Paulo Roberto de Aguiar
Universidade Estadual Paulista - UNESP
Faculdade de Engenharia
Departamento de Engenharia Elétrica
17033-360 Bauru, São Paulo. Brazil

Rodrigo Eduardo Catai
Universidade Tecnológica Federal do Paraná
Departamento Acadêmico de Construção Civil
80930-901 Curitiba, PR. Brazil

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

Roberto de Freitas
Universidade Estadual Paulista - UNESP
Faculdade de Engenharia
Departamento de Engenharia Mecânica
17033-360 Bauru, SP. Brazil

Studies on the Cooling Minimum Quantity and Conventional Cooling at Hardened Steels in Grinding Process

The purpose of this work is to explain the concept of cutting fluids reasonable usage through the fluid minimum quantity in grinding processes. On that purpose, the development of a new nozzle and an own and adequate methodology should be required in order to obtain good results and compare them to the conventional methods. The analysis of the grinding wheel/cutting fluid performance was accomplished from the following input parameters: flow rate variation by nozzle diameter changes (three diameters values: 3mm, 4mm and 5mm), besides the conventional round nozzle already within the machine. Integral oil and a synthetic emulsion were used as cutting fluids and a conventional grinding wheel was employed. The workpieces were made of steel VC 131, tempered and quenched with 60HRc. Thus, as the flow rate and the nozzle diameter changes, keeping steady fluid jet velocity (equal to cutting velocity), attempted to find the best machining conditions, with the purpose to obtain a decrease on the cutting fluid volume, taking into consideration the analysis of the process output variables such as cutting strength, cutting specific energy, grinding wheel wear and surface roughness. It was verified that the 3mm diameter optimized nozzle and the integral oil, in general, was the best combination among all proposed.
***Keywords**: grinding, cutting fluid, grinding wheel, optimized process*

Introduction

One of the finish processes most employed in the precision workpieces manufacturing is the grinding, even being a low technology machining process, when compared to conventional machining processes (drilling, milling and so on). Its performance depends upon the operator's ability and sensibility and the grinding wheel machining conditions. The decisions during grinding are usually taken by the machine's operator, which, despite his many years of experience, not always has theoretical knowledge of the process.

This fact is specially serious in Brazil because conventional grinding wheel are yet widely employed. Those conventional grinding wheel have lower material remotion capacity and surface quality, when compared to superabrasive grinding wheels, especially for grinding operation of high hardness materials (above 50 HRc).

The foreign competition has led the national industries to reach international standards, with even more sophisticated workpieces manufacturing, with high geometrical tolerance degree and superficial finishing, at low cost with no environment pollution. For that reason, the cutting fluids (essential for grinding processes), once discharged straight to the environment, must now have a preceding treatment, according to federal laws, and to a new production concept, which brings the "green stamp". The stamp informs that the processes employed in some workpiece production, do not pollute the environment.

Many researches concerning the cooling quantity decrease have been performed, once the tendency is to decrease the cutting fluid usage at machining processes for many reasons. According to Howes [1], the environmental impacts brought by the industries were not taken as crucial technical factors for some project accomplishment; however, such fact has been meaningfully changed. According to the public opinion and the government rules, the industries have started to behave in such a different way concerning their industrial garbage.

According to Machado and Wallbank [2], the cutting fluids may also bring serious problems, such as health and security problems (the latter the most serious). People exposed to cutting fluids may have contact through their skin, to inhale vapors or even to swallow particles. Such things might cause dermatitis, digestive and respiratory systems problems, and in some cases even cancer, due to its high toxicity. Before the environmental matter, recycling and discharge problems as well as the fluids handling have played their role in the environmental maintenance.

Through their experiences, Howes [1] came to the conclusion that the cutting fluids employed at industries are risky factors for laborers, and also that for the greatest majority of cases, the main effects from the contact with such substances are respiratory and dermatological damages.

According to Gadian (1983) apud Howes [1], the dermatological damages caused by the cutting fluid contact may occur, basically in two ways: skin irritation, through contact, ranging 50% to 80% from all cases; and the allergic effect due to contact, responsible for 20% up to 80% of all cases. The skin irritation is caused by the constant contact with the fluid; however, such effects may be avoided, decreasing the exposure time. The allergy comes from the human skin intolerance before the chemical compounds within the fluids, in which the allergy is not treatable, in such way to be fully healed.

Currently, the cutting fluids industry is researching with the variable pressure, not only to improve their products' performance, but also to protect the environment and to provide health and security. Heidenreich (1985) apud Machado and Wallbank [2] discuss over these problems, and Deodhar (1995) apud Machado and Wallbank [2], point out to procedures in order to control them.

For that, a deeper analysis of the consequences of this type of change concerning the final status of the machined workpiece should be required.

According to Ebbrell et al. [3], the cutting fluid provides many benefits to industrial sector; however these fluids storage is

Paper accepted October 2006. Technical Editor: Atila P. Silva Freire.

inadequate. This way, high amounts of cutting fluids are wrongly employed at industries. As an example of bad employment, at many industries, great fluid dispersion at the machining time, take place, leading to great fluid loss. The lubrication and cooling depend upon the actual fluid intake at the workpiece's cutting region with the tool, with no high fluid volume requirements, even if part of this fluid would not be passing through the adequate region. The type of nozzle positioning performs great influence on the cutting process.

Following Webster [4], some caution should be taken with the employment of water-based cutting fluids, when compared to oil-based cutting fluids, once the first ones have small density, so that great fluid dispersion at the fluid employment to conventional round nozzle, might occur. This way, great cutting fluid quantity is required in order to compensate the dispersion loss, and also the employment of high load machinery, with huge cutting fluid reservoirs, cooling units and high power pumps.

The target of this research are all industries which employ cutting fluids in grindind, with the purpose to rationalize their usage, making machining process possible with meaningful decrease on fluid discharge cost (sometimes up to 30 times the purchase cost), which could only be made by specialized enterprises. So, with the reduction on the fluid volume required in the porcess, there will be a consequent reduction on the discharge cost.

Based on those factors previously described regarding cutting fluids in grinding, which were the motivation of the current research, this work aims at developing a methodology to optimize the quantity of cutting fluid application in grinding process. In general, the results have shown the 3mm diameter nozzle and the integral oil employed were the best choice, among the other combinations studied, into the optimization of the grinding process by using minimum quantity of cutting fluid.

Remarks Concerning the Grinding Process

Grinding Wheel

According to Krar & Ratterman [5], the grinding wheels, most important products manufactured from abrasives, are composed of abrasive grains linked by an adequate bonding material. The main purposes of grinding wheels at the metallurgical industry are: the generation of plane, cylindrical and/or composed (plane and cylindrical) surfaces; the removal of difficult-to-grinding materials, usually hardened ones; the output of good superficial finish with controlled and dimensional errors.

Nailor [6], already assured, back in 1989 that machining with superabrasive grinding wheels should provide a lower cost of production by workpiece, of about 30% up to 50%, comparing to machining with conventional grinding wheels, once machining conditions promote the least weariness as possible of its cutting surface (grinding wheel surface responsible for metal removal from the ground workpiece)

For Klocke e König [7] the grinding process improvement may be only achieved with the employment of superabrasive grains such as CBN. The high performance of the abrasive material is due its extreme hardness and its wear strength, allied to its high temperature resistance and thermic conductibility (heat absorbing capacity). At CBN grinding wheel field, a fast growth of vitrified bonding employment in industries is observed. This type of bonding is fragile and extremely resistant to wearing, and also has good thermic stability. Another meaningful advantage on the employment of bonding at CBN grinding wheels comes from its good porosity and good self-sharpening properties, what usually simplifies the conditioning method.

Cutting Fluids

In the grinding process, the chip originated from the material removal begins through the action of several cutting edges, aleatory spread and guided in the grinding wheel structure. Following Kovacevic and Mohan [8], this material removal is followed by a high energy requirement.

According to Mayer and Fang [9], Jahanmir and Strakna [10], due to health and environmental agencies pressure, the cutting fluid manufacturers have industrialized "healthier" products for the tool-machine operator and less dangerous for the environment.

The conventional methods for cutting fluids employment are not much different from one another especially under severe employment conditions. In most cases, the stored energy in the fluid during its employment is not enough to overcome the grinding wheel centrifugal force or to penetrate the air barrier around the moving grinding wheel. Following Guo and Malkin [11], the efficiency of cutting fluids is no smaller than 5% and no greater than 30%.

The cutting fluids are shown as an important part of the workpieces manufacturing, through chips removal, within a context including the operating machine, the cutting tools, the workpieces output and the cutting fluids [12].

In some cases, the cutting fluids employment at machining might reduce costs, increase output and generate profits, since the adequate type of cutting fluid is chosen. This chosen cutting fluid must also follow specific machining conditions, in which it will be exposed to, thus allowing its better performance [13].

Following Minke [14], the great friction from the grinding process is such an important factor, which takes place in the machined workpiece final status. This way it's so important the development of fluids with higher friction reduction capacity in order to turn machining ecologically and economically viable.

Metodology

For the performance of the tests and of the studies on the influence of process intake parameters (type of cutting fluid employment, type of employed cutting fluid and type of grinding wheel), were developed a set of tests, which could express the obtained results adequately. The set of tests was divided into two parts: computational and mechanical, this last one composed by a CNC cylindrical grinding machine, manufactured by SulMecânica enterprise.

Computational Part

For the acquirement of cutting tangential force values (from the electric power signal of the main spindle motor drive), and the grinding specific energy in real time, a program in the so-called LabVIEW software was developed, employing a data acquisition board from National Instruments enterprise.

The LabVIEW program records the voltage values related to the electric power required to drive the motor. With the electric power values (P_e), the grinding wheel rotation (n) and the grinding wheel outer diameter (d_s), the cutting tangential force is obtained (F_{tc}), which is calculated by the equation (1):

$$F_{tc} = \frac{2 \cdot P_e}{d_s \cdot n} \tag{1}$$

Thus, with the cutting tangential force measurement and with the grinding wheel rotation values (n), the grinding wheel peripheral velocity (v_s), the grinding width (b), the infeed rate (V_f) and the workpiece diameter (d_w), the specific grinding energy (u_c) is easily monitored in real time on the window program for data acquisition, through the equation (2):

$$u_c = \frac{F_{tc} \cdot v_s}{b \cdot d_w \cdot v_f \cdot \pi} \quad (2)$$

Mechanical Part

Besides the computational part, the set of tests was composed by a cylindrical grinder, in which the workpiece to be machined was fixed. In that purpose, two types of fluids were employed (a 5% emulsion and a integral oil). Four cutting fluid employment methods were also employed on the workpiece. The first one through a conventional nozzle (with 6mm of diameter), and the other three with round nozzles of different diameters (3mm, 4mm and 5mm). Figure 1 shows the cylindrical grinding machine (model RUAP 515 H-CNC), the workpiece, the optimized nozzle of 3 mm of diameter and one of the grinding wheels employed during the test.

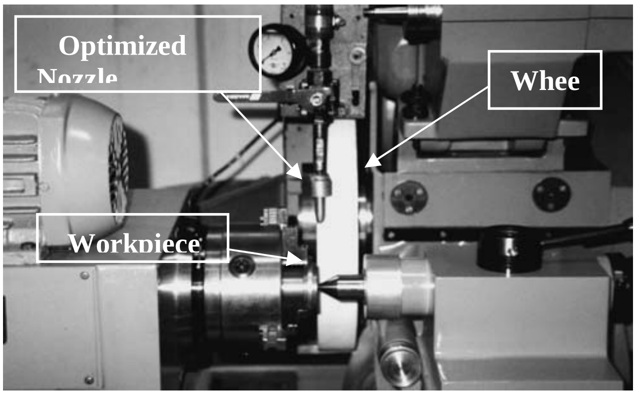

Figure 1. General disposition of employed components.

The output speed of the cutting fluid was controlled through a butterfly valve and the pressure by a manometer for all the nozzles and tests. It is important to point out that for all nozzles, except for the conventional one, the unity ratio proposed by Webster [4] was employed, that is, the output velocity of the cutting fluid at the nozzle was always equal to the grinding wheel speed at 33m/s steady for all tests. The nozzle position was kept the same and standardized for all nozzles.

The material of test specimens was the VC 131 steel, tempered and quenched, 60HRc, in a cylindrical shape. A number of 100 grinding cycles for each workpiece were performed (whereas each grinding cycle removed 0.1mm from the diameter of the workpiece), for all tested nozzles. The grinding wheel used was an aluminum oxide (conventional) whose especification is 38A46KVS.

The cutting conditions applied in the grinding tests were: cutting speed (v_s)=33m/s; workpiece diameter (d_w)=60mm; spark-out time of 8 seconds; infeed rate (v_f)=1.5mm/min; h_{eq}=0.025µm; grinding wheel penetration (a)=100µm, grinding width (b)=3mm.

At the end of each test, the roughness measurements as well as the grinding wheel radial wear marking were performed in a 1020 steel piece reserved for this purpose as shown in Figure 2.

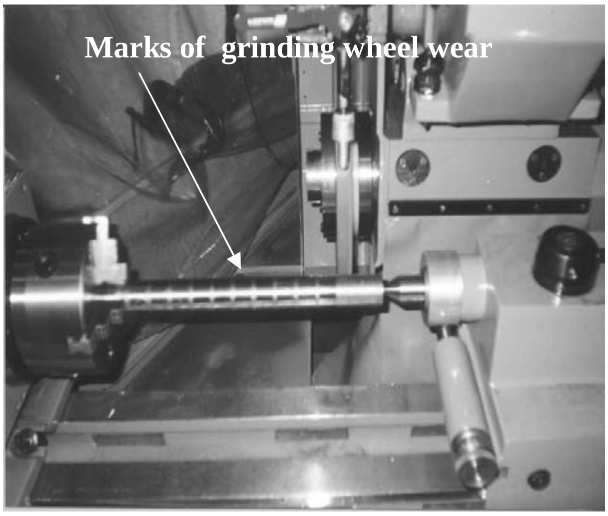

Figure 2. Grinding wheel diametral wear measurement.

Results and Discussion

Cutting Tangential Force

The Figure 3 shows the cutting tangential force behavior through the samples collected during the grinding process.

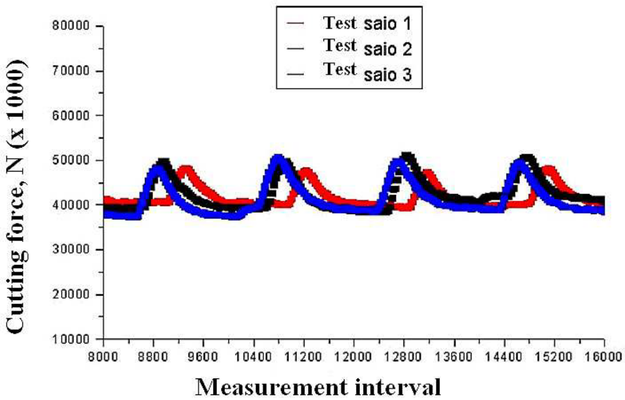

Figure 3. Example of cutting force behavior and the points acquired during grinding process.

In order to get a better comparative effect, three repetition tests for the same machining condition were performed: cutting fluid, grinding wheel, infeed rate and nozzle diameter. The cutting tangential force analysis was obtained through a filter algorithm by mathematical software and the maximum values of each grinding cycle were taken. There are four grinding cycles in Figure 3. From the maximum values, a mathematical average was calculated in order to be reached a convenient value, possible for a comparison with the other test conditions proposed by the research. Figure 4 shows the effective cutting tangential force results comparatively for the types of nozzles and fluids employed.

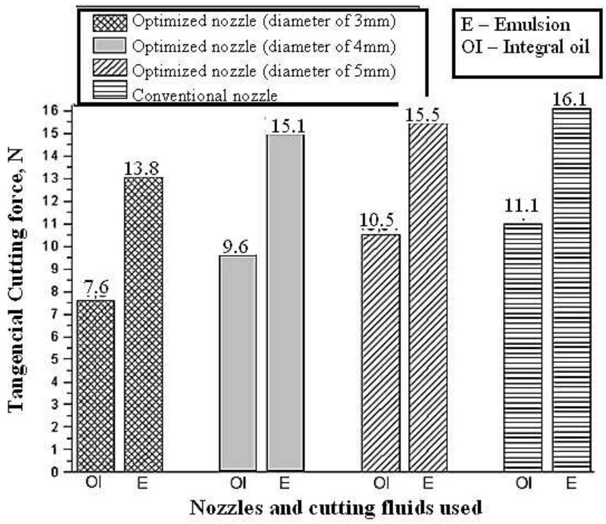

Figure 4. Tangential cutting force to the differents nozzles and types of cutting fluids employed.

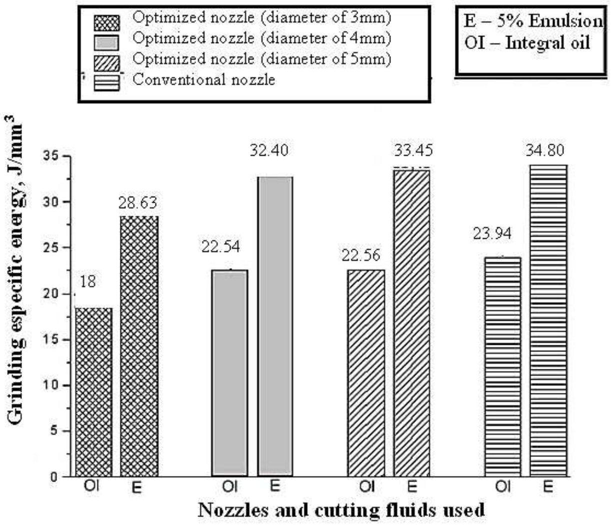

Figure 5. Grinding specific energy to the differents nozzles and types of cutting fluids employed.

Analysing Figure 4, can be noticed that the 3mm diameter optimized nozzle, employing integral oil as fluid, was the one with best performance, proving its efficiency, manufactured for this research. Generally analysing, can also be observed that the integral oil behavior was better than the fluid 5% sinthetic emulsioin-base. This phenomenon is explained by the following factors: the oil lubricating power is greater than the emulsion's power and the integral oil is denser than the emulsion, what makes it to break the air barrier between the workpiece and the tool, both running, reaching the cutting region easier and more effective than with the emulsion employment.

Concerning the variations, for the same nozzle (concerning the greatest variation, 3mm diameter optimized nozzle), the tangential force, with emulsion employment, was 72% greater than the integral oil employment. For a wider analysis, the efficiency for the smaller nozzle with integral oil was 112%, comparing to the conventional nozzle with 5% synthetic emulsion.

Therefore, the manufacturing and employment of smaller diameter nozzle, with integral oil employment, was the most effective condition in all research for the effective cutting tangential force. For the same nozzle diameters, the emulsion-base fluid was effective, but only when compared to the same, once it has lower performance comparing to the integral oil.

Grinding Specific Energy

The grinding specific energy was obtained straight from a relation between the effective cutting tangential force and the cutting velocity. In the same way for the cutting force, the values were filtered and further each cycle maximum values were collected and an average was calculated from the three tests, in order to facilitate the performance analysis of each nozzle and each fluid employed, as shown in Figure 5 (grinding specific energy and employed nozzles for both types of cutting fluids).

The integral oil had better lubricating power than the synthetic emulsion, what makes it to reduce more easily the energy spent on the workpieces in the grinding process. Analyzing the 3mm diameter optimized nozzle, the integral oil has a performance of 54% comparing to the emulsion-base fluid, once due to the phenomenon of breaking the aerodynamic barrier within the workpiece and the tool (moving), the integral oil fluid jet is even more directed towards the grinding region. For this, the tool has a lower friction force (against the movement) to overcome and, therefore, less energy is required.

The best performance on the grinding specific energy reduction was with the employment of smaller diameter nozzle together with the integral oil fluid employment, which has an improvement range of 86% comparing to the conventional nozzle.

Roughness

The roughness was measured at four different points of the workpiece for each machining condition. From these values, the arithmetic average was calculated as shown in Figure 6.

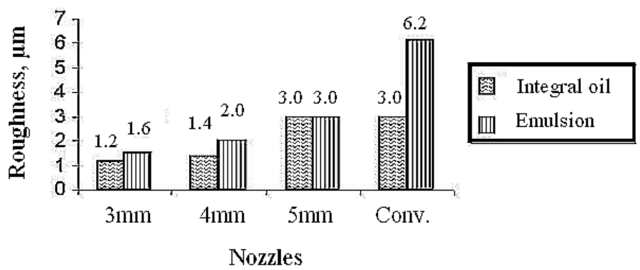

Figure 6. Surface roughness in the workpieces after of the use of different nozzles.

The roughness values, when the emulsion-base fluid was employed, were greater than when integral oil was employed, due to the oil higher density and lubricating power, what leads to a better superficial finish.

A progressive increase of the superficial roughness values was observed with the increase of the employed nozzle diameter and with the change from emulsion to integral oil, once the fluid jet pressure at the grinding region decreased, then leading to a lower effectiveness of process concerning the finish.

The equal values observed for the 5mm diameter and the conventional nozzles with the employment of integral oil fluid are due to two important factors: the efficciency loss of the pump, as it would not distinghish the required pressure for the respective nozzle as well as temper problems, bringing on the workpiece's final regions to have alike properties, even with the proposed variations for the tests.

For the conventional nozzle, the great difference between both fluids employed for the tests (107%), is due to the difference of density between them, bringing about, for the integral oil, the breaking of air barrier between the workpiece and the cutting tool, and therefore, making the lubricating properties to be better applied.

The 3mm diameter optimized nozzle along with the integral oil fluid was the condition that best showed the superficial finish, in other words, the lowest roughness. The jet pressure at this condition is better directed toward the cutting region, together with the fluid highest density. That makes the toll to work with lower cutting force, and to improve the workpiece finish.

In a more general analysis, there was a great roughness variation when values from 3mm diameter nozzle with integral oil and from conventional nozzle with sinthetic emulsion-base fluid are compared, 440% approximately, showing the outstanding outcome of this nozzle for outer cylindrical grinding process.

Grinding Wheel Wear

The grinding wheel wear was acquired for all tests performed with aluminum oxide grinding wheels. For each machining condition, a value from this variable was measured, and then the Figure 7 was built.

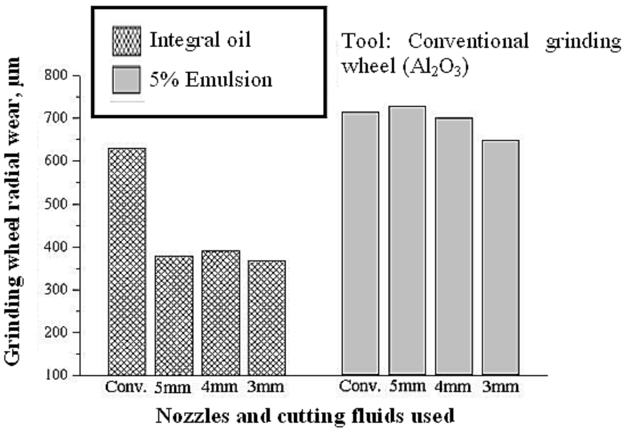

Figure 7. Grinding wheel radial wear to the differents nozzles and types of cutting fluids employed.

The grinding wheel wear is straight related to the cutting tangential force and, consequently, to the employed fluid lubricating property. The integral oil has the required preperty better than the 5% synthetic emulsion, and since the cutting force increased as the nozzle diameter increased; the wear also followed this behavior.

The "breaking" of the wear growth by the 4mm and 5mm diameters nozzles with integral oil and synthetic emulsion fluids respectively, is due to the differents quenchs of each tested workpiece, leading to different variations in the tool wear. Factors such as the pump non-accuracy and the fluid density, as explained for the preceding variables, also apply to these results.

It is interesting to notice the values next to the 4mm and 5 mm diameter nozzles for both cutting fluids. The phenomenon that explains such fact is the pump "inaccuracy", once for this range of power to be supplied, the pump cannot distinguish it.

Figure 8 highlights the 3mm diameter conventional and optimized nozzles results for both employed fluids.

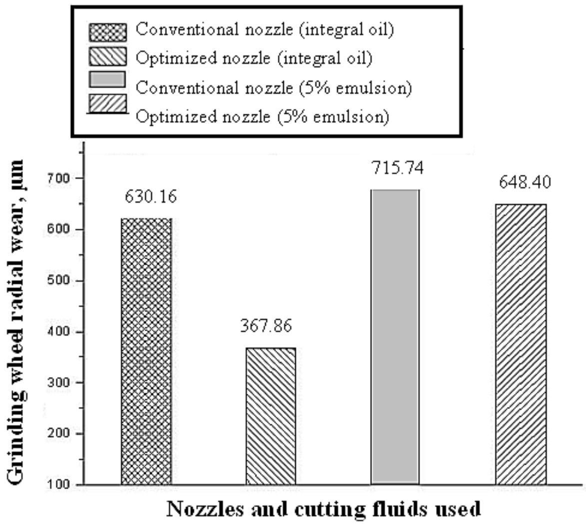

Figure 8. Analysis of grinding wheel radial wear to the optimized and conventional nozzles.

The Figure 8 shows that 76% and 16% were the differences between the optimized and conventional nozzles respectively, with the employment of integral oil and synthetic emulsion-base fluids, proving, once again, the great importance of the lubricating property and the oil density, and 95% was the greatest difference for the output variable, that is the grinding wheel wear due to the low cutting force, explained by the lower tool effort, better fluid guiding and also better oil lubrication; such factors decrease the friction force, which acts against the material cutting, there was a smaller material loss from the aluminum oxide grinding wheel, leading therefore, to a smaller wear relation for the employment of 3mm diameter nozzle, along with integral oil.

Conclusions

The 3mm diameter optimized nozzle, manufactured for this research, along with the employment of integral oil, was the best combination among all proposed, for the great reductions of values from the output variables.

In order to get a better finish and a longer tool useful life, fluid must be applied effectively between tool and workpiece, and the smallest nozzle performed the task successfully. It also decreased the tool effort (and consequently its wear), due to its better guiding and higher fluid jet pressure.

The roughness was also reduced with the employment of the integral oil and the 3 mm optimized nozzle, bringing advantages and better superficial finish.

Concerning the worldwide reality, which employes the least amount of cutting fluid on grinding processes as possible, with no damage for the process at all, it can be observed that the employment of optimized rather than conventional nozzles was extremely viable and favorable, once the conventional nozzle runs with a higher cutting fluid quantity at the grinding zone.

References

[1] T. D. Howes, H. K. Toenschoff, W. Heuer, Environmental Aspects of Grinding Fluids. CIRP Grinding STC Keynote Paper, August 1991.

[2] A. R. Machado, J. Wallbank, The effect of extremely low lubricant volumes in machining. Universidade Federal de Uberlândia, Minas Gerais, Brazil; University of Warwick, Conventry, UK; 1996, p 76-82.

[3] S. Ebbrell, N. H. Woolley, Y. D. Tridimas, D. R. Allanson, W. B. Rowe, The effects of cutting fluid application methods on the grinding process. International Journal of Machine Tools & Manufacture, School of Engineering, Liverpool John Moores University, Liverpool L3 3AF, UK. 8 June 1999.

[4] J. Webster, Optimizing coolant application systems for high productivity grinding. ABRASIVES Magazine, October/November de 1999.

[5] S. F. Krar, E. Ratterman, Superabrasives: Grinding and Machining with CBN and Diamond. McGraw-Hill, Inc., USA. 1990. 196 p.

[6] B. Nailor, Truling parameters for conditioning vitrified bond wheels. INTERNATIONAL CONFERENCE, 27.Illinois: GE Superabrasives, 1989. 20p.

[7] F. Klocke, W. König, Appropriate Conditioning Strategies Increase the Performance Capabilities of Vitrified-Bond CBN Grinding Wheels. In Annals of the CIRP. 1995. Vol. 44/1, p. 305 – 310.

[8] R. Kovacevic, R. Mohan, Effect of high speed grinding fluid on surface grinding performance. SME Technical paper MR95-213, 1995, p. 919-931.

[9] J. E. Mayer, G. P. Fang, Diamond grinding of silicon nitride ceramic. Machining of advanced ceramics Conf. NIST, julho de 1993, p. 171-183.

[10] S. Jahanmir, T. J. Strakna, Effect of grinding on strenght and surface integrity of silicon nitride. Machining of advanced ceramics Conf. NIST, July of 1993, p. 263-277.

[11] C. Guo, S. Malkin, Analysis of Fluid Flow through the Grinding Zone. ASME Journal of Engineering for industry, Vol. 104, 1992, 427p.

[12] P. R. F. Runge, G. N. Duarte, Lubricants in industries – Production, maintenance and control (in Portuguese). Triboconcept, Technical Editions, p. 71-171, 1990.

[13] M. F. Motta, A. R. Machado, Cutting fluids: Types, functions, selection, application methods and maintenance (in Portuguese). Machining and Metals Journal (Revista Máquinas e Metais), sept. 1995, p. 44-56.

[14] E. Minke, Contribution to the Role of Coolants on Grinding Process and Work Results. 3rd International Machining & Grinding Conference, Westin Hotel - Cincinnati, Ohio. October 4-7 of 1999.

