ANALYSIS OF THE INFLUENCE OF DIFFERENT CUTTING FLUIDS IN THE WEAR OF CBN WHEEL IN HIGH SPEED GRINDING

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Abstract. *The objective of this work is to evaluate the influence of different types of cutting fluids in the wear of a vitrified CBN wheel in high speed grinding. New combinations of wheel types and cutting fluids are being sought, due to the growing need of adaptation to the current environment requirements including the operator safety. To investigate the phenomenon that causes the wear in CBN wheel, tests of external cylindrical plunge grinding were performed in rough condition. Hardened steel was ground at cutting-speed of 80 m/s. Different cutting fluids types (cutting oil, synthetic fluid in the concentration of 3 and 20 °Brix and water) were tested. The evaluation parameters were roughness and radial wheel wear. In order to identify the existence of chemical reaction between the CBN grains and the water based fluids, the presence of boron compounds in the water was done. It could suggest the occurrence of chemical reaction between CBN and the water steam. The Inductively Coupled Plasma-Optical Emission Spectroscopy technique was used to quantify boron concentration in the grinding fluid. As a result, it was possible to determine which cutting fluid lead to the best performance. The wear mechanism (mechanical, thermal or chemical) of the CBN wheel could be identified.*

Keywords *CBN wheel, cutting fluid, wheel wear.*

1. Introduction

Due to the growing need to adapt current safety requirements operators and environment, new combinations of wheel types and cutting fluids are being sought. As a result, the grinding process is being optimized by adopting grinding strategies that lead to a decrease in the energy expended during the cutting process, and its rapid dissipation out of the grinding zone. These procedures include the use of CBN wheels, which allow a larger amount of heat to be removed from cutting area through a superabrasive (wheel) (Kohli et al, 1995). In addition, adopting a suitable cutting fluid reduces the coefficient of friction and specific grinding energy between grain and workpiece. In the CBN grinding, a significant improvement in the process is observed, which translates to the reduction of thermal damage and workpiece temperature.

High-speed grinding offers excellent potentials for good component quality combined with high productivity. It is characterized by the reduction in grinding forces and grinding wheel wear. The advantages promised by high-speed grinding are an increase in the quality of the workpiece material, or alternatively, an increase in productivity. (Jackson et al, 2001). Although high-speed grinding increases the amount of heat generated in the process, only superabrasives, which expel a larger amount of heat from the cutting area, should be used. The cutting fluids need to be used only to minimize the generation of heat.

The grinding fluid is probably the most misunderstood and most overlooked factor in optimizing the performance of grinding wheel. Improvements in productivity and low cost results can be generated by the suitable combination of grinding wheel and cutting fluids. According to Bennett in Monici et al (2001), the use of oil base fluids and superabrasives wheels (CBN) were shown to be satisfactory because the CBN wheel has resistance characteristics at high temperatures. Besides, it favors the ease heat dissipation. Experiences with CBN wheels showed that oil base fluids are more suitable for high rates of material removal. For normal and low rates of material removal, synthetic or soluble oils are more suitable. To obtain high performance with the CBN wheel, a special attention should be given to the dressing operation and type of cutting fluid, which, for several reasons, should preferably be cutting oil. At high temperatures soluble oils give place to steam formation in the contact point between the wheel and the workpiece. This steam can chemically attack the CBN grain, hence decomposing it. According to Carius (1989), there is limited direct evidence to confirm that this chemical reaction leads to CBN degradation even though specific tests and chemical analysis of the fluid used during grinding operation could identify whether or not chemical degradation of the CBN wheel was supposed to be occurring or not.

This paper presents a comparative study of the influence of different types of cutting fluids on the wear of vitrified CBN wheel in high speed grinding. The parameters for evaluation used were roughness and wheel wear. Considering the rough condition used is not a coarse operation, the roughness was considered as a analyze parameter. The main aspects that influence the performance of the cutting fluid during the grinding operation are presented. The influence of the different types of cutting fluid on the lubricant and cooling action in the grinding process are also presented. The wearing behavior of the wheel due to the fluid adopted was measured and the possible chemical degradation of the CBN wheel was investigated using Inductively Coupled Plasma-Optical Emission Spectroscopy. This test allows the quantification of boron concentration in the cutting fluid before and after grinding. With these results, the wear mechanisms can be evaluated for each cutting fluid. The most appropriate cutting fluid for use was then determined.

2. Aspects that Influence the Performance of Cutting Fluids used in Grinding

Due to the mechanism of chip formation, a large part of the energy produced during grinding is converted into heat and thus high temperatures are generated at the interface between the abrasive grain and the workpiece. These temperatures are the main source of damage on the surface of the machined (Shaw, 1984). Cutting fluids are therefore used to reduce this thermal damage. The main function of cutting fluids is to reduce friction between abrasive grains and workpiece and hence the thermal energy generated in the contact zone. The technological advantages of fluid are reduction of the wheel wear and thermal damage, an improvement on the transportation of chips out of the grinding zone, and a good protection against corrosion of the workpiece and the machine tool. (Tönshoff et al, 2002).

Grinding fluids can be classified into four major categories: synthetic (chemical), semi-synthetic, soluble oil (emulsion) and cutting oil. These categories differ from one another in their chemical and performance characteristics. Some of them are listed in Tab. (1). No fluid however, can be considered ideal in all aspects. Each of them must be evaluated on the basis of the requirements and limitations of the process, Wheel life, quality of workpiece. Equipment capabilities and environmental considerations must also be taken into account (Webster, 1995).

Table 1. Cutting fluids characteristics (Webster, 1995)

1= poor 4=best	***Synthetic***	***Semi synthetic***	***Soluble oil***	***Cutting oil***
Heat removal by convection	4	3	2	1
Lubricity	1	2	3	4
Maintenance	3	2	1	4
Filterability	4	3	2	1
Environmental	4	3	2	1
Cost	4	3	2	1
Wheel life	1	2	3	4

Grinding fluids are traditionally used as an external means to improve the process performance by providing lubrication and cooling at the wheel-workpiece interface. However, the effectiveness of the grinding fluid depends upon many factors, such as the location of placement, flow velocity, quantity of flow, direction of application, the design of the nozzle, among others. Within the grinding zone, convective cooling by grinding fluid can usually be neglected in regular grinding due to film boiling (Lavine & Malkin, 1990).

The phenomenon of film boiling affects water-soluble fluids and cutting oils in a different ways (Yasui & Tsukuda, 1983). As reported by these authors, the occurrence of the film boiling in water-soluble fluids lowers the heat transfer coefficient of the fluid to almost that of air. As a result, the cooling performance in these fluids deteriorates to almost that of dry. Since the physical properties of water-soluble fluids are almost the same as those of water, film boiling may seems to occur at a temperature slightly in excess of 100 ^{o}C. On the contrary, cutting oil is a mixture of different oils having different boiling temperature and its average boiling point is about 300 ^{o}C. Therefore, at rougher grinding conditions, the effect of film boiling is more critical when a water-soluble fluid is used.

The use of CBN grinding wheels can lead to a reduction in film boiling. It was found out by Kohli *et al*. (1995) that in aluminum oxide abrasive wheel, 60-75 percent of the grinding energy is transported to the workpiece as heat compared to only 20% in CBN wheels. Analyses of these results indicate that the much lower energy partition to the workpiece in CBN can be attributed to its very high thermal conductivity (CBN = 3.3 cal/ºC.cm.s and Al_2O_3 = 0.08 cal/ºC.cm.s) due to a significant portion of the heat of grinding being transported to the abrasive instead the workpiece. The much lower energy partition to the workpiece in CBN wheels results in much lower grinding temperatures and a significantly reduced tendency to thermal damage at the workpiece. Therefore, improving the use of water-soluble fluids can reduce the hazards caused by film boiling on CBN wheels.

Therefore, for coolant to be really effective, it should not only provide good convective cooling of the workpiece but also promote cutting as opposed to plowing. Consequently, there is a decrease in the grinding specific energy required in the process (Malkin, 1989). The fluid would inhibit glazing and capping of the grits by reducing the coefficient of friction between grit and workpiece. This allows blunter grits to cut, as well as reduces the overall level of forces for a given stock removal rate. This has a twofold benefit: the energy to be dissipated is lowered and secondly it is more easily dissipated.

Due to the superior lubricant ability of the cutting oils compared to water-based oils, there is a reduction of specific grinding energy (Malkin, 1989), maximum grinding temperatures, and thermal damages due to cutting instead of plowing. Besides, the ineffective convection heat by the oil is outweighed by its high lubricant ability (Hitchiner, 1990) considering that convective cooling in regular grinding can be neglected (Lavine and Malkin, 1990). According to Carius (1989) cited by Webster (1995), in almost all cases, wheel wearing is reduced by the use of cutting oils. The high lubricity of these oils compared to soluble oil results in lower specific energies and hence the reduction in specific energy and rate of growth of wear flats on the grits.

The performance of the cutting fluids can be improved if the cutting fluid delivery system is improved too (Webster, 1995). This means that the integral system (pump, nozzle design, and pipes) must be well managed to obtain high quality workpieces. Round nozzles based on fire hoses (Rouse *et al.*, 1952) can improve jet coherence (Webster, 1995).

The jet velocity should be increased to match the grinding wheel speed in order to overcome the air barrier created by the grinding wheel spindle. According to Webster (1995, 1999) a matching wheel-coolant speed ratio is optimum for most applications except where the cost of pumps or power consumption is excessive. Shoe nozzles (Klocke et al., 2000) are suitable for cutting fluid application at high grinding speeds. In this case, the wheel acts like a “pump” accelerating the fluid.

3. Suggested chemical reactions and CBN degradation due to employed cutting fluid

Vitrified bonds for CBN, like their conventional counterparts, consists of alumina-borosilicate glasses with various basic oxides fired at temperatures equal or greater than 600 ^{o}C (Hitchiner, 1999). Several of the constituents are quite chemically reactive with CBN. In fact, the first vitrified bonds taken directly from conventional wheel technology literally dissolved the CBN. The chemical reaction can occur between water vapor and CBN grain (Eq. (1)) when soluble oils are used. It should be taken into account that the formation of B_2O_3 on the surface of CBN grain creates a protective surface layer that impedes subsequent oxidation and deterioration (Eq (1) and (2)). Once B_2O_3 is soluble in high-temperature water (Eq (3)), it allows further oxidation of the CBN particles. These reactions, although very slow, can cause accelerated breakdown of the CBN particles and thus, shorten wheel life (Leal, 1993). The use of cutting oil grinding fluids minimizes this effect.

$$2BN + 3H_2O ? \quad B_2O_3 + 2NH_3 \quad ? \tag{1}$$
$$4BN + 3O_2 ? \quad 2 B_2O_3 + 2N_2 \quad ? \tag{2}$$
$$B_2O_3 + 3H_2O ? \quad 2H_3BO_3 \tag{3}$$

4. Methodology

The cutting conditions applied in the grinding tests were presented in the Tab. (2). In the tests, the cutting fluid application system was developed in the laboratory. It consists of a shoe nozzle, suitable for high speed grinding, which has function to improve cutting fluid application, overcoming the air barrier that decreases the fluid performance. The shoe nozzle is showed in Fig. (1).

Table 2. The cutting conditions applied in the grinding tests.

DESCRIPTION	CHARACTERISTICS
Test specimens	SAE 52100, 55 HRc, workpiece diameter (d_w) = 48.0 mm and 35 mm long
Cutting fluids	E.P. cutting oil
	3% semi-synthetic (vegetable based)
	20 % semi-synthetic (vegetable based)
	water
Grinding wheels	Vitrified CBN wheel B181 concentration 125 (31,25%)dressing: cross-axis using electroplated diamond disc (wheel speed in dressing v_s=45m/s, peripheral disk dresser velocity v_r=38m/sec, transverse velocity v_d 100 mm/min, dressing depth of cut a_d=2μm)
Cutting conditions (one grinding cycle)	cutting speed (v_s) = 80 m/s; workpiece diameter (d_w) = 47.0 mm; plunge speed (v_f) = 2,6 mm/min; stock = 10 mm, grinding width (b) = 8 mm, workpiece rotation = 300 rpm, flow rate of cutting fluid = 65 L/min. Number of workpieces ground per test: 10.
CNC cylindrical grinding	Zema, model G 800 HS
Evaluation parameters	Roughness and radial wheel wear.

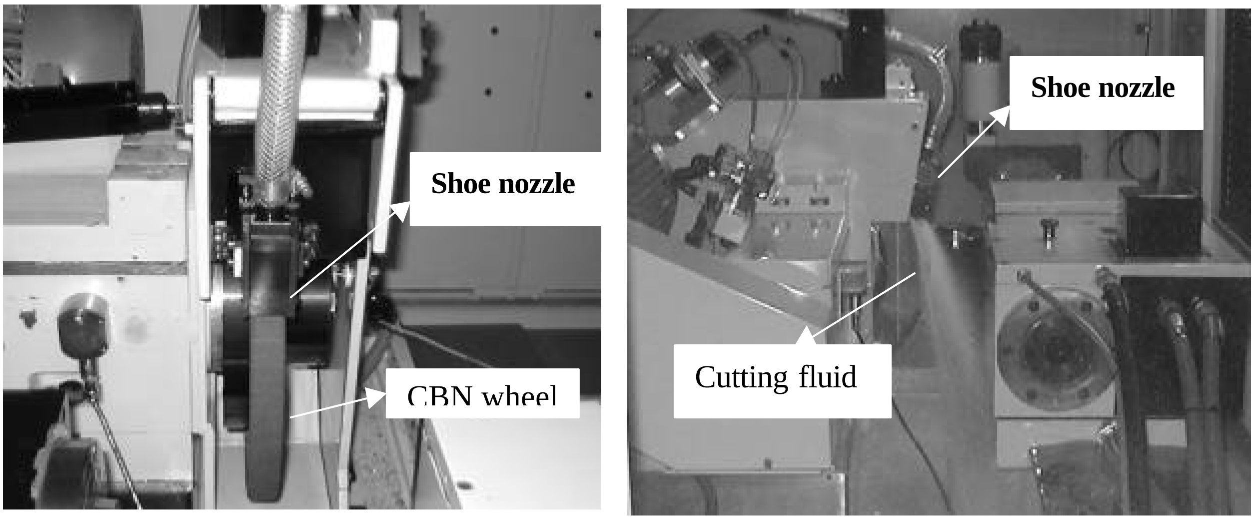
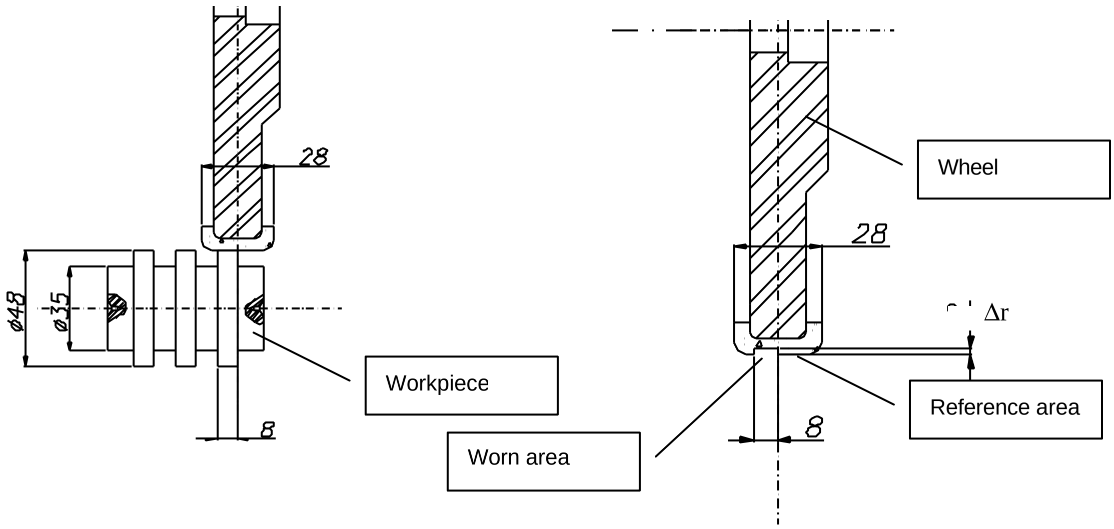


Figure 1. Shoe nozzle : a) frontal view; b) side view, nozzle under operation

The grinding tests were performed in the same Z position in the face of wheel. Each workpiece ground section had width of 8 mm. Consequently, only a part of the total wheel width was used in the grinding tests. In a single cycle, a stock of 10 mm in the diameter was ground per workpiece. This grinding configuration is presented in Fig. (2a). After grinding ten workpieces, if the wear occurs, the wheel presented the following worn profile (Fig. 2b). The wheel surface not used in the grinding tests was used as reference for the wheel wear evaluation.



(a) (b)

Figure 2. (a) Positioning of the workpiece and (b) wheel wear area.

The radial wheel wear, generated after each test using different fluids types, was measured using the acoustic mapping of the wheel surface. Acoustic maps of the wheel surface after each grinding test were created.

The Figure (3) shows of basic configuration of acoustic emission system, developed by Oliveira et al. (2000). The acoustic emission signals obtained by contact between dresser and wheel are converted to RMS (root mean square) and acquired by computer, using an analog to digital acquisition board. These signals are plotted in a graphic in which the intensity of the AE signal is converted into a color scale. The greater the signal, the brighter is the obtained image. The lack of contact or the lower contact intensity between the dresser disc and the wheel surface are represented by the darker areas. The vertical and horizontal directions are the circumferential length of wheel and its width, respectively. The intensity of colors shows to the values of emission acoustics RMS measured through the interaction between the dresser abrasive and acoustic sensor. The acoustic mapping obtained in the dressing operation prior to the grinding test is presented in Fig. 4 (a)

The measuring methodology using the acoustic mapping consists of evaluating the obtained graphic image during the dressing operation after each grinding tests. In the dressing procedure, the infeed per dressing stroke was 2 microns. If the wheel wears, the obtained map in shown in Fig. 4b. Considering than only a portion of the wheel width was used in the grinding tests (b = 8 mm), two distinct regions are present in the graphic. The darkness area represents the worn one and the other the reference area.

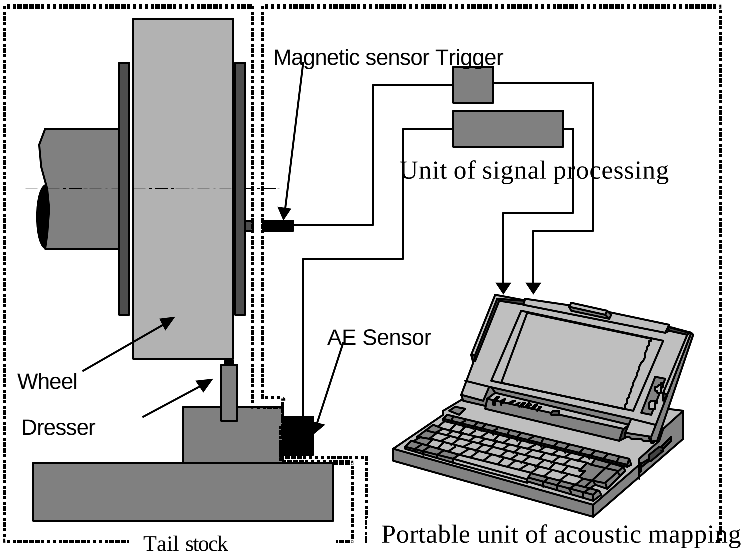


Figure 3. Basic configuration of the acoustic mapping system (Oliveira et al., 2000)

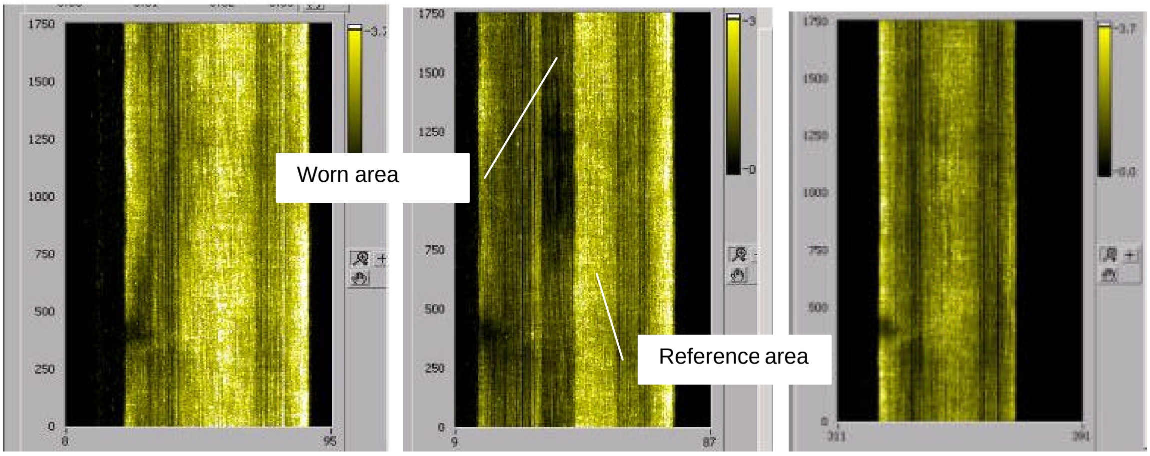


Figure 4. (a) Acoustic Map of wheel surface after the dressing operation performed before each test, (b) Wear surface of CBN wheel and (c) The uniform surface of wheel after successive passes of dressing.

Successive dressing strokes of 2 microns in diameter are performed until a uniform graphic pattern is obtained. When no more distinct areas are detected in the obtained acoustic map (Fig. 4 c), the dressing procedure is interrupted. The number of strokes is multiplied by the depth of cut per dressing stroke, resulting in the value of radial wheel wear.

The wheel wear was also measured reproducing the wheel surface profile in a mild steel (SAE1020). This procedure was denoted as printed profile technique. A cylindrical workpiece was ground using the total grinding width. The obtained profile was measured by Talysurf equipment. This technique is based on scanning the workpice surface with a needle, which is capable to verify little steps in the surface. The differences in the step of the two distinct wheel regions “printed” in the workpiece were evaluated for each grinding tests.

The roughness measurements were performed using a cut-off of 0,8 mm. Each roughness value represents the average of four measurements, spaced 90° one from other.

The possible chemical reactions between the grains of CBN and the cutting fluids were analyzed using the Inductively Coupled Plasma-Optical Emission Spectroscopy. This is a quantify analysis to determine the boron concentration. Water samples, before and after of grinding, were analyzed, in order to verify if the amount of boron increases after the grinding.

5. Results and discussions

5.1Radial wheel wear

The radial wheel wear values were measured by two techniques: acoustic mapping of the wheel surface and printed profile technique.

Analyzing the radial wheel wear results presented in Fig. (5) and (6), it can be noticed the influence of the type of cutting fluid in the radial wear of CBN wheel. It was also possible to verify that the wheel wear can be significantly reduced if cutting fluid with high lubricant ability were used, as also observed by Hitchiner (1990). The use of the cutting oil eliminates the wheel wear for the amount of removed material in the grinding tests (6764 mm^3/mm). On the other hand, the higher wheel wear was observed in the grinding test using the water (higher cooling ability and no lubricant properties), approximately 8μm in the radius. The semi-synthetics fluids tested presented an intermediate behavior. The different results observed are related to the measuring techniques (Fig. 5 and 6). While in the printed profile technique, the worn area was measured by the step between two regions (worn and reference), the acoustic mapping technique considers all the peripheral wheel imperfections. The uniform pattern is only obtained when all the imperfections were corrected.

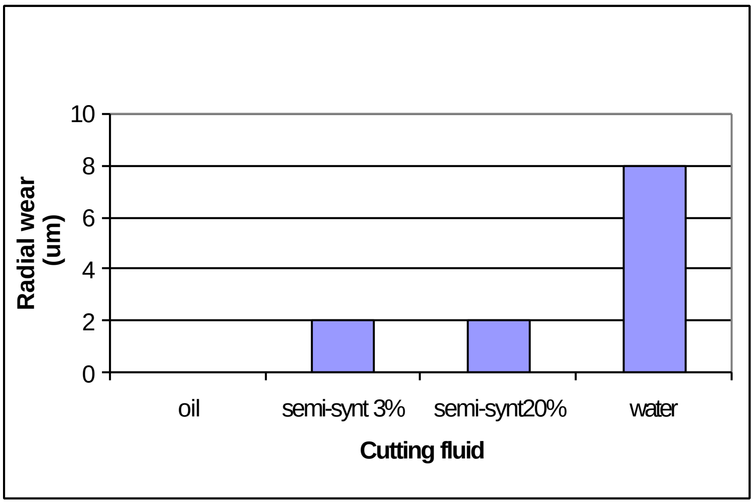


Figure 5. Radial wheel wear values – acoustic mapping technique.

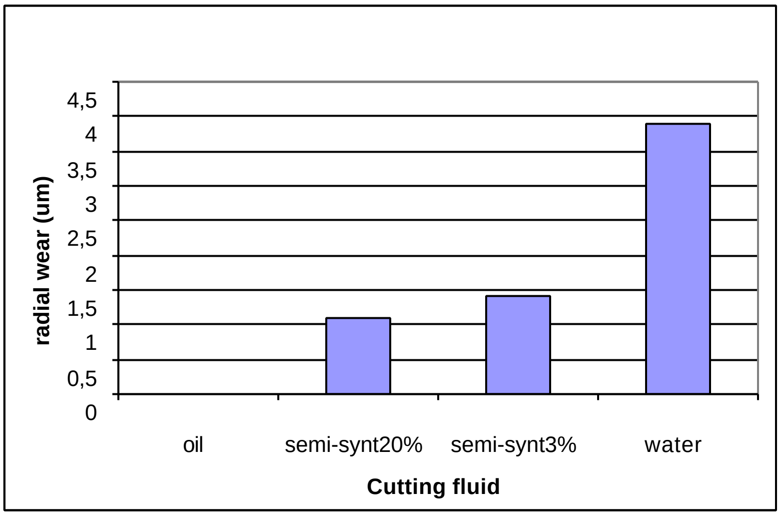


Figure 6. Radial wheel wear values –printed profile technique.

The main purpose of the grinding test with water was to verify if a chemical reaction between CBN and water steam occurs. Samples of water before and after the grinding tests were collected. The semi-synthetics fluids were not analyzed because the grinding temperature reached with these fluids are lower than obtained with water, generating less quantity of steam. The contents of the semi-synthetics fluids could also affect the results of the boron concentration.

As presented in the Tab. (3), after the grinding test, it could be detected that the amount of boron in the water was greater than before grinding. The boron concentration increased 19 percent. Considering that the tank used has capacity equal to 250 l, the measured increase in the amount of Boron in the fluid after grinding was 40,5 mg. This small value is not significant for the wheel wear analysis. Although, if water-based cutting fluids were used, the wheel wear mechanisms could be considered as a consequence of the both increased friction, the thermal grain shock and a small chemical degradation contribution. On the other hand, when using the cutting oil, with an absence of water, the friction wear is reduced and the other mechanisms are much less significant.

Table 3. The Results of boron analysis

Sample	***Concentration (mg/L)***
Water before grinding	0,821
Water after grinding	0,983

For the amount of removed material, the increase in the concentration of the semi-synthetic fluid didn't result in measurable wheel wear when the acoustic mapping technique was used (Fig. 5). Although, wheel wear was detected when using the printed profile technique (Fig. 6).

The semi-synthetic fluids contain some percentage of oil, which adds lubricity and protection to the CBN abrasive particle. Increasing the concentration of these fluids in the water base generally improves their effectiveness. The results show that increasing the concentration from 3% to 20% will produce a small decrease in the wheel wear. This cannot be advantageous in comparison of the adding cost. Also, using a too high a concentration foam formation was observed.

5.2 Roughness

The roughness results for the grinding test using different cutting fluids are presented in the Fig. 7. The cutting fluid type influenced the roughness values. The higher the lubricant ability the lower is the roughness. This fact can be seen when the water was used as cutting fluid. Increasing the amount of removed material (number of workpieces ground) there was an increase in the roughness values, due the low lubrication ability of the water and the effect of removed material in the wheel sharpness. The values varied of 0,26 μm to 0,57 μm. This tendency was more pronounced for water than for the others cutting fluids.

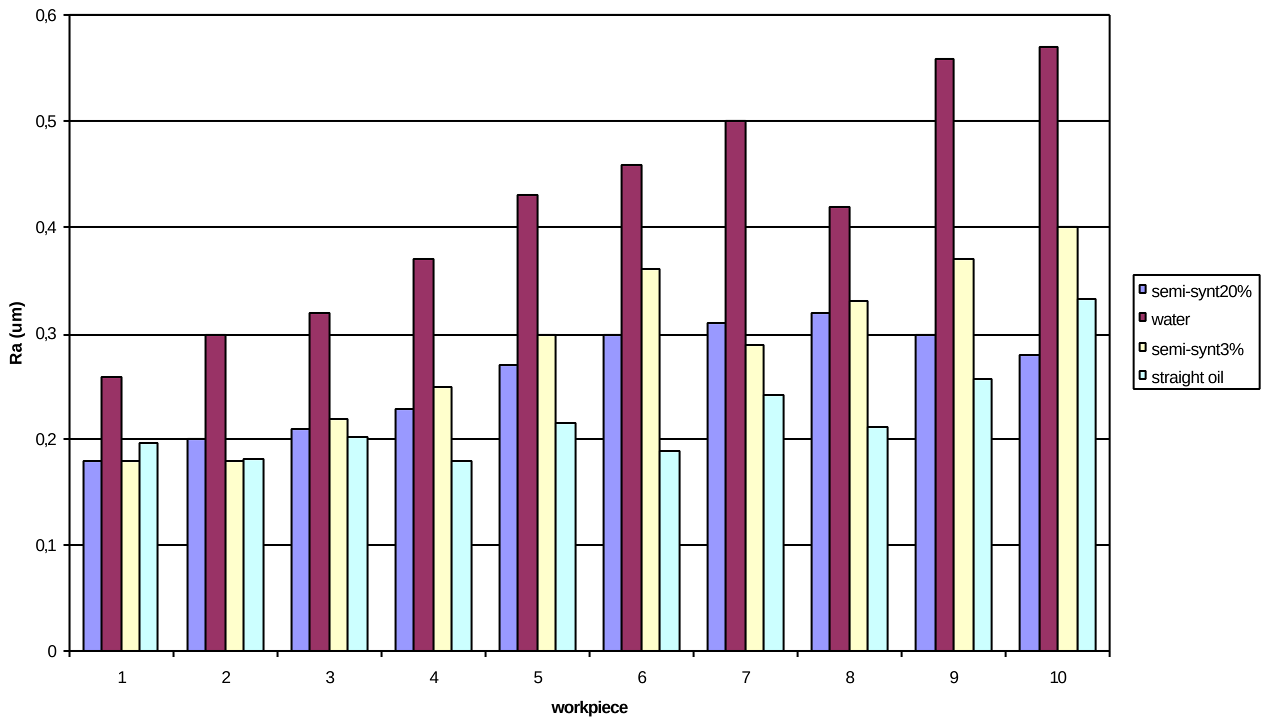


Figure 7. Roughness values (Ra) for the different cutting fluids.

The low lubricity causes an increase of friction between the chips and the bond and leads to the increase of roughness values. The better performance was observed by using cutting oil, where the roughness was lower than 0,33μm. The increase tendency of the roughness value with the increase of the removed material observed for the water could not be observed for the cutting oil.

The semi-synthetic fluids presented a similar behavior of the water, with trend of increasing the roughness values, with the increase of the volume of removed material. The semi-synthetic fluid with concentration 20% presented better results, mainly when a great amount of material was removed, as it can be observed in the pieces 9 and 10. In this case, the variation of the roughness values, for semi-synthetic 3 and 20%, is approximately of 0,1 μm. In this test it can be confirmed that the lubrication ability of fluids is a major factor in the performance of cuttings fluids.

6. Conclusions

Based on these experimental results, the following conclusions can be drawn:

- The lubricity of the cutting fluid is the key factor for its performance and can influence the radial wheel wear and workpiece roughness. The wheel wear was completed eliminated when cutting oil was used and the roughness values were smaller than semi-synthetic fluids and water.
- When the water was used as cutting fluid, it can be observed a higher wheel wear level, which is consequence of its poor lubricity that increases the friction wear, chemical degradation and thermal shock of the grain and bond.
- For the amount of removed material, increasing the concentration of the semi-synthetic fluids (3% to 20%) leads to an improvement in the roughness values and a slight tendency in reducing the wheel wear. Although, the high concentration used has caused foaming or give no additional benefit while adding cost.
- The best performance in grinding operation was obtained when cutting oil was used as cutting fluid.

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