Evaluation of the oil flow using the MQL technique applied in the cylindrical plunge grinding of AISI 4340 steel with cbn grinding wheel

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Abstract

The grinding process is defined as an abrasive cutting action of a tool known as grinding wheel, which is submitted to high rotations, promoting excellent finishing and accuracy in dimensions, respecting the parameters established in each project. During the machining, the cutting edges of the abrasive grains undergo wearing and this increases the contact surface of the tool with the workpiece, increasing the machining temperature and creating possibilities of damaging it. Therefore, it is necessary to use a cutting fluid, responsible for lubricating and cooling the cutting zone, removing the chips from the cutting region between the workpiece and the wheel, and even having an anticorrosive action. However, its composition causes contamination to the environment and to the operator. In face of the increasingly strict environmental laws, it has become necessary to search for new methods of cooling that are at least as effective as conventional one and economically practicable. Thus, the Minimum Quantity of Lubrication was developed as a mist of air and oil applied at high pressure, reducing drastically the use of contaminants. In this work, two oil flows were used for the MQL technique, 30 ml/h and 120 ml/h. The wheel used was a CBN (Boron Cubic Nitride) one, composed of synthetic grains and the workpiece, in a ring format, were produced in AISI 4340 steel quenched and tempered. It was observed from results that MQL can be applied in the industrial processes without losing piece quality.

keywords: cylindrical plunge grinding, minimum quantity of lubrication, cubic boron nitride grinding wheel, AISI 4340 steel.

1. Introduction

The use of abrasives to reach the object's final shape and dimensions comes from over 2000 years ago. Abrasive compounds were used to make knives, tools and weapons. Abrasives may also have been used to cut and shape rocks, such as pyramids, as well as polishing gemstones. Nowa-days, abrasives are being used in many applications and many of the modern technologies depend on the industry to exist. Grinding fits into the abrasive processes, as it contains in its tool, the grind-ing wheel, abrasive grains responsible for removing material from the machined part. For Pereira *et al.* (2009), grinding is a manufacturing process of significant importance, mainly where there is need of precision in the dimensions and low surface roughness. The grinding process is usually the last surface machining process, and therefore has a high added value. Finally, it is one of the most complex machining processes, due to the substantial number of variables present, with many pa-rameters that influence each other (Chen *et al.,* 2002), influencing directly and indirectly in the re-sult.Mainly, due to the elevated temperatures generated by the friction of the grinding wheel and the workpiece, it is necessary to use a cutting fluid. On the other hand, this fluid is responsible for heat transfers with the workpiece (cooling), and is responsible for removing chip and other impuri-ties found or in the workpiece's surface or in the tool, reducing friction and minimizing wheel's wear by acting as a lubricant (Pawlak *et al.,* 2004). However, its composition makes it clear that its use is extremely harmful to the environment and to people who work in uninterrupted contact with this harmful atmosphere. Proper disposal is required, which involves prohibitive costs and complex chemical processes for separating the oil from the water and all the treatments that, from the eco-nomic point of view, makes the conventional method of cooling lubrication many times higher than the cost of the wheel, when considering the total expenses with fluid acquisition, maintenance, fil-tration and disposal (Nguyen and Zhang, 2003). With stricter laws, apparent environmental and health damage, in addition to the prohibitive costs, research into new methods of refrigeration has been made necessary. The search for a better superficial quality (roughness) and the increase of the useful life of the wheel should also be understood as objectives that are completed to the other ne-cessities, like tolerances and surface finishes, for example. The MQL (minimum quantity of lubri-cant), also called "Near-dry machining", works by injecting a mist of air and oil at high pressures towards the machining surface (Pusavec *et al.,* 2014).

In accordance with such prerogatives, it is necessary to study and develop new techniques that minimize the use of conventional cooling methods. Therefore, the objective of this work is to eval-uate the MQL technique, varying the oil flow in the cylindrical grinding process of AISI 4340 steel, as well as the results of surface roughness, circularity deviations, grinding wheel wear, microhard-ness, acoustic emission and vibration.

2. Materials and methods

All the tests were conducted in the Abrasion Machining Laboratory (LUA) from the Faculty of Engineering – UNESP – Bauru, where there was used a cylindrical plunge grinder model RUAP515H from Sulmecânica, equipped with CNC controls from Fagor in order to access the X-axis. Two CNC programs were used; one for the machining of the test pieces and another for the printing of the wear on the grinding wheel surface.

The workpieces used for the tests were made of AISI 4340 steel, quenched and tempered, with a hardness of approximately 58 HRc and have the following dimensions: external diameter of 58 mm, internal diameter of 30 mm and a thickness of 4.5 mm.

For grinding, a Boron Cubic Nitride grinding wheel (CBN) from Nikkon-Saint Gobain was used, with the specification SN-B151Q12VR2. It consists of a vitrified bond with CBN grains, with an external diameter of 350 mm and a thickness of 19 mm.

Table 1 shows the machining conditions adopted in this work.

Table 1
Cutting conditions used in the grinding of AISI 4340 steel.

Grinding process	External cylindrical plunge
Grinding wheel	Cubic Boron Nitride grains
Grinding wheel speed (v_s – m/s)	v_s = 30 m/s
Radial feed v_f– mm/min (Specific rate of removal of material– mm^3/s)	0.50 (1.41)
Workpiece speed (v_w)	v_w = 0.58 m/s
Effective Depth of Cut (a_e)	a_e = 1.2; 2.5; 3.7 μm/revolution
Lubrication-cooling parameters	Conventional (flood) e MQL
Conventional cutting fluid	Emulsion with semi-synthetic vegetable-based oil at a con-centration of 3%
Fluid for the MQL technique	Vegetable based product, biodegradable, viscosity 32 to 39 cSt (40° C)
MQL oil flow	30 ml/h and 120 ml/h
Air Pressure in MQL	0.8 MPa
Workpiece material	AISI 4340 steel, quenched e tempered (58 HRc)
Dresser	Diamond Conglomerate - dimensions 15 mm × 8 mm × 10 mm
Dressing depth (a_d)	a_d = 0.040 mm (20 cycles – 0.002 mm each)
Sparkout (t_s)	t_s = 1.78 s
Dressing speed (v_d)	v_d= 740 mm/min

For this study, two different oil flows were evaluated by the MQL technique in comparison to the conventional (flood) technique, being three parameters analyzed: conventional fluid, MQL 30 ml/h and MQL 120 ml/h. In order to find a tendency line in the results, the cooling system's param-eters had two replications, which aimed to increase the statistical reliability of the process and thus the data obtained.

For the conventional flood cooling system, the semi-synthetic ME-1 cutting fluid from Qui-matic Tapmatic Ltda. was used, with an emulsion corresponding to 3%. For the MQL system, the Accu-Lube LB-1000 fluid from ITW Chemical Products Ltda. where used.

Average arithmetic roughness (Ra) was measured with the help of a Surtronic 3+ rugosimeter from Taylor Hobson. For that, a cut-off length of 0.25 mm and a total path of measurement (ln) of 1.25 mm were adopted. In all measurements, for each test specimen, 10 measurements were per-formed in various positions. In each test body, 3 measurements were performed in distinct positions (120° each).

The wheel width made it possible to perform two tests at each dressing interval. In order to analyze the wear of the wheel, cylindrical workpieces made of AISI 1020 steel with a length of 120 mm and a diameter of 40 mm were used, where they were subjected to machining cycles with feed speed (vf) of 0.50 mm/min, with the objective to print its surface with the relief of the cutting sur-face of the wheel. After printing, with their respective markings, it is possible to study the differ-ences of altitudes between the grinded region and the region that did not perform the grinding. In this way, the diametrical wear of the grinding wheel can be measured using the Taylor Hobson ru-gosimeter with the Talyprofile program of the same brand for computer use. Fig. 2 exemplifies the graph for the respective measurement of the diametrical wear of the wheel.

To determine the microhardness of the sample, the equipment from Mitutoyo, model Mi-croWizhard version 1.04 was used. This machine uses the micro-hardness system on the Vickers scale, using a load of 300g to ease the visualization of indentations at the moment of measurements. For each sample, three sets of indentations were performed, each series representing 6 measure-ments of microhardness tested at distances, equidistant from each other and below the machined surface (indentation of the surface towards the center).

The circularity error, how the piece is not perfectly circular, was obtained by using a Taylor Hobson Tayround 31C circular flowmeter. The gauging mechanism is, in summary, consists of one end of the arm where there is a probe with a diamond tip, being this tip the element that makes con-tact with the part to obtain the deviation.

For the metallographic procedures for analysis of optical microscopy and microhardness, the samples were prepared following these procedures: cutting of the part and its respective inlay, using a metallographic filling machine from Taclago model EM30D. Sandpapers were subsequently used in the following sequence: 80, 120, 220, 320, 400, 500 and 600 grits, and polishing with alumina of 1 µm granulometry. After the samples were chemically attacked using a chemical compound of HNO3 and C2H6O (Nital, in which the acid concentration was 2%), with the aid of an Olympus BX51M microscope belonging to the Laboratory of Anelasticity and Biomaterials of Faculty of Sciences of UNESP, Bauru, the optical micrographs were performed with a magnification of 1000x, enough to detect possible changes in the microstructure of the sample.

3. Results

In this topic, the output data obtained in the experiment of grinding AISI 4340 steel with su-per abrasive grinding wheel (CBN) will be presented. It is interesting to note that, for each cooling parameter, three tests were performed. The values presented in this section are the mean values ob-tained by the analysis of all the workpieces.

3.1 Roughness

The application of the MQL technique causes the formation of an oil and chip mixture that is retained in the machining area, increasing the errors (Alves *et al.*, 2009). The same occurs with cy-lindrical plunge grinding, where a paste forms and remains on the surface of the test piece, damag-ing the quality of the grinding. The obstruction of the wheel (the pores of the grinding wheel struc-ture are filled by chips, fluid and impurities), which occurs principally in the use of the MQL technique, is explained by Oliveira *et al.* (2012), who state that, in addition to increasing the grinding forces and causing a high roughness, it also increases circularity deviations.

Fig.1 presents the results of circularity deviations according to the established cooling param-eters. It is possible to notice similarities between the results of different MQL's oil flows.

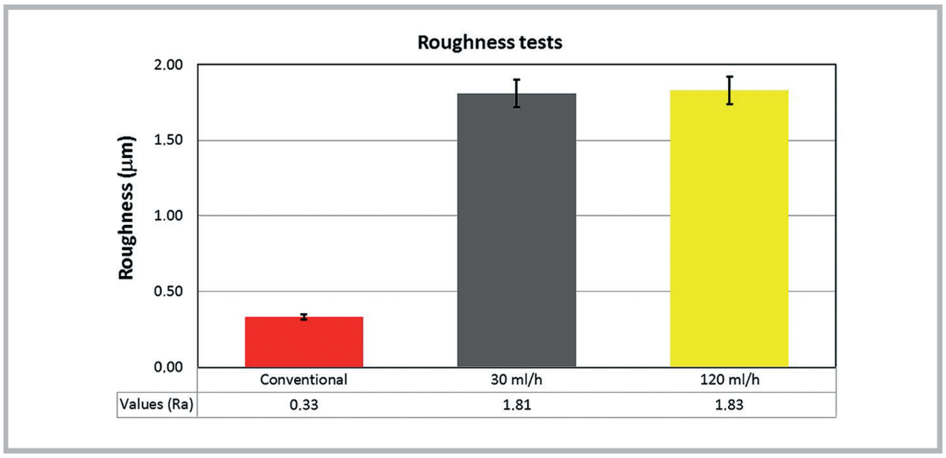

Figure 1
Arithmetic Mean Roughness (Ra) as a function of cooling parameters.

According to Puerto *et al*. (2013), by being a process of abrasive machining, finishing grind-ing, especially for materials of high hardness, the surface roughness is very low (Ra results between 0,1μm to 2,0μm). With these results, it is possible to verify that flood (conventional) cooling is more effective when talking about final surface quality, where the mean roughness for this parame-ter is 0.32 μm, whereas for MQL, the lowest mean roughness was 1.81 μm (when the volume of oil was 30 ml / h).

The resistance of the fabricated components is significantly affected by the surface roughness, due to the fatigue stresses generated by the work to which the pieces are subjected (Malkin & Guo, 2008). Thus, the roughness of a workpiece is directly linked to the cooling technique, the abrasive grain size of the wheel, in addition to dressing conditions, material removal rate and spark-out time.

From Fig. 4 it is possible to note that the roughness values found for the different oil flows in the MQL technique are similar, demonstrating that the amount of oil did not have a major influence on the result. However, as mentioned above, they are higher than that found in the conventional art. At the lowest flow rate, the most likely reason for the high roughness was that there was not enough oil to lubricate the cutting edges that are in contact with the workpiece during machining. At the higher flow rate, the high oil flow may have accelerated the clogging process of the grinding wheel pores by generating a more abundant mixture of oil and chips, while the compressed air flow of the MQL system is sufficient only for cooling and not for cleaning the surface of the grinding wheel, damaging the results of the machining.

3.2 Roundness

In Fig. 2, the circularity values are presented according to the cooling parameters. It is no-ticed that flood (conventional) cooling presents a better result only than that of MQL of 30 ml / h and similar to that of 120 ml / h.

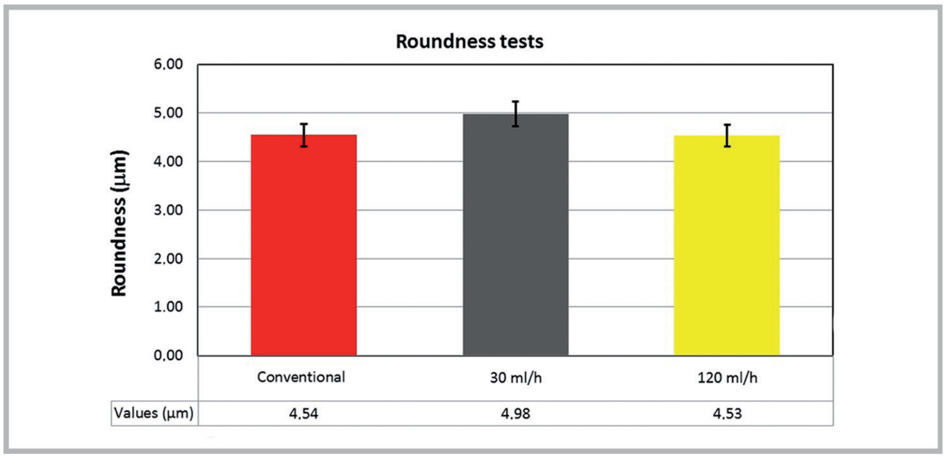

Figure 2
Roundness as a
function of cooling parameters.

According to Wang (2008) the circularity deviation is a value that must be within the toler-ance specifications of the project, since this parameter is significant for the grinding processes.

Some reasons may be able to justify these deviations, such as an inefficient cooling, a misa-lignment of mandrels or a clearance between components in the machine. In addition, the obstruc-tion of the wheel (pores of the tool structure are filled with a mixture of oil, impurities and chips) caused by the MQL technique increases the grinding forces, roughness and circularity (Oliveira *et al*. 2012).

A CBN wheel with higher porosity may be a solution to avoid impregnation of oil with chips in its structure, which has a good combination of abrasive grains and bond material, great chip stor-age capacity, high grinding rate and good dressing response.

3.3 Diametral tool wear

Fig.3 shows the average value of diametral wear for each cooling parameter. A widely used method for evaluating the wear of a grinding wheel is through the ratio G. This relationship is shown capable of measuring the efficiency of the wheel by the ratio between the volume of material removed and the worn wheel volume. That is, a simple division determines the

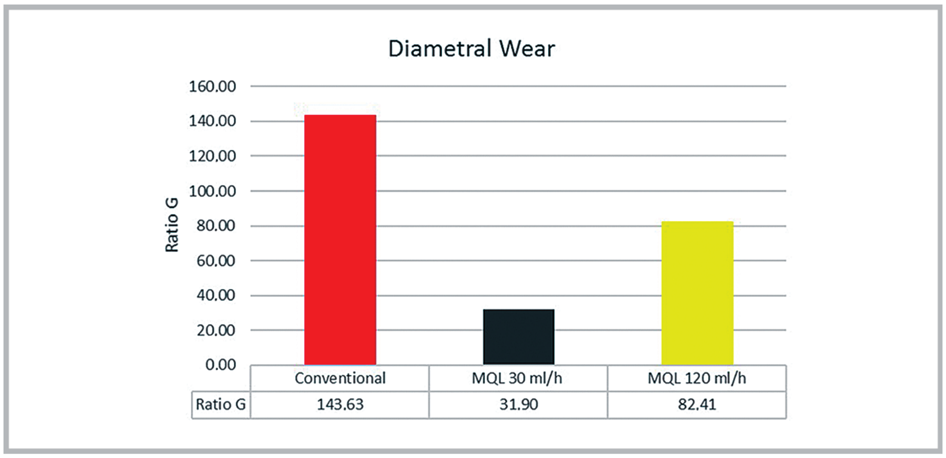

Figure 3
Diametral wear of the grinding
wheel represented by the ratio G.

efficiency of a wheel. According to Jiang *et al.* (2013), wear of the grinding wheel is a strong indication of the use-ful life of this tool, since high wear is related to thermal damage or other unexpected failures in the machined part. It can be stated that the conventional lubrication leads to less wear of the grinding wheel because the higher the value of the G ratio, the lower the wear. In a study by Valarelli *et al.* (2002), in which it compared several parameters resulting from grinding with CBN and Al_2O_3 grinding wheels, it was observed that the G ratio of a CBN grinding wheel is 20 times higher than that of the Al_2O_3 wheel.

Comparing only the values obtained with the MQL lubrication-refrigeration, the wear using a flow of 120 ml/h was the smallest one, showing to be more effective in this wear problem. As in the other analyzed parameters, the tendency is that the wear increases with the decrease of the oil flow from MQL system.

3.4 Microhardness

Fig. 4 shows the Vickers microhardness results, found by measuring six points with three replicates in different parts of the sample, starting from the surface towards the center of the piece, and for this reason the distance to the machined surface. The reason for this would be to determine whether there was an increase in hardness on the ground surface.

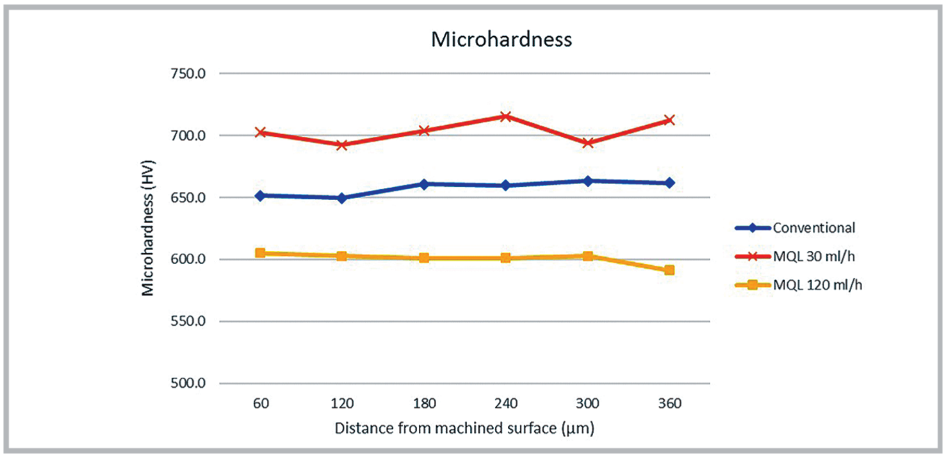

Figure 4
Microhardness as a function of the distance from machined surface.

The results obtained with the microhardness are added to the results of the micrograph, bringing a more complete report and determining the occurrence or not of thermal damages. Fig. 4 shows that the microhardness was higher in the sample that was machined with MQL of 30 ml / h and that the results show a tendency where increasing the oil flow of the MQL, increases the hard-ness. However, the sample that was machined with conventional lubrication-refrigeration obtained an intermediate result, being only smaller than the result obtained with MQL at 30 ml / h. Even with these microhardness differences, it is not possible to conclude that there were thermal damages, since there are not significant changes in the hardness between the distinct levels of the samples in comparison to a not-machined piece of the same AISI 4340 steel.

4. Conclusion

From this present study, it can be concluded that:

- in the analysis of the roughness, noticed is that the conventional cooling (flood) obtained more satisfactory results for the MQL technique. The results obtained for different oil flows in the MQL technique indicate that with a surface cleaning, a smaller amount of oil can be used in order to obtain the same roughness value;
- in the study of the final geometry of the workpiece, circularity deviations were presented similar to the conventional technique as to the MQL with 120 ml/h, while the one obtained for MQL with 30 ml/h was superior to the others. Thus, it is concluded that the MQL technique with 120 ml/h of oil can replace the conventional technique when the geometric precision for the limiting factor in the final quality of the part;
- the MQL technique requires a smaller wheel replacement interval due to lower wear than that obtained by the conventional technique. Thus, under these machining conditions, a lot of time is lost to perform a tool replacement, generating extra costs;
- none of the lubrication-cooling parameters used caused thermal damage to the respective workpieces, according to microhardness profiles, even with the most severe machining condition (30 ml/h of oil). In the micrograph, it was not possible to identify the microstructure, such as burn-ing or loss of carbon, and it was possible to easily identify a martensite matrix of the material;
- given the differences obtained between the results of two oil flows for MQL, it may be de-termined if there is an oil flow between 30 ml/h and 120 ml/h for the MQL technique that provides superior results. It starts with an oil flow of 60 ml/h.

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