GRINDING OF HARDENED STEELS USING OPTIMIZED COOLING

RECTIFICADO DE ACEROS ENDURECIDOS USANDO REFRIGERACIÓN OPTIMIZADA

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RESUMEN

La rectificación, proceso final de fabricación de una pieza, hace uso intenso de fluidos de corte con la finalidad de lubricación, refrigeración y remoción de astillas (imperfecciones). Sin embargo, estos fluidos son extremamente agresivos al medio. Con el avance tecnológico la tendencia mundial es producir piezas cada vez más sofisticadas, con elevado grado de tolerancia geométrica, dimensional, con buen acabamiento superficial, con bajo costo y, principalmente, sin causar daños al medio. Para ello, al proceso de rectificación está intrínseco el reciclaje del fluido de corte, que se destaca por su costo. A través de la variación de la velocidad de avance en el proceso de rectificación cilíndrica externa del acero ABNT D6, racionalizando la aplicación de dos fluidos de corte y usando una muela superabrasiva de CBN (nitruro de boro cúbico) con ligante vitrificado, se evaluaron los parámetros de salida fuerza tangencial de corte, rugosidad, circularidad, desgaste de la herramienta, la tensión residual y la integridad superficial a través de la microscopia electrónica de barrido (SEM) de las piezas de prueba. Con el análisis del desempeño fluido, muela y velocidad de inmersión se encontraron las mejores condiciones de fabricación propiciando la disminución del volumen de fluido de corte, disminución del tiempo de fabricación sin perjudicar los parámetros geométricos, dimensionales, el acabado superficial y la integridad superficial de los componentes.

Palabras clave: Rectificación, refrigeración optimizada, velocidad de avance, muela esmeril CBN.

ABSTRACT

Grinding – the final machining process of a workpiece – requires large amounts of cutting fluids for the lubrication, cooling and removal of chips. These fluids are highly aggressive to the environment. With the technological advances of recent years, the worldwide trend is to produce increasingly sophisticated components with very strict geometric and dimensional tolerances, good surface finish, at low costs, and particularly without damaging the environment. The latter requirement can be achieved by recycling cutting fluids, which is a costly solution, or by drastically reducing the amount of cutting fluids employed in the grinding process. This alternative was investigated here by varying the plunge velocity in the plunge cylindrical grinding of ABNT D6 steel, rationalizing the application of two cutting fluids and using a superabrasive CBN (cubic boron nitride) grinding wheel with vitrified binder to evaluate the output parameters of tangential cutting force, acoustic emission, roughness, roundness, tool wear, residual stress and surface integrity, using scanning electron microscopy (SEM) to examine the test specimens. The performance of the cutting fluid, grinding wheel and plunge velocity were analyzed to identify the best machining conditions which allowed for a reduction of the cutting fluid volume, reducing the machining time without impairing the geometric and dimensional parameters, and the surface finish and integrity of the machined components.

Keywords: Grinding, optimized cooling, plunge velocity, grinding wheel, CBN.

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.

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Various conventional machining processes use cutting fluids to lubricate and cool the workpiece. The worldwide trend is to produce increasingly sophisticated components with tight geometric and dimensional tolerances and a high degree of surface finish, at a low cost and without harming the environment. The cutting fluids normally employed in grinding operations often used to be discharged into the environment. However, this is no longer a feasible practice in view of the stringency of today's environmental regulations and law enforcement practices, and the new concept of "green seal" production. The green seal indicates that the processes employed to produce a given component are environmentally friendly. Thus, the mass use of cutting fluid has tended to decrease over time, which has required researches aimed at reducing the participation of these fluids in productive processes and, hence, their discharge into the environment, without altering the quality of the machined component.

According to Ebbrell [1], cutting fluids provide the industrial sector with enormous benefits, but these fluids are usually stored inappropriately. Thus, large quantities of cutting fluid are used incorrectly. As an example of this inappropriate use, in many companies, the machining operations scatter large amounts of cutting fluid, thus generating substantial losses. Lubrication and cooling depend on the effective penetration of fluid into the cutting region at the workpiece-tool interface, but large volumes of fluid are not necessary, considering that part of the fluid does not effectively penetrate the cutting region [2].

The difficulties of carrying out proper maintenance, the discharge of fluids, and the environmental problems caused by the cutting fluids used in machining processes have led to a worldwide tendency to use a rational amount of fluid in the process, based on optimized cutting fluid application techniques.

The study reported here, involving cylindrical plunge grinding, analyzed the influence of the plunge velocity, the performance of the CBN grinding wheel, and the influence of different cutting fluids using optimized lubrication and cooling. Output variables such as surface finishing, roundness errors, diametral grinding wheel wear, tangential cutting force, acoustic emission, residual stresses were analyzed, as was the microstructure of finished components.

METHODOLOGY

In this study, the test methodology involved the use of a SULMECÂNICA model RUAP 515H cylindrical grinding wheel equipped with a Fagor CNC numerical control. Plunge cylindrical grinding was employed. The input parameters were the variation in plunge velocity, v_f (five values providing different magnitudes of material removal rates), and the use of two distinct cutting fluids.

The tool was a superabrasive 876-L360N3 CBN (cubic boron nitride) grinding wheel manufactured with vitrified binder, with an external diameter of 350 mm, width of 20 mm and thickness of 5 mm. This type of grinding wheel (superabrasive) allows for significant gains in productivity and quality. The dressing operations of the abrasive tool were kept constant in all the tests, using a 15x8x10 conglomerate-type dresser. In this operation, the removal of material from the grinding wheel was approximately 100 µm, or until the abrasive tool no longer displayed any markings produced by machining.

The test specimens were made of ABNT D6 steel (AISI/SAE D6, GERDAU D6, DINW.NR 1,2436, X210CrW12, VC 131) tempered and quenched to a hardness of 62 HRc.

The cutting fluids were a vegetal-based emulsive oil (based on synthetic esters), specification DMS 3200 F-1, in a concentration of 3.5%, with pH kept at 9.0, and a synthetic fluid, specification AGECOOL 939/B, in a concentration of 5%, with pH also kept at 9.0.

A circular nozzle was used, as proposed by Webster [2], with a circular Ø4mm beak to distribute the cutting fluid at a velocity approximately equal to that of the grinding wheel's peripheral velocity (V_s). This velocity is necessary to enable the cutting fluid to overcome the air barrier generated by the high rotation of the grinding wheel and penetrate the region of the workpiece-tool interface without the loss of speed and pressure [3], thus favoring cooling in the process.

The analysis of the tests involved the output variables by which the performance of the process can be evaluated. These output variables were:

- Roughness: The arithmetic mean of the roughness (R_a) was measured using a portable Taylor Hobson Subtronic 3+ rugosimeter and TalyProfile®, version Lite 3.1.4 software. The rugosimeter was adjusted to measure a sampling length of l_c = 4 mm and a cut-off = 0.8 mm and was positioned to allow the measurements to be taken in the axial direction of the workpiece.
- Tangential cutting force "F_{tc}": The tangential cutting force (F_{tc}) was measured by monitoring the electric

power (P_c) consumed by the motor driving the axletree of the grinding wheel, which was obtained by monitoring the values of voltage and electric current of this electric motor.

- Grinding wheel radial wear: The radial wear of the grinding wheel was determined by marking the worn profile of the wheel on an ABNT 1045 steel dowel, measured with a digital TESA, model TT60 gauge with a precision of 0.1 µm.
- Acoustic Emission: The level of acoustic emission was captured with a piezoelectric acoustic emission sensor connected to a SENSIS model DM42 signal-treating unit.
- Residual Stress: The residual stress was determined using a Siemens model D5000 X-ray diffractometer and applying the multiple exposure method (to determine the interplanar distance at various angles of inclination of the sample). The data thus obtained were analyzed using S2003 (R.M/2003) software.
- Roundness error: The roundness errors were measured with a Taylor Hobson Talyrond 31C roundness checking machine equipped with an arm/column set that allows for movement on two axes (vertical and horizontal).
- Surface integrity: Analyzed with a Leica, model Stereoscan 440 scanning electron microscope (SEM). SEM was used to check for possible damage on the surface of the material caused by thermal and mechanical loads.

The cutting parameters used were: cutting velocity: $V_{s=}$30 m/s, penetration of the grinding wheel into the workpiece: a=0.1mm, sparkout time: t_s=8s, peripheral velocity of the workpiece: V_w = 1.24m/s, diameter of the workpiece: d_w=62 mm, grinding width: b=3mm, cutting fluid jet velocity: V_j =30m/s, cutting fluid flow: 22.6L/min, circular nozzle: Ø4mm (optimized cooling). One hundred machining cycles were carried out for each test.

The tests were divided intro groups of three, indicating the repeatability at each plunge velocity and resulting in the data presented in table 1.

RESULTS AND DISCUSSION

Presented below are the results of the analysis of the output variables of tangential cutting force, residual stress, grinding wheel radial wear, acoustic emission, roundness error, and analysis of the surface integrity of the machined components.

Table 1. Testing modes.

Tests	Cutting Fluid	Plunge Velocity (V_f) (mm/min)
1 to 3	DMS 3200 F1 vegetal-based emulsive oil	2.00
4 to 6	DMS 3200 F1 vegetal-based emulsive oil	1.50
7 to 9	DMS 3200 F1 vegetal-based emulsive oil	1.00
10 to 12	DMS 3200 F1 vegetal-based emulsive oil	0.50
13 to 15	DMS 3200 F1 vegetal-based emulsive oil	0.25
16 to 18	Agecool 939/B synthetic fluid	2.00
19 to 21	Agecool 939/B synthetic fluid	1.50
22 to 24	Agecool 939/B synthetic fluid	1.00
25 to 27	Agecool 939/B synthetic fluid	0.50
28 to 30	Agecool 939/B synthetic fluid	0.25

Tangential Cutting Force

As can be seen (figure 1), the behavior of the cutting force was the same with both fluids, since the lowest cutting force was attained with a plunge velocity of 0.25 mm/min.

An overall analysis of all the graphs reveals that the highest cutting forces were achieved with a plunge velocity of 1.5 mm/min using the vegetal-based emulsive oil and with a plunge velocity of 1.0 mm/min using the synthetic fluid.

The lowest cutting forces were attained with a plunge velocity of 0.25 mm/min using the vegetal-based emulsive oil and 0.50 mm/min with the synthetic fluid.

Note that, under all the conditions tested, the initial cycles showed higher cutting forces, which declined as the cycles progressed due to the renewal of the cutting edges and the grinding wheel’s ability to sharpen itself.

According to Tonshoff [4], reducing the peripheral velocity of the workpiece causes the temperature in the region of contact to increase because the tool and workpiece are in contact for a longer period. As the peripheral velocity of the workpiece decreases, there is an equivalent reduction in the cutting thickness due to the decrease in the diameter of the workpiece, generating lower cutting forces because of the lower load imposed on the abrasive grains.

Bianchi [5] found that an increase in the wear of the binder tends to diminish the anchoring of the grains by increasing the stresses acting at the interface between the binder and the abrasive grain, and the wear of the grains, in turn, tends to reduce the tension acting at the aforementioned interface, since the wear causes the moment applied on the abrasive grain to diminish.

It was found, here, that the abrasive tool was subjected to a greater load under conditions of more aggressive plunge rates. Franzo [6] also reported the same finding.

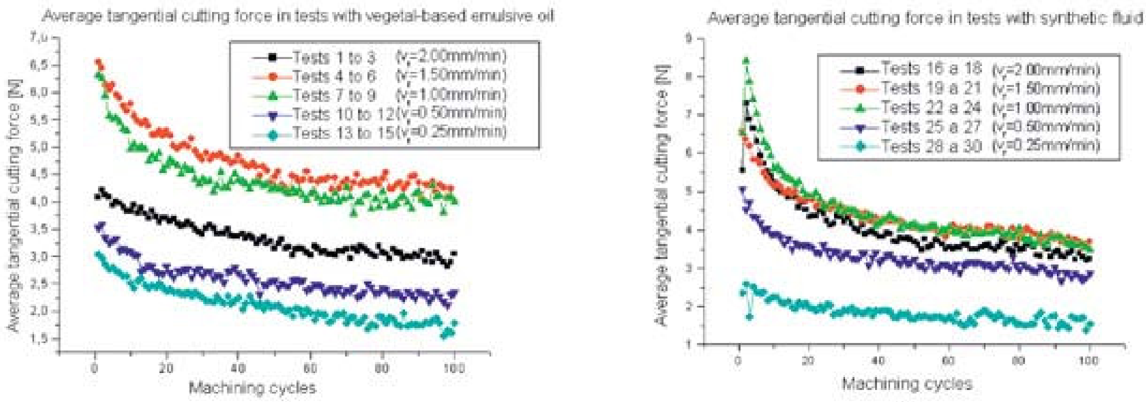
Good lubrication of the cutting region leads to lower cutting forces because it facilitates the sliding of the chip as it forms, thus generating lower specific grinding energy values [7].

The tangential cutting force is directly related to the final roughness of the component. This variable also allows one to analyze the performance of abrasive tools, such as the ability of the binder to fix the abrasive grains, the occurrence of macro and micro wear, among other parameters.

Acoustic Emission

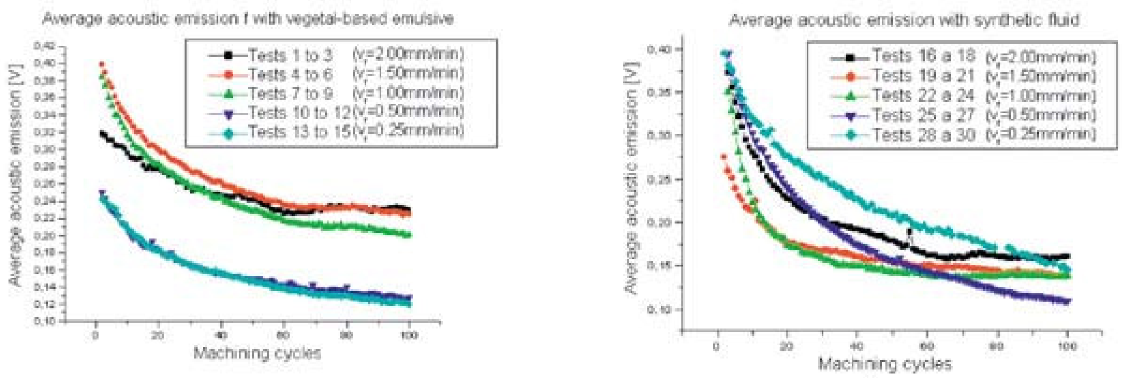
Figure (2a) illustrates the acoustic emission measured in the tests carried out with vegetal-based emulsive oil, while figure (2b) shows this parameter using the synthetic fluid.

An analysis of figure (2a), corresponding to the use of vegetal-based emulsive oil, indicates that the acoustic emission values were practically the same at plunge velocities of 0.50 mm/min and 0.25 mm/min, and that these were the lowest values obtained. The plunge velocities of 1.50 mm/min and 1.00 mm/min also presented very similar acoustic emission values and were the highest attained in these tests.



a b

Figure 1. Average tangential cutting force in tests with vegetal-based emulsive oil (a) and synthetic fluid (b) at the five plunge velocities applied.



a b

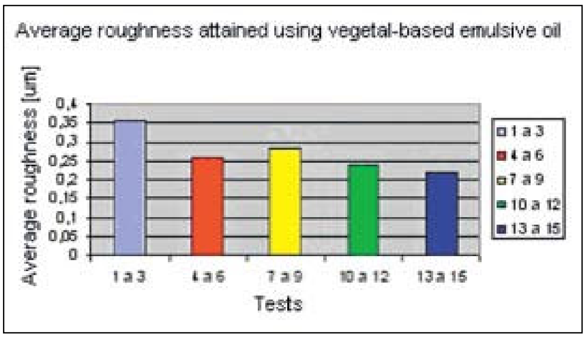
Figure 2. Average acoustic emission for tests carried out with vegetal-based emulsive oil (a), and with synthetic fluid (b) for the five plunge velocities applied.

Figure 2b indicates that the acoustic emission values at plunge velocities of 1.50 mm/min and 1.00 mm/min were very similar, but were the lowest values recorded practically up to one half of the machining cycle. The plunge velocity of 0.25 mm/min presented the highest acoustic emission throughout the cycle.

The cutting oils favored lower grinding forces due to their greater lubricating capacity, allowing for a reduction of the attrition coefficient, keeping the tool sharp and generating lower temperatures in the cutting region [8].

Based on his studies, Franzo [6] concluded that acoustic emission increases with the plunge rate and, hence, a higher material removal rate. The same tendency was found in our tests using the vegetal-based emulsive oil as cutting fluid, but the synthetic fluid did not show the same behavior.

Roughness



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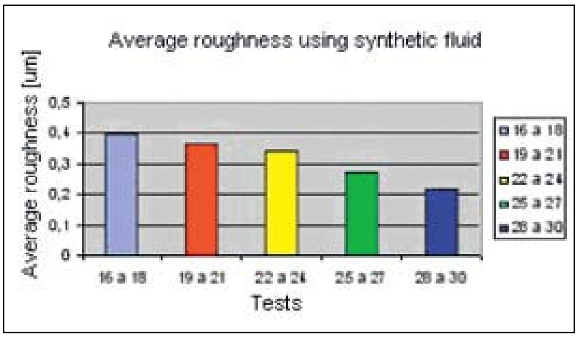


b

Figure 3. Average roughness attained in tests using vegetal-based emulsive oil (a) and synthetic fluid (b) at the five plunge velocities applied.

The roughness (R_a) results are illustrated in the form of graphs. The average roughness values were determined based on three measurements of the surface taken in each test.

Higher roughnesses were also found at higher plunge velocities, and lower roughnesses resulted in the tests using the emulsive oil.

The results of roughness revealed a characteristic behavior. A search of the literature indicated the existence of two different points of view regarding the behavior of roughness. Lee and Kim [9] state that roughness should be higher at higher plunge rates than under milder conditions. On the other hand, Hara [10] states that the effect of roughness could be completely eliminated by the fact that the tests involved 8-second sparkout regions. In other words, no characteristic behavior would be observed.

Grinding Wheel Diametral Wear

Figure 4 shows the average radial wear of the grinding wheel in the tests carried out with emulsive oil and synthetic fluid at the five different plunge velocities.

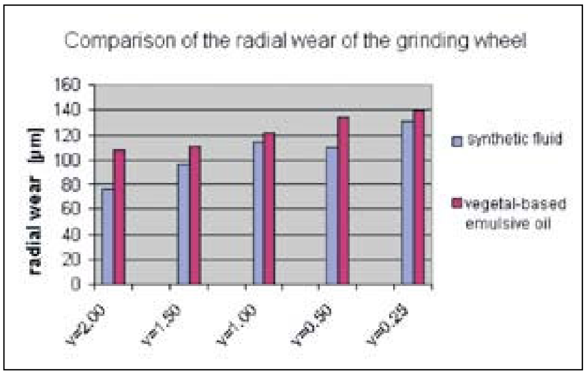


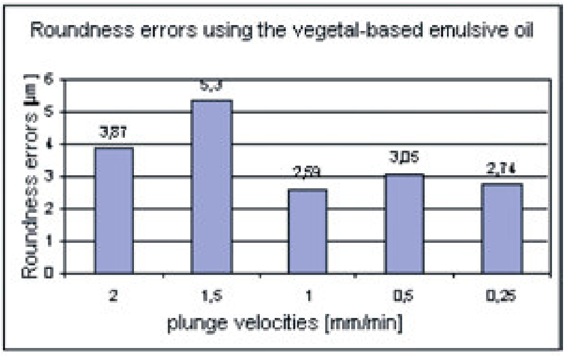
Figure 4. Comparison of the radial wear of the grinding wheel.

An analysis of figure 4 indicates that the highest grinding wheel wear occurred at a plunge velocity of 0.25 mm/min and the lowest at 2.00 mm/min. The diametral wear of the grinding wheel is a strong parameter for evaluating different grinding conditions. Lower tool wear means a longer tool service life; therefore, higher plunge velocities within the tested range should be chosen to ensure a longer tool service life, considering the high cost of CBN grinding wheels.

Roundness error

The results of the roundness errors were analyzed by plotting separate graphs for each type of cutting fluid and plunge velocity employed in the tests.

Using synthetic fluid, the plunge velocity of 2.00 mm/min presented the best machining conditions since it produced the lowest roundness error. The synthetic fluid presented the best results at the higher plunge velocities, while the emulsive oil presented optimal results at lower plunge velocities. The mean values of roundness of the two cutting fluids showed 3.51 µm for the emulsive oil and 4.54 µm for the synthetic fluid, indicating the greater viability of using vegetal-based emulsive oil in machining under the proposed conditions.



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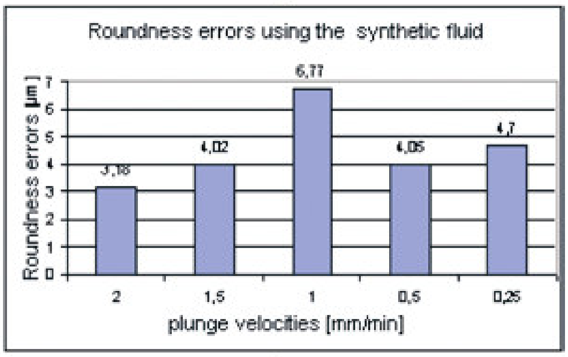

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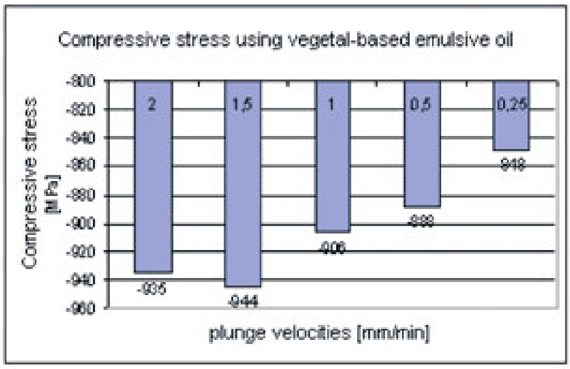
Figure 5. Roundness errors using the vegetal-based emulsive oil (a) and synthetic fluid (b) at the five different plunge velocities employed.

Residual Stress

The values of residual compressive stresses generated with optimized cooling indicate that the jet of fluid penetrated the cutting region efficiently, providing good lubrication, reducing the friction between the workpiece and the tool and contributing to maintain the tool's sharpness.

Note that the tested conditions resulted in residual compressive stresses that are beneficial for the mechanical properties of the material, thus improving its surface integrity.

The vegetal-based emulsive oil was found to provide the best results, with the highest values of residual compressive stress.



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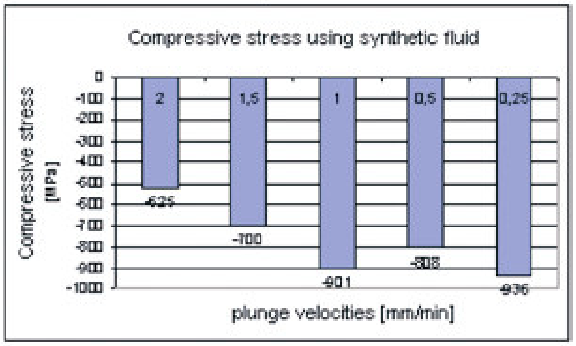

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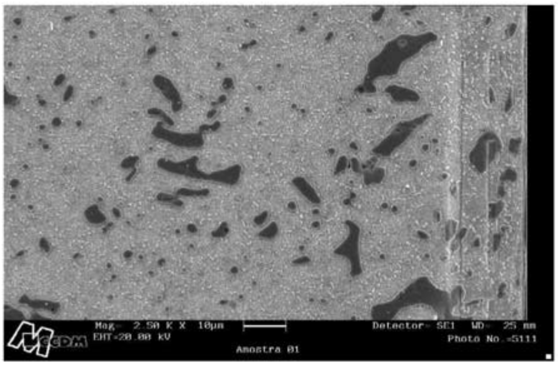
Figure 6. Compressive stress using vegetal-based emulsive oil: a) and synthetic fluid (b) at the five plunge velocities tested.

The CBN grinding wheel, whose grains present high thermal conductivity, is much less sensitive to variations in the quantity of material removed, ensuring residual compressive stresses even after long periods of grinding [11].

Cutting fluids should promote the predominance of the cutting mechanisms instead of plastic deformation without the removal of material (plowing) by maintaining the grinding wheel's sharpness and reducing the workpiece-tool friction coefficient [12]. This reduces the specific grinding energy generated in the machining process [13], reducing the temperature in the cutting region and the possible occurrence of thermal damage. However, this phenomenon does not occur in conventional grinding [14].

Surface Integrity based on Scanning Electron Microscopy (SEM)

The micrographs of the test specimens taken under all the machining conditions tested here were identical, without microstructural alterations. The figures below depicts two of these micrographs.



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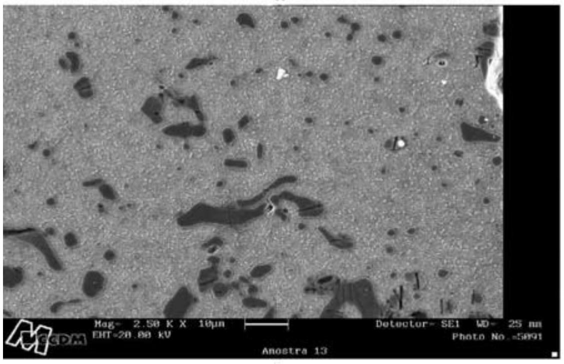

b

Figure 7. SEM micrograph of specimens tested with vegetal-based emulsive oil at a plunge velocity of 2.00 mm/min (a), and 0.25 mm/min (b).

Based on our SEM analyses, no microstructural differences were found to occur when varying the plunge velocity or the type of cutting fluid, since the cutting conditions employed here were not sufficiently aggressive to alter the microstructure of the tempered and quenched ABNT D6 steel. Probably, the amount of heat generated in the process and absorbed by the workpiece during grinding was insufficient to produce subsurface alterations, indicating that the optimized fluid application method provided efficient cooling. Klocke [15] reported similar results in external plunge grinding, using a bolster nozzle (24 l/min) and the MQL technique (215 ml/h).

CONCLUSIONS

This research work, which involved an investigation of the behavior of plunge cylindrical grinding using a superabrasive CBN grinding wheel with vitrified binder at varying plunge velocities, led to the following conclusions:

- At the lowest plunge velocities, corresponding to 0.50 mm/min and 0.25 mm/min, the highest acoustic emission values recorded were obtained when using the synthetic cutting fluid.
- With respect to the grinding wheel's plunge velocity, the roundness error values were similar, but the plunge velocity of 1.0 mm/min provided the best result.
- Our SEM analyses showed similar results for all the velocities and types of cutting fluid used, indicating the absence of surface damage.
- Considering the results obtained with roughness, acoustic emission and tool wear and those obtained for residual stress, roundness errors and SEM, it can be stated that the best results were achieved with the vegetal-based emulsive oil at a plunge velocity of 2.00 mm/min.
- A comparison of the two cutting fluids indicated that the vegetal-based emulsive oil produced the lowest cutting forces and grinding wheel wear, as well as the best results in terms of residual stress, since this oil, compared with the synthetic fluid, provides lower cooling rates and higher lubricating capacity, which reduces the friction and the generation of heat in the grinding region.
- With regard to the roughness values, variations were found that demonstrate a behavior related to the plunge velocity, i.e., higher plunge velocities produce greater roughness.

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