INCREASING TOOL LIFE IN GRINDING THROUGH CUTTING FLUID SUPPLY WITH SHOE NOZZLES

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Abstract. *The appliance of high speed grinding and the utilization of CBN grinding wheels are trends in the machining universe. The characteristics of the grinding process are the high generation of heat, due to plastic deformation, and friction, being the temperature increase proportional to the wheel speed. The heat generated during the grinding process is transferred to the workpiece, abrasive grain, grinding wheel, bond and environment. This leads to high risk of thermal damage on the workpiece surface as well as to excessive wear of the grinding wheel. Cutting fluids are generally employed, due to the combined lubrication and cooling effect, in order to improve grinding results. However, the simple wetting of the wheel/workpiece interface does not necessarily guarantee better grinding results. It is important to force the fluid into the grinding zone. Therefore, different methods of fluid supply are employed. In this study, a free jet nozzle and a shoe nozzle have been used with the aim to investigate the influence of the cutting fluid application method on grinding. The investigations have shown that the utilization of a shoe nozzle led to low tool wear even under low coolant flow rates.*

Keywords: *grinding, cutting fluid, CBN, shoe nozzle*

1. Introduction

It is well known that cooling and lubrication play a decisive role in abrasive processes. Specially in grinding, the heat produced is critical in terms of workpiece quality and tool wear. However, in many cases, the utilization of cutting fluids does not have the necessary attention. Generally, for the optimization of the grinding process, variables as cutting speed, feed rate, dressing conditions and grinding wheel properties, among others, are used as a kickoff. Moreover, many manufacturing industries have shown a preoccupation concerning environmental aspects related to cutting fluids. Therefore, efforts to reduce environmental impacts caused by cutting fluids trough the minimization of its utilization, application of more efficient supply methods, or search for possible environmentally friendly alternatives, are concentrated at research institutes and academic field.

In order to achieve better process results in respect of economical, technological and ecological aspects, a more efficient cutting fluid supply should be idealized. The efficiency of cutting fluid application while grinding with CBN grinding wheels depends not only on coolant type and composition but also on supply pressure, flow rate, nozzle design and velocity of delivery. Therefore, problems with the boundary layer of air around the wheel circumference, which restricts the flow of cutting fluid onto the grinding zone, and the chemical affinity of CBN to the overheated water vapor, should be considered for the correct application of cutting fluid.

Considering the importance of aspects related to cutting fluid application in manufacturing processes, mainly in grinding, the present paper discusses the influence of the cutting fluid supply method on the grinding process of nodular ductile cast iron with CBN grinding wheels.

2. Cutting Fluid Application in Grinding

According to the norm DIN 51385, the cutting fluids are divided into water-based and oil-based ones. In grinding with CBN grinding wheels both kinds are applied, but major of processes with this kind of abrasives use oil-based coolant-lubricant fluids (Oliveira, 2003; Tonshoff, 1995). The main reason to restrict the cutting fluid to oil based fluids is the wear of the CBN grains, which is higher when in applications with water-based coolants (Beck, 2002; Brinksmeier, 1999; Oliveira, 2003; Wittmann, 2000).

As suggested by König (1989), one of the possible causes of the high wear while grinding with water-based coolant is the chemical affinity between the overheated water vapor and the boric oxide layer of the abrasive grains, resulting in high chemical wear of the grains.

Even though the appliance of a water-based coolant offers a less favorable condition to the grinding process with CBN wheels, in many cases its applicability is related to the workpiece material (Wittmann, 2002). The type of the ground material influences the contamination of the coolant, which acts directly over the filtering process (König, 1989). For the maintenance of the characteristics in a grinding process, the cleanness of the coolant is indispensable (König, 1989; Wittmann, 2002). According to Webster *apud* Oliveira (2003), filtering systems which work with coolants as integral oils require two times more capacity of cooling and filtering than it is required for systems which work with water-based coolants.

An example of that is the appliance of emulsion on grinding of cast irons using CBN grinding wheels. Even though the oil is more proper for grinding with CBN wheels, the costs of the filtering of graphite particles can turn the gains of a longer wheel lifetime non viable. The oil has a higher viscosity than the emulsion, being for this reason, more difficult to be filtered (König, 1989; Wittmann, 2002).

Not only the type of coolant which is used, but also the way it is applied are both determinant to the achievement of better results on grinding (Beck, 2002; Brinksmeier, 1999; Chen, 2002; Klocke, 1997; Klocke, 2000; Oliveira, 2003; Rowe, 2000; Webster, 1995; Wittmann, 2000; Wittmann, 2002). According to several authors (Beck, 2002; Klocke, 1997; Klocke, 1997a; Wittmann, 2002) the most applied conception of coolant supply systems on the industry is the one called "free jet nozzle". In this case the coolant has its direction set to the grinding zone through a tube, flexible hose, or other similar conductor. Next to the contact zone the coolant leaves the tube and at least a fraction of fluid reaches the grinding zone. With such a nozzle high flow rates are generally applied.

Especially in high speed grinding, while using free jet nozzle, the air layer formed around the grinding wheel turns it more difficult for the coolant to reach the grinding zone (Beck, 2002; Brinksmeier, 1999; Oliveira, 2003; Rowe, 2000; Webster, 1995; Wittmann, 2000). The air is accelerated by the rough surface of the grinding wheel, which leads to the formation of an air cushion. The pressure of the air cushion and the air flow direction, which is opposite to the direction in which the coolant is provided, turns the cutting fluid application inefficient (Rowe, 2000).

Rowe *et al* (2000) carried out tests to investigate the effects the air flow could cause on the supply of coolant. A "fluid tank for static delivery" has been applied, as illustrates Figure 1. The tests have been made for the flat surface grinding process, where a wheel with a diameter of 178 mm has been applied. The cutting speed was 33,5 mm/s. The coolant has been flown into the tank while the grinding wheel was in contact with the workpiece. Thereafter the wheel has been brought far from the workpiece, using increments of 20 μm, and the volumetric flow rate between wheel and workpiece has been measured at each step. The results have shown that for distances below 80 μm, there was no flow through the gap. It happens because a significant portion of air which reaches the grinding zone is reverted at the proximity of the minimal gap between tool and workpiece. The air with reverse direction in relation to the cutting fluid direction has enough power to "push" the coolant out from the grinding zone.

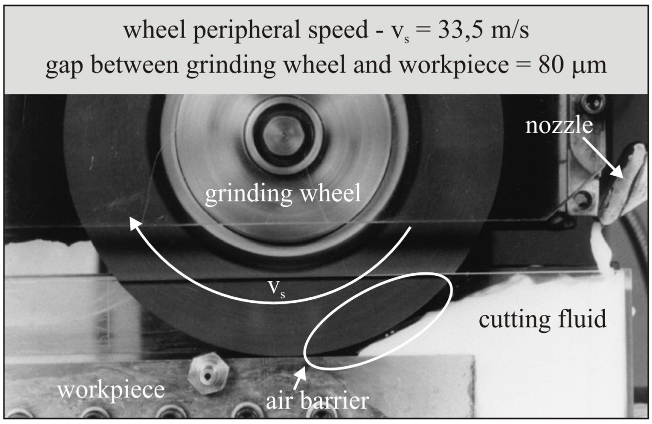

Figure 1. Boundary layer effects (Rowe, 2000)

To break this air cushion the coolant requires kinetic energy (Beck, 2002). The solution generally used as a kickoff to improve the process is to increase the flow rate. But, according to Webster *apud* Oliveira (2003) and Wittmann *et al* (2002), the coolant flow rate applied in the grinding process is not directly related with its efficacy in the grinding zone. A bad positioned jet of coolant, deflected, with low speed or excess of dispersion on the outlet orifice combined with a grinding wheel with low porosity, can influence the quantity of coolant which effectively reaches the grinding zone (Oliveira, 2003; Chen, 2002). Some authors, as Rouse *apud* Oliveira (2003) and Webster (1995), considered that to increase the efficiency of fluid supply, its speed at the outlet of the nozzle should be increased until the cutting speed of the wheel.

This unitary fraction between cutting speed and coolant speed can be proper to some processes, but the tendency of using higher cutting speeds in grinding (Jackson, 2001; Muckli, 2000) turns the use of this method non viable. To reach those speeds usual in high speed grinding, it is necessary to implement pumps with elevated pressure and flow rate, which increases the consume of energy on the coolant delivery system. Moreover, increasing energy consume means ecological and economical disadvantages (Klocke, 1997; Oliveira, 2003).

In a grinding process, for example, supplying coolant through a free jet nozzle with a rectangular cross section of 25 x 2 mm (A_s = 50 mm^2) requires a flow rate of 300 l/min of fluid to reach a jet speed of 100 m/s. Furthermore, the increase of coolant pressure leads to the formation of high rates of fluid mist, and mainly regarding integral oils, it results in a workplace with explosive air oil mixture, which means risks for the machine integrity and for the machine operator (Oliveira, 2003). For these reasons, methods to reduce the effects of the air boundary layer, and consequently the necessity of high pressures and high flow rates, are being developed (Brinksmeier, 1999). One method consists in employing an air scraper (Heuer *apud* Brinksmeier, 1999). This blank should be positioned and adjusted to the grinding wheel by grinding, to provide an effective result. Moreover, the blank must be constantly repositioned because of the reduction on the wheel diameter caused by wear and dressing procedures.

One possibility to combine the employment of a scraper as a barrier for the air boundary layer with a high speed coolant delivery (close to the grinding wheel speed) is to use a shoe nozzle (Beck, 2002; Brinksmeier, 1999; Klocke, 1997; Klocke, 2000; Muckli, 2000; Webster, 1995; Wittmann, 2000; Wittmann, 2002). The shoe nozzle is adjusted to the wheel profile by grinding, until the gap between the nozzle and the wheel is restricted to the empty spaces between the grains. Thereby, the air boundary cushion is deflected and, while comes in contact with the cell full of coolant inside the nozzle, the wheel works as a pump, accelerating and directing the coolant which is inside the wheel pores to the grinding zone. Figure 2 shows a schema of the shoe nozzle action while "pumping" coolant to the grinding zone and forming a barrier to the boundary layer of air.

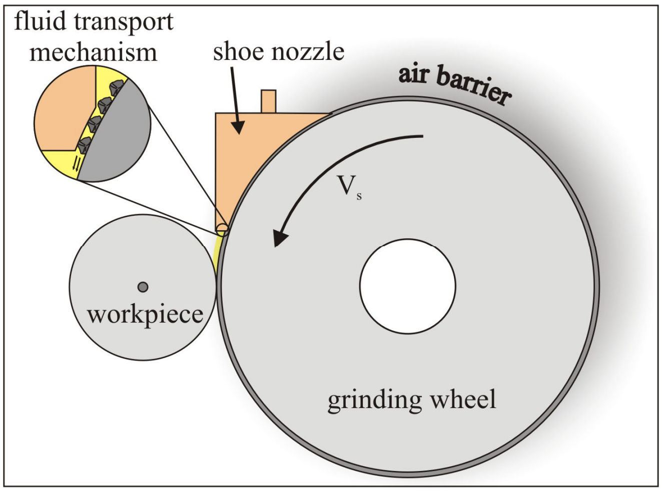

Figure 2. Fluid transport mechanism by the rotation of the grinding wheel

In grinding, efficient lubricating-cooling of the grinding zone results, generally, in improvement of work results, as it can be observed on the diagram concerning radial wear of the grinding wheel (Figure 3).

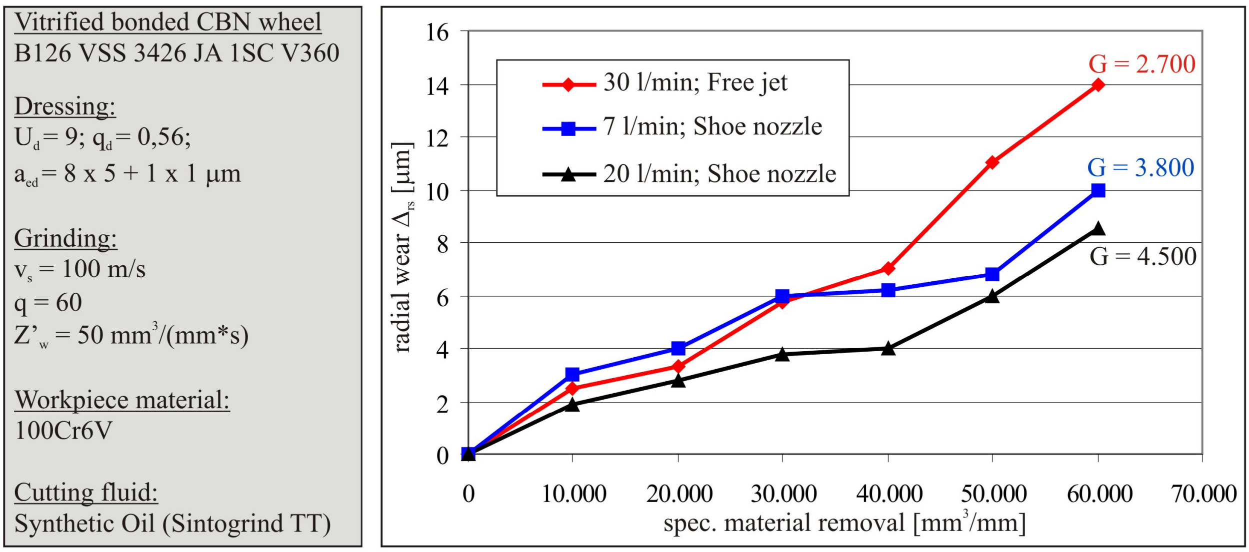

Figure 3. Increase of the G-ratio by using the shoe nozzle (Klocke, 2000)

In Figure 3 (results obtained by Klocke *et al,* 2000) is presented a comparison between free jet nozzles and shoe nozzles in coolant supply for the external cylindrical grinding process of the material 100Cr6V by using a vitrified bonded CBN wheel. As coolant-lubricant fluid, synthetic oil “Sintogrind TT” has been applied. Using the shoe nozzle and a flow rate of 20 l/min the G-ratio was approximately 4.500, while with the free jet nozzle and a flow rate of 30 l/min, it was approximately 2.700. When the shoe nozzle was used, also better results concerning the quality of the surface were obtained, expressed by the decrease of the roughness values R_z. These results are complemented by the experiments carried out by Heuer *apud* Brinksmeier (1999), Beck (2002) and Wittman (2000), who also stated the advantage of less burning of the workpiece surface by applying the shoe nozzle, even using low quantity of fluid and low supply pressures.

The employment of the shoe nozzle propitiates also goods concerning environmental aspects. With the shoe nozzle it is possible to reduce the required quantity of coolant for the grinding process (Beck, 2002; Brinksmeier, 1999; Brinksmeier, 2000; Klocke, 1997; Klocke, 1997a; Klocke, 2000; Oliveira, 2003; Wittmann, 2000; Wittmann, 2002). Comparing the shoe nozzle with the free jet nozzle, for the same work result, it is possible to reduce up to 90% the volume of coolant with the shoe nozzle (Brinksmeier, 2000; Wittmann, 2000).

Another important point is related to the magnitude of the gap between grinding wheel and nozzle, and consequently the size of the orifice through the one the coolant flows out. This is presented as one of the main disadvantages on using the shoe nozzle (Klocke, 1997; Klocke, 2000; Wittmann, 2000). The wear of the grinding wheel and the volume of abrasives removed by the dressing process make the diameter of the wheel to be reduced, which leads to larger gap between wheel and nozzle. On this account, it is necessary to adjust the distance between wheel and nozzle each time the optimized configuration reaches the limit. Beck (2002) verified the influence of this distance on coolant providing by running tests to different distances in a range up to 2 mm. The evaluation has been made with basis on the visualization of the coolant flow inside the nozzle. The results have shown that the distance between nozzle and wheel influences not only the jet development, but also the amount of air which enters into the nozzle through the gap. With the increase of this distance, the angle in which the coolant flows out is increased and the jet is more dispersed. For distances over 0,5 mm, Beck (2002) verified that the amount of air inside the nozzle has considerably increased, leading to the formation of suds and to difficulties in obtaining a coolant film around the wheel.

3. Experiments

To evaluate the influence of the coolant providing system on the grinding process, experiments of external cylindrical plunge grinding have been carried out. The machine tool used was a CNC grinding machine, manufactured by ZEMA Zscelics Ltda, model Pratika Flexa-600L.

The material used in the experiments was a perlitic nodular cast iron, classified according to DIN 1693 as GGG70. As cutting tools two types of CBN grinding wheels were used: a resin bonded and a vitrified bonded. The resin bonded one was a 1A1 300 15 3 127 B126 KSS10 N B V120, provided by Winter do Brasil. The vitrified bonded wheel was a 14A1 V B151 C150 CB7 18B12 ST, provided by Dr. Kaiser do Brasil.

The dressing tool used for the resin bonded wheel was a 1A1 100 15 3 20 D301 BZ 469 E C100 diamond profile roller, provided by Winter do Brasil. The sharpening has been made using aluminum oxide blocks. The vitrified bonded wheel has been dressed using a RI40 IN2515 110 0,8 6 40 10 TK D251 C150 diamond disc, provided by Dr. Kaiser.

In the experiments a water-based lubricant-coolant emulsion with a concentration of 5% of oil ECOCOOL MH 6.000, provided by Fuchs do Brasil, has been used.

The free jet nozzles employed in the experiments with the resin bonded wheel were the original from the machine and consist of 4 flexible segmented hoses with 110 mm² of circular section area. With the CBN vitrified bonded wheel a free jet nozzle with 50 mm² of rectangular section area has been used.

Two shoe nozzles have been manufactured for the experiments, being each one for a respective wheel type. In all the experiments carried out (except in the one presented at the item 4.3), the theoretical gap between nozzle and wheel was zero, i.e., the nozzle was adjusted to the wheel by grinding and left at the same position during the machining process.

4. Results

At the item 4.1 the results obtained with the CBN resin bonded grinding wheel are presented and in the items 4.2 until 4.4 are presented the results obtained with the vitrified bonded grinding wheel. In each following diagram of grinding wheel radial wear, the marked points represent the average value of four measurements made in equidistant points along the workpiece circumference.

4.1 Influence of the nozzle type on the grinding wheel radial wear of the resin bonded wheel

With the employment of CBN resin bonded grinding wheel, the first considerable difference noticed between the appliance of free jet and shoe nozzles was the quantity of sparks generated (Figure 4). Even for a flow rate (Q_{CL}) four times lower in comparison to the free jet nozzles, and for the same specific material removal rate (Q'_w) of 10 mm³/(mm.s), the employment of the shoe nozzle propitiated an almost complete reduction in sparks generation. This fact evidences the function exerted by the shoe nozzle, when it minimizes the effects of the air boundary layer around the wheel and orients the coolant to the grinding zone. The grinding wheel radial wear values obtained by using the resin bonded wheel and the correspondent G-ratios are presented in Figure 5.

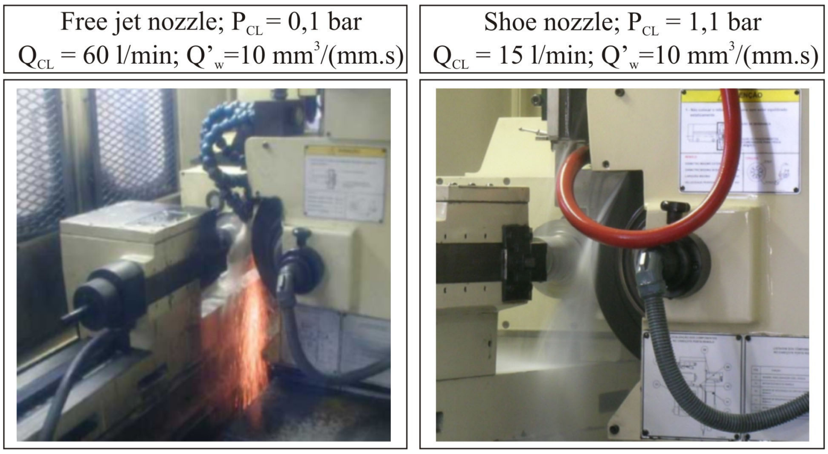

Figure 4. Reduction of sparks generation by employing the shoe nozzle

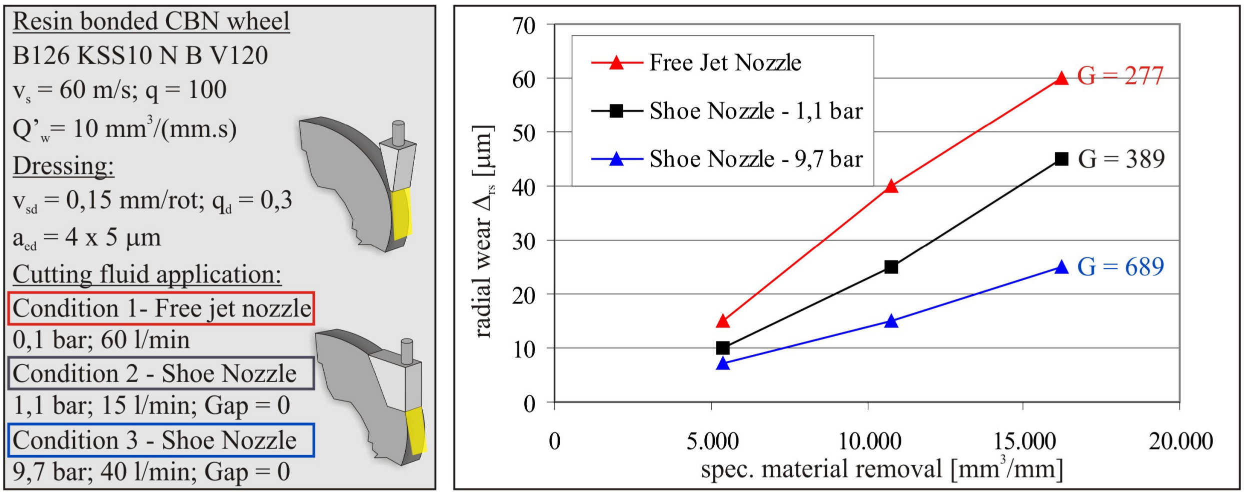

Figure 5: Reduction of the grinding wheel radial wear by using the shoe nozzle and increasing supply pressure.

For a specific material removal of 16.200 mm³/mm grinding wheel radial wear values of 25, 45 and 60 µm have been measured, respectively for the employment of the shoe nozzle with supply pressure (P_{CL}) of 9,7 and 1,1 bar, and for the free jet nozzle, corresponding to G-ratios of 689, 389 and 277.

The low supply pressure in the case of the free jet nozzles, the influence of the air boundary layer around the wheel, and the quantity of sparks generated in process, support the statement that this condition is similar to dry grinding. With the employment of the shoe nozzle it is possible to achieve a condition of more coolant flowing along the grinding zone, which reduces the friction between the abrasive grain and the chip, between the bond and the chip and, consequently, influences the heat generated in the process. This heat can change the wearing procedure of the grains, since high temperatures in the grinding zone cause high chemical wear of CBN grains (affinity to the overheated water vapor). Thus, by employing the shoe nozzle, which provides better lubrication-cooling condition in the grinding zone, it has been possible to obtain a decrease of radial wear, even with a reduction of until 75 % on the amount of coolant used.

These experiments carried out using the CBN resin bonded grinding wheel evidence an important aspect concerning the necessary amount of coolant required for the process. By employing the shoe nozzle it has been possible to obtain better results of grinding wheel radial wear, even with reduction on the amount of coolant used. On this account, it is possible to notice that the flow rate itself is not a fundamental parameter in a coolant providing system. In the same way, it is also possible to assume that an optimization of the system should not have focus on increasing the amount of coolant brought into the process, but on the providing pressure as well as on the conception of the coolant supply (the way it flows out).

4.2 Influence of the nozzle type on the grinding wheel radial wear of the vitrified bonded wheel

To evaluate the influence of the nozzle type on the radial wear of the grinding wheel, a test has been carried out under a providing pressure (P_{CL}) of 2 bar. The results obtained by employing the shoe nozzle and a comparison of this nozzle type with the free jet nozzle are presented in Figure 6. The G-ratio was about 10 times higher by employing the shoe nozzle. This better performance can be associated with the barrier which is formed by the nozzle to the air boundary layer and with the effect of coolant pumping to the grinding zone caused by the wheel. Both phenomena propitiate an increase on the quantity of coolant which penetrates the grinding zone. Therefore, there is a decrease on the heat generated in process and, as stated in the item 4.1, the possibilities of chemical wear of the CBN are reduced.

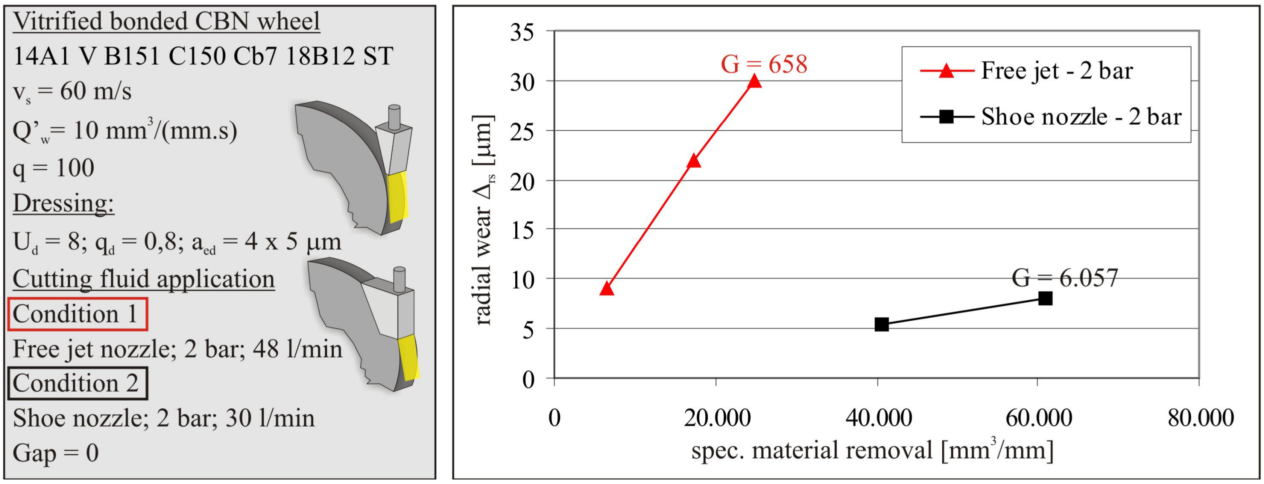

Figure 6. Reduction of the grinding wheel radial wear by using the shoe nozzle (P_{CL} = 2 bar)

The problem of chemical wear of the CBN on the presence of overheated water vapor becomes more evident when the results of the tests here presented are compared to those obtained by Klocke (2000) (Figure 3). Klocke (2000) employed a CBN vitrified bonded grinding wheel in the grinding of the alloy 100Cr6V, and while comparing the performance of the free jet with the shoe nozzles he did not obtain such a significant difference as noticed in the present work. By the way, he used an oil-based coolant, which leads to disclaim the possibility of chemical wear of the CBN, considering that no aqueous basis was employed.

It is important to state that there was a significant decrease of the coolant amount employed by using the shoe nozzle. This allows to reduce costs with maintenance, filtering and discard of coolant, which are generally very high. Thereby, not only technological and economical gains are achieved, but also environmental costs of employing coolants in grinding are reduced. The results obtained in the present work are in accord with the ones obtained by some authors (cited previously), which present the shoe nozzle as being one of excellent potential to minimize the coolant amount employed in grinding.

Other important point is the achievement of a reduction on the grinding wheel radial wear, more expressive for the vitrified bonded grinding wheel than for the resin bonded one. One of the explanations for that is the fact that the vitrified bonded wheel has a structure which is more open. Therefore it is possible for this wheel to carry a bigger amount of coolant to the grinding zone, providing another fluid transport mechanism.

4.3 Influence of the gap between the nozzle and the wheel

The grinding wheel radial wear values obtained by employing the nozzle direct in contact with the wheel and with a distance of 0,5 mm were very similar, as observed in Figure 7.

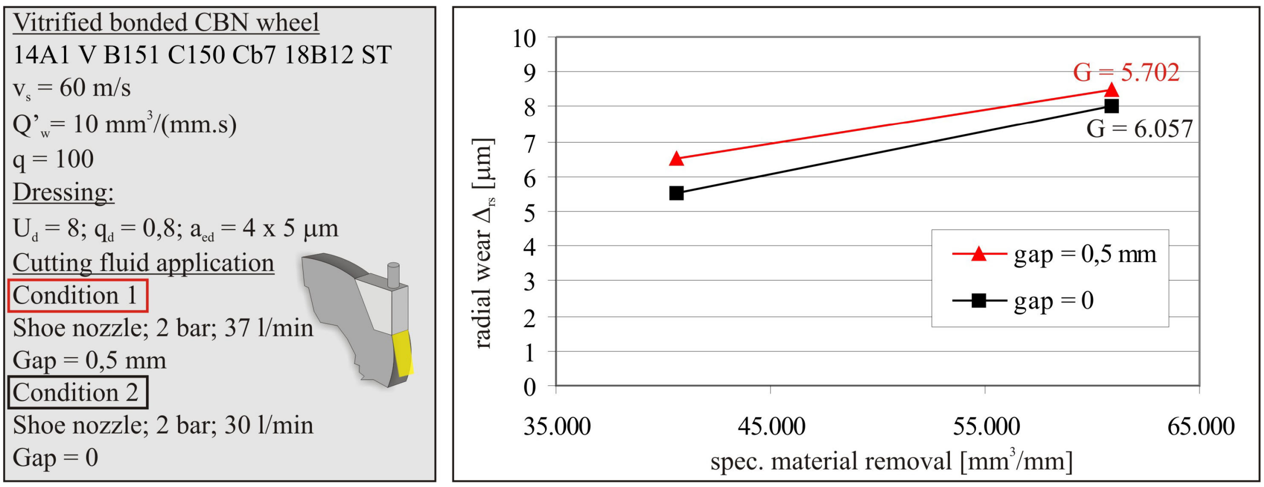

Figure 7. Influence of the gap between nozzle and wheel concerning grinding wheel radial wear

The radial wear was about 5% higher in the case of the nozzle 0,5 mm distant, where the G-ratio was 5.702. By bringing the nozzle far from the wheel, the flow rate is increased in approximately 25%. Considering that after each dressing procedure the radius of the wheel is reduced in 30 µm (wear and profiling), 17 runs/procedures would be necessary for this distance of 0,5 mm to be achieved. This total of procedures corresponds, according to the tests, to a specific volume of approximately 1 million of mm³/mm of material removed from the workpiece. That becomes important in a production line, since the new set up of the nozzle can be made at each maintenance stop, not being necessary to do it while the wheel has movement.

4.4 Influence of the cutting speed

With the increase of the cutting speed there is a reduction of radial wear, as observed in Figure 8. For a specific material removal of 60.800 mm³/mm, G-ratios of 6.057 and 8.117 have been obtained for cutting speeds of 60 and 80 m/s, respectively. With the increase of the cutting speed there is also a flow rate increase caused by the pumping effect exerted by the wheel.

The chip thickness h_{cu}, which represents a value of the thickness of the undeformed chip, is inversely proportional to the cutting speed. Therefore, an increase on the cutting speed leads, for a same specific material removal rate, to the reduction of the chip thickness. This has a positive influence on the cutting forces. The increase of the friction speed, as well as of the frequency of usage of an abrasive cutting edge, is compensated by the reduction of the period of action of a cutting edge and by the decrease of the cutting force, resulting in less radial wear of the wheel.

It is important to notice that by increasing the cutting speed, the amount of air around the wheel and the heat generated in process are increased as well. Therefore, it can be expected that the employment of the shoe nozzle is so more important as higher is the cutting speed, since under high speeds more difficulties are faced with a free jet nozzle.

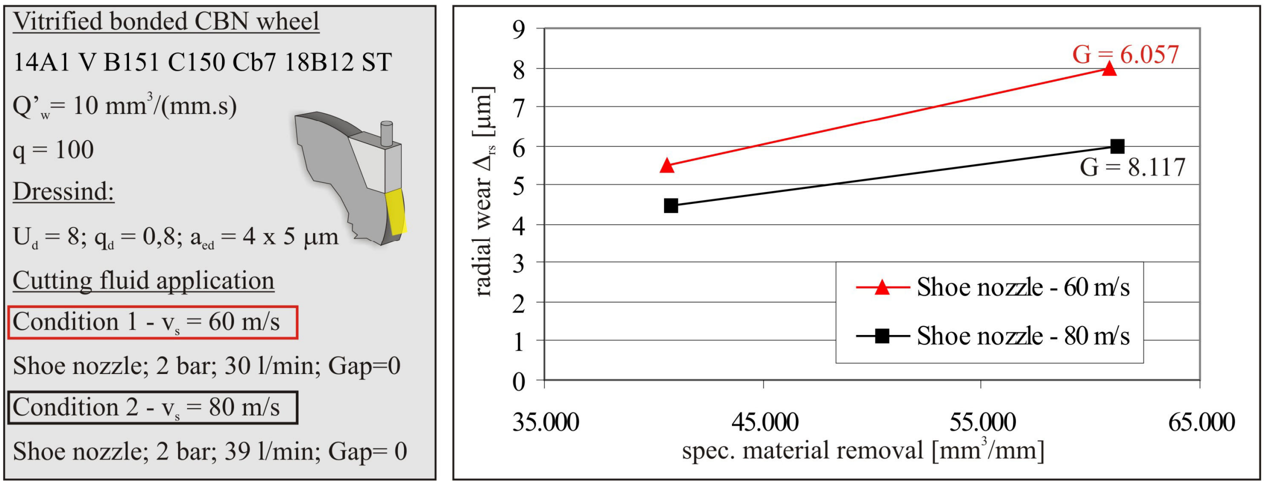

Figure 8. Reduction of the grinding wheel radial wear by increasing cutting speed

5. Conclusions

The results obtained in this work show that the entry parameter "lubricant-coolant fluid" should be treated as of first importance in the grinding process, since a simple change in the conception of the fluid providing system resulted in significant improvements for the process.

With the employment of the shoe nozzle better results concerning grinding wheel radial wear have been obtained for both the resin bonded and the vitrified bonded wheels. With the vitrified bonded wheel these improvements were more expressive, and for the same grinding conditions, changing the free jet nozzle by the shoe nozzle, an increase of approximately 1000% in the G-ratio was observed (increasing the G-ratio from 658 to 6.057). Those improvements occurred because of the flow of coolant in the grinding zone, which has been increased in a way to reduce the friction between grain and chip as well as between bonding and chip, reducing the heat generated in process. The advantages of the vitrified bonded wheel are in the structure, which is more open (higher porosity) and propitiates a favorable condition to carry the coolant onto the grinding zone.

The efficiency of the shoe nozzle observed in the results of grinding wheel radial wear is reason of two distinct facts. The first one is related to the reduction of the air resistance opposed to the coolant penetration in the grinding zone, caused by the air cushion around the wheel. This problem is solved because of the short gap between nozzle and wheel and because the wheel surface "dives" into a cell full of coolant (inside the nozzle). In this cell, the pores of the wheel, until that moment filed with air, are then filled with coolant. The second fact is related to the coolant pumping effect, caused by the rotation movement of the wheel. The wheel, which has a rough surface, works as a pump, "carrying" coolant from inside the nozzle to the grinding zone. Both facts led to better conditions of lubrication-cooling in the grinding zone.

By increasing the cutting speed of the vitrified bonded wheel and employing the shoe nozzle, the best results have been obtained (G-ratio of 8.117). Maintaining the same specific material removal rate, an increment of cutting speed provides a reduction on the undeformed chip thickness, and consequently, a reduction of the forces over each abrasive grain. Thus, the radial wear of the wheel is reduced.

Even though the appliance of oil-based coolants in grinding is stated as the best option, the usage of emulsion has shown itself viable when applied in combination with the providing conception of shoe nozzle. This becomes important, especially concerning the grinding of nodular cast irons, which propitiate high contamination of the coolant by the graphite. This coolant must be filtered (generally an expensive process). The difficulties in filtering are mainly related to the viscosity of the fluid, being therefore easier to filter water-based coolants. Even though there are advantages with the employment of emulsion, concerning the filtering process there is a problem of affinity between the CBN and the overheated water vapor, which might lead to premature wear of the wheel. The chemical reactions occur mainly under high temperatures and therefore it is important to have efficiency while the coolant is applied, minimizing the temperature of the process and the possibility of wear. With the employment of the shoe nozzle it became possible to improve the lubrication-cooling conditions in the grinding zone, turning viable the appliance of a water-based fluid in grinding with CBN wheels.

With the employment of the shoe nozzle it is possible to reduce the amount of coolant required for the grinding process. This became evident in all the experiments carried out in this work. Based on these results, a reduction in the costs of set up, maintenance, discard and filtering can be accomplished.

Another important point is related to the fact that it is not necessary to adjust the nozzle after each dressing step. With the increase of the distance between wheel and nozzle the G-ratio was not significantly reduced.

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