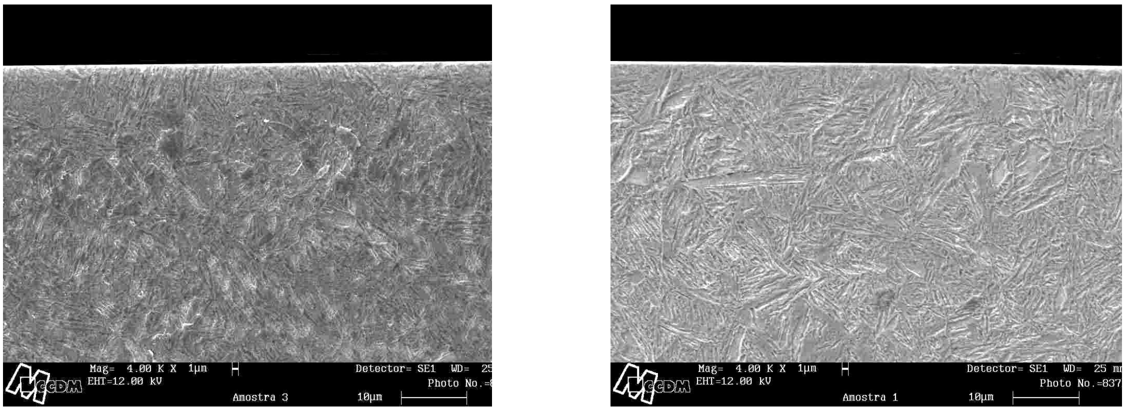
Figure 4 shows that residual stresses were produced under both MQL and conventional conditions. Residual compressive stresses are considered beneficial for the mechanical properties of materials, increasing their fatigue strength and the service life of components. These properties are important when using ABNT 4340 steel.

The MQL technique produced higher residual compressive stresses than did the conventional cooling system, which is a positive aspect. Compared with near-dry grinding, there was an increase in the residual stress values under both MQL and conventional conditions tested.

Compared to turning followed by heat treating, grinding with MQL and conventional conditions led to a significant increase in the residual compressive stress values, conferring positive characteristics on the mechanical properties of the machined piece.

4.3. Analysis of the Microstructure

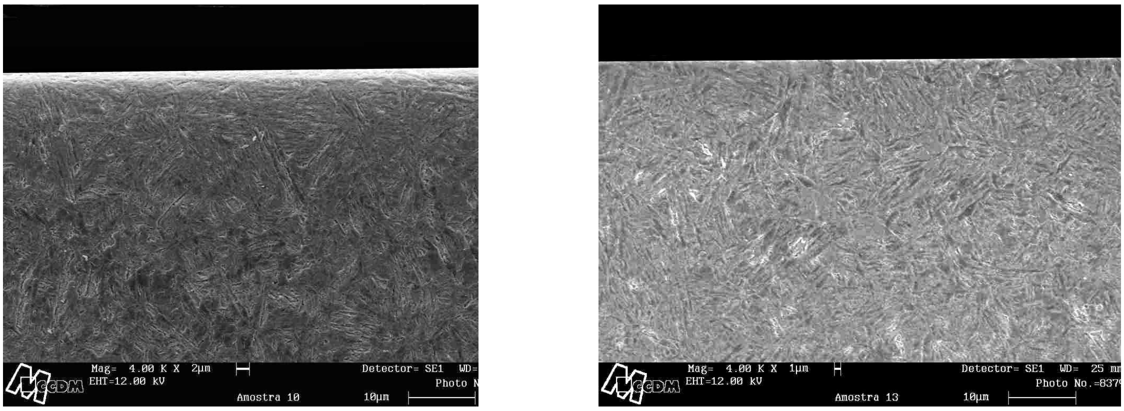
Figures 5 and 6 are micrographs of sample cross-sections, they illustrate the subsurface alterations that took place in the samples when the aluminum oxide grinding wheel was used with conventional cooling, dry cooling and with the use of the MQL technique. Note that the subsurface alterations produced by the various lubrication and cooling conditions were minimal, without significant differences between the conditions tested. Sandpapering and polishing the samples manually to ensure their planeness for the desired magnification was not an easy task due to the material's great hardness.



(a) Conventional cooling

(b) MQL (air = 30m/s and lubri. = 40ml/h)

Figure 5. Subsurface microstructures obtained after 90 cycles (V_s = 30m/s; V_f = 1mm/min and a = 100µm) 4.000X



(a) Without cooling (b) Heat treatment

Figure 6. Subsurface microstructures obtained after 90 cycles (V_s = 30m/s; V_f = 1mm/min and a = 100µm) 4.000X

4.4 Measurement of Microhardness

Measurements of the microhardness were taken on the cross-sectioned samples. Figure 7 represents the variation in microhardness as a function of the depth below the machined surface using the aluminum oxide grinding wheel under conventional cooling, dry cooling and MQL. To identify the influence of the grinding process on the microhardness, measurements of a sample were taken directly from the heat treatment, i.e., without grinding, as shown in the Figure 7.

The results obtained from the microhardness measurements for the two lubricating and cooling conditions did not indicate significant subsurface modifications, confirming our microstructural analyses. Steels usually undergo grinding after they have been heat treated. Depending on the temperature of the cutting process, annealing of the piece may occur during grinding, causing softening close to the finished surface. Loss of superficial hardness is a complex phenomenon relating to annealing of the martensitic structure and to carbon diffusion, and is dependent on the temperature and time involved in the cutting process.

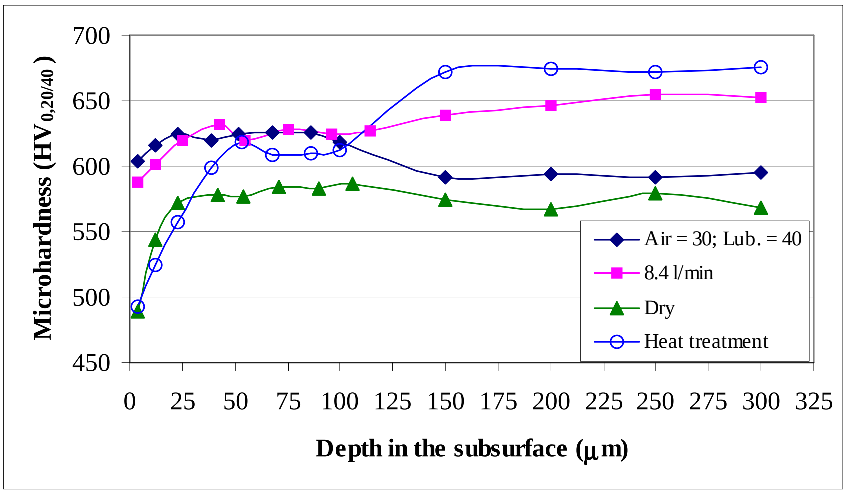


Figure 7 - Variation of microhardness as a function of depth in the subsurface after 90 cycles (Vs = 30m/s; Vf = 1mm/min; a = 100µm).

Malkin (1989) stated that, in practice, it is interesting to combine the annealing behavior with a thermal analysis in order to predict the drop in hardness of the piece. Experimental results demonstrate that high temperatures and long periods of exposure of the piece to such temperatures, at low velocities or with longer contact lengths of the piece, lead to greater losses in hardness.

5. CONCLUSIONS

An analysis of the experimental data of this study led to the following conclusions regarding the plunge cylindrical grinding of hardened ABNT 4340 steel:

-The analyses of the various results indicated that the MQL technique can be applied efficiently in the grinding process, providing environmentally friendly and technologically relevant gains.

-The Ra values were substantially reduced with the use of the MQL technique, probably due to excellent properties of lubricity.

-No significant clogging of the grinding wheel pores was found with the MQL technique.

-Residual compressive stresses were obtained under all the conditions tested. The MQL technique led to the highest residual stress value.

-The use of MQL did not negatively affect the surface integrity.

-No significant subsurface alterations in the microstructure were detected under conventional cooling and with MQL.

6. ACKNOWLEDGEMENTS

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