PERFORMANCE OF THE VEGETABLE OIL BASED EMULSION WHEN DRILLING 15-5 PH MARTENSITIC STAINLESS STEEL GRADE

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Abstract. *The combination of good mechanical properties and high resistance to the corrosion make stainless steels an indispensable material for several products. However, these steels present difficult machinability with tendency to adhesion on the tool leading to formation of built up edge. In order to achieve an economic tool life and acceptable surface quality, machining these steels is generally performed using cutting fluid, mainly in drilling processes where it has great importance also in the removal of the chip, in addition to cooling and lubrication. Also the traditional emulsions based on mineral oils, currently, emulsions based on vegetable oils can also be found. The most studied stainless steel grade is the austenitic steel grade, for it is the most used. Therefore, the machinability of other types of stainless steels is not very known. This work aims to verify the performance of a vegetable oil based emulsion compared to a mineral oil based emulsion during machining of 15-5 PH precipitation hardened martensitic stainless steel, very employed in the aerospace industry. The results demonstrate that the tool life was dependent of the emulsion type and of the fluid concentration. The tool wear curves show that the growth of the wear was continuous, without long spaces of stability or sudden increase. It was also observed that the wear mechanism was adhesive with removal of small particles of the tool. No influence of the emulsion type and concentration in the dispersion of the hole diameter was observed with cutting parameters investigated.*

Keywords: *stainless steel, vegetable emulsion, tool life, wear mechanism*.

1. INTRODUCTION

Drilling process is one of the most common machining processes. Usually, there is at least a hole in each industrial part, with many different purposes (to clamping, to open screw with tap, to assembly guide pin, etc). In drilling, it is indispensable the use of cutting fluid to improve the productivity of the process. In this process the cutting fluid has, besides the function of cooling the chip formation area, the function of transport the chip outside of the hole being produced. The chip transportation is maximized with the application of the fluid through channels made inside the drill.

The chemical formulation of the traditional cutting fluids has been changed in the last years to adapt them to environmental demands. One of these changes is substitution of mineral based oils by vegetable based oils in both emulsions and neat oils. This substitution minimizes both, the fluids disposal costs and also human health problems.

In the stainless steels machining the cutting fluid is very used because they are considered as difficult-to-machine materials. Nordin et al. (2000) say that the difficulty to cut austenitic stainless steel is due to its tendency to work-harden, caused by the previous machining operation with worn tool. Additionally, the relative low thermal conductivity of the stainless steel, approximately 35% of the conductivity of the carbon steel, elevates even more the temperature in the cutting zone. According to Diniz et al. (2001), these steels present a tendency to adhere on the tool, generating build up edge formation. The formation of an adhered layer on the tool rake face is facilitated by the large amount of heat generated (Tieu et al., 1998). Moreover, due to the high temperature, diffusion and dissolution between two types of materials formation of a strong union point may occur. This will depend on the mutual diffusivity and solubility of the chemical elements present. When cemented carbide and stainless steel are the only two materials in contact, the conditions to form this strong chemical union are present. The cobalt from tool and the iron and nickel from austenitic stainless steel have strong affinity and they can dissolve one in the other (Sun et al., 1998). For these reasons, understanding thermo chemical phenomena represent a key role in the tool wear (Grzesik, 1999). Besides the thermo chemical phenomena, mechanical wear (e.g. chipping of the cutting edge) may also occur when stainless steel is machined. Due to the rapid tool deterioration, tool life is frequently short, material removal rate is low, high cutting forces and high power consumption occur, together with the deterioration of the workpiece surface quality (Nordin et al., 2000; Diniz et al., 2001; Grzesik, 1999; Ribeiro et al., 1998; Lin, 2002). Most of times machining is the main cost factor of a stainless steel part (Bossert, 1995).

As most of the machining researches are carried out using the austenitic stainless steel grade, the feasibility of using fluid in the machining of other grades of stainless steels is not well established. In the aerospace industry, the most used stainless steel is the precipitation hardened martensitic grade. It is chosen due to its high mechanical resistance (close to the martensitic steels) and good ductility (close to the austenitic) (Arisoy et al., 2003; Brucker, 1995; Meyrick, 2002; ASM Handbook, 1997). The precipitation hardened martensitic stainless steel is frequently machined in the annealed condition, requesting only a simple aging treatment to reach the desirable level of mechanical resistance. Depending on the use, this kind of steel can also be machined in the aged condition, in order to avoid the thermal treatment and, so, making tight tolerances easier to be obtained (ASM Handbook, 1997).

This work aims to verify the performance of a vegetable oil based emulsion compared to a mineral oil based emulsion during drilling of 15-5 PH precipitation hardened martensitic stainless steel.

2. MATERIALS AND METHODS

2.1. Materials and equipments

The workpiece material was the 15-5 precipitation hardened martensitic stainless steel plate in dimensions 355 mm of length x 205 mm of width x 43 mm of height. The hardness of the material was of 31 ± 1 HR_C.

An indexable insert twist drill with 15 mm of diameter (maker's code (Sandvik) R416.2-0150C5-31) was used in the experiments. The diameter of the drill was chosen in function of the thickness of the plate and length/diameter ratio (L/D) around 3. The drill has 2 indexable inserts which worked together, an insert assembled in the periphery of the drill diameter, which cut from the half diameter of the hole to the wall of the same. The other insert is assembled in the central area of the drill and was responsible for the machining from the center of the hole to the half of the diameter, as it can be seen on Fig. 1. With this configuration, the two inserts complemented each other and only one cutting edge cut a specific region of the hole. The inserts have the same geometry, but different cemented carbide grade. As characteristic of the drilling process, the cutting speed varies along the cutting edge. In the center of the drill the speed is zero and in the periphery of the same the cutting speed is maximum. Thus, each insert has characteristics appropriated according to the working area. Central insert code was LCMX020204C-53, grade ISO M20 - M40 and PVD coating of TiN. Peripheral insert code was LCMX020204P-53, grade ISO M20 - M40 and TiCN PVD coating. Both insert has nose radius of 0.4 mm.

Figure 1. Indexable insert twist drill used in the experiments. (Sandvik, 2006)

The experimentation was carried out in a Mori Seiki vertical machining center, model SV 40, with available power in the spindle of 22 kW and 12,000 rpm.

The flank tool wear measurements were carried out several times during tool life using a stereoscope microscope (with maximum magnification of 50x) connected to an image acquisition system composed of CCD camera and a computer with image acquisition software with measurement resources. In order to facilitate the measurement of the cutting edges of the drill, a device was incorporated under the stereoscopic to allow the clamping of the tool through its tool holder in a position close to the vertical. The positioning of the cutting edges under the stereoscope was made rotating the drill manually on its support.

The measurement of the internal diameter of the hole was accomplished with an internal micrometer (Mitutoyo) with measurement range of 12 to 16 mm, with accuracy of 0.005 mm.

2.2. Experimental procedure

To each sequence of holes machined (20 to 30 holes for sequence, depending of the severity of experimental condition) the experiment was interrupted for the measurement of the flank wear. This measurement was repeated up to the moment the tool reached its tool life criterion (maximum flank wear equal 0.2 mm).

Hole diameter measurements were performed after tool reached its life criterion in each experimental condition. This procedure was chosen in order to take 7 measurements uniformly distributed along tool life. The first of the 7 holes measured was the first one machined, 5 holes were distributed homogeneously inside of the group of holes machined in the specific tool life and the last measured hole was the last hole machined. The measurement in each hole was made in three positions of the hole: at beginning, at the middle and at the end of the hole along its length.

3. EXPERIMENTAL PLANNING

Two input variables were selected for the experimental trials:

Cutting speed - it has great influence on the mechanism of wear and on tool life. Moreover, it also influences the productivity of the machining. Two cutting speeds were used - 120 and 160 m/min. These speeds were defined through preliminary tests.

Cooling/lubrication condition - The cooling/lubrication condition can be divided into two parts: first part is related to the form of fluid application and second part is related with the type and concentration of the emulsions used. Only one form of emulsion application was tested: with fluid applied internally to the drill, with flow rate of 25 l/min. In relation to the type and concentration of emulsions, two emulsions were employed: one of vegetable based (VE) and another one of mineral based (ME). For both, the concentrations used were 7% and 12% brix respectively.

The grade of cemented carbide was a constant during all the experimentation. Feed was defined, by preliminary experiments, in 0.06 mm/rev. The holes were machined in a continuous way, i.e., without peck-drilling. The performance of the cutting fluid was evaluated through: tool life, tool wear and diameter dimensional dispersion.

For emulsion concentration of 7% brix, both cutting fluids were tested with both cutting speeds. When the concentration was elevated to 12% brix (for both emulsions) only the cutting speed of 160 m/min was tested. Table 1 shows the matrix of experiments.

Table 1 – Matrix of experiments

Stage	Cutting speed [m/min]	Cooling/lubrication condition		Experimental condition
		Emulsion	Concentration [%]	
1	120	VE	7	120_VE_07
	160	VE	7	160_VE_07
2	160	VE	12	160_VE_12
3	120	ME	7	120_ME_07
	160	ME	7	160_ME_07
4	160	ME	12	160_ME_12
VE – Vegetable based emulsion; ME – Mineral based emulsion				

Each experiment was carried out at least twice. The order of experiment execution was randomly chosen. For the repetition of the experiments another random order was chosen.

The evolution of the wear throughout each experiment was monitored to plot the curves of wear pattern. Aiming to search for explanation for the different tool life values obtained and the differences in the curves of wear evolution for all the conditions tested, it was necessary to identify the predominant wear mechanisms. To reach this objective, pictures of SEM (Scanning Electron Microscope) and analyses of EDS (Energy Disperse Spectroscope) on the worn edges were taken.

4. RESULTS AND DISCUSSION

4.1. Tool life

Tool life values represented by effective cutting time showed in Fig. 2 is a result of average two lives recorded under the same machining condition. The dispersion of the life was represented in the form of a line in the top of the bar of mean tool life. Each line represents ± 1 standard deviation around the mean (there is a condition it did not have dispersion, because this condition was experimented only once).

The results show that, for the 7% concentration (regardless the emulsion type), the increase of that cutting speed decrease tool life, as it was expected. For v_c = 160 m/min, increase in emulsion concentration produced an opposite results, dependent on the emulsion type. For vegetable based emulsion, the concentration increase to 12% resulted in increase in tool life. On the other hand, for mineral based emulsion, the same increase of concentration reduced tool life.

For both cutting speeds tested, in concentration of 7%, the mineral based emulsion presented a performance slightly superior. However, the vegetable based emulsion was much better than mineral based emulsion with concentration 12% and v_c = 160 m/min. The influence of the increase of fluid concentration was so high for the vegetable based emulsion that made tool life for v_c = 160 m/min equal to the tool life obtained with the same fluid, lower fluid concentration and v_c = 120 m/min and almost the same of that obtained with mineral based emulsion and v_c = 120 m/min. In other words, the increase of fluid concentration for vegetable based emulsion compensated the increase of cutting speed and avoided the reduction of tool life.

According to Daniel et al. (1996), thermo-physical properties of the cutting fluids depend on fluid type, fluid concentration and operating temperature. Daniel et al. (1996) also affirm that heat transfer to the cutting fluid in machining depends on chemical formulation of the fluid, among other factors. The addition of oil into water making an emulsion increases the viscosity and reduces the specific heat of the mixture compared to pure water. Both reduce Nusselt number and therefore the convective heat-transfer coefficient. Sales et al., (1999) could verify that changes in the concentration of an emulsion or a synthetic fluid modify the heat-transfer capacity, which is associated to addictive types, present chemical elements and its quantity. Based on these results, from this research it can be affirmed that the increase of concentration in vegetable based emulsion elevated the oil and additives of this emulsion at an appropriated level to support process demands under used cutting parameters. For the mineral based emulsion the increase of concentration lead to a decrease in tool life because its oil type and addictives stimulated the wear mechanisms occurring in this range of cutting speed. The heat present on chip formation area has great influence on predominant wear mechanism.

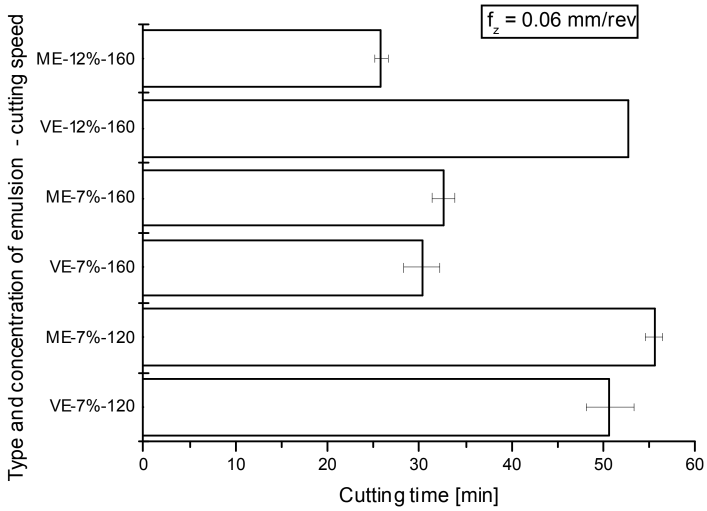


Figure 2. Influence of the cutting speed and type and concentration emulsion in the tool life.

4.2 Tool wear pattern

Fig. 3 presents tool wear curves versus cutting time for all experiments. For Fig. 3(a-d), where the concentration of the emulsions was 7%, the evolution of the wear curves was very similar. The wear growth was continuous, without long spaces of stability or sudden elevations.

For the concentration of 7% (Fig. 3(a-d)) it was noticed that the cutting speed or the emulsion type did not present any significant influence on the curves of maximum flank wear.

For the concentration of 12% (Fig. 3(e-f)) the pattern of the wear curve was a function of the emulsion type. For the mineral based emulsion (Fig. 3(f)), the evolution of the two experiments was almost identical. However, the wear found in the first measurement point, for the two curves, was much higher when compared with the other graphs of the Fig. 3. In this case, the concentration of 12% for the mineral based emulsion produced a very high initial wear, but the wear evolution along the experiment run similar to the evolution found in the experiments with 160 m/min and 7% of concentration, regardless of the emulsion type (Fig. 3(c-d)).

The wear curve for the vegetable based emulsion in the 12% concentration (Fig. 3(e)) grew in steps. It should notice that the tool life criterion was not reached, the experiment was halted after 250 holes machined (55 minutes of cutting time).

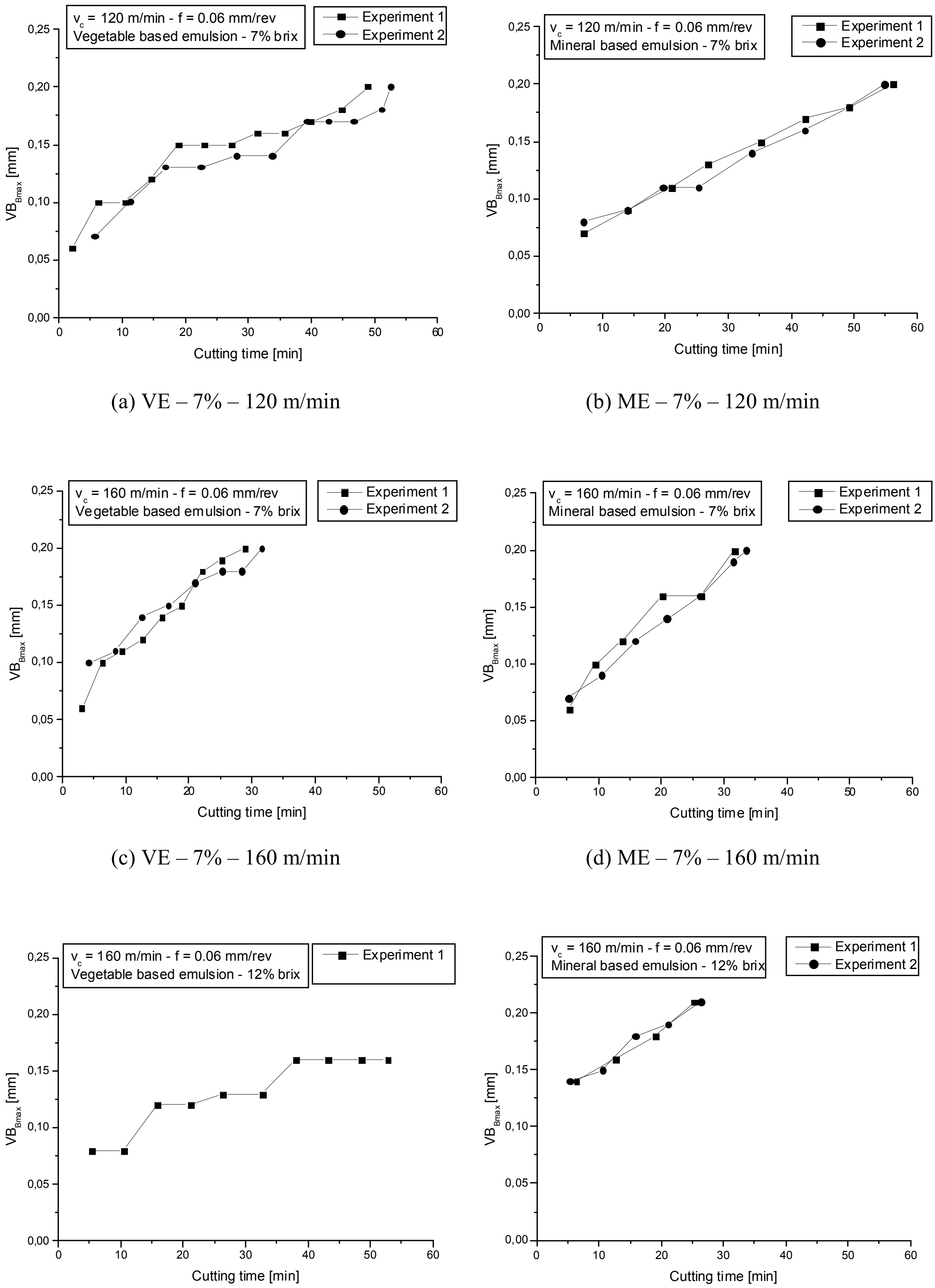
In order to identify the tool wear mechanisms and to try to understand the causes of all these occurrences, the worn tools were analyzed using Scanning Electronic Microscope (SEM) with EDS device. The results of these observations are showed in the following section.

4.3. Tool wear mechanism

Both cutting edges (central and peripheral) of one tool used in each experiment condition were photographed in the SEM, after they had reached the end of tool life. The EDS analysis identifies, semi quantitatively, the main chemical elements of the tool substrate (W and Co), the workpiece material (Fe, Cr and Ni) and the tool coating (Ti).

It could be observed in the EDS analysis of all the tools used that the flank wear lands were full of workpiece material adhered. Fig. 4 shows a sequence of pictures which exemplifies the wear for central inserts. It can be observed in Fig. 4(a), that flank wear was very regular in the whole edge. It is also noticed that there was no accentuated loss of tool material. In the amplification shown in Fig. 4(b), it is observed that workpiece material adhesion on the tool substrate occurred, but it was not complete. The EDS analysis indicated that, the area identified in this figure as EDS1 was full of workpiece material adhesion (predominance of Fe, Cr and Ni in the EDS results) and that in the EDS2 area the tool substrate was exposed (predominance of W and Co).

In the amplification of the central area of the worn edge, in Fig. 4(c), it can be observed that in the whole wear land there was workpiece material adhesion. This adhesion was not continuous, it varied in thickness. The EDS analysis of the darkest area of the wear (EDS 4) shows the predominant presence of workpiece material. However, the EDS analysis in the lightest areas of the wear (EDS 3) shows that the elements of the substrate are predominant. The intensity of the adhesion varied slightly in function of the experimental machining condition and of the area of the worn edge observed. However, the wear mechanism, for the central edges, was similar to the mechanism presented in the Fig. 4 for all the experiments carried out.



(a) VE – 7% – 120 m/min

(b) ME – 7% – 120 m/min

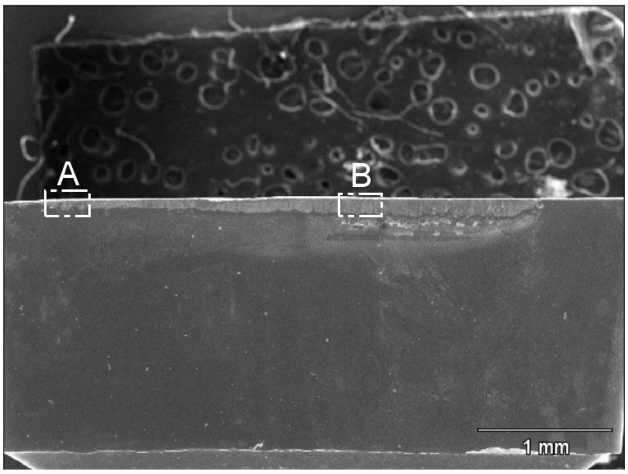
(c) VE – 7% – 160 m/min

(d) ME – 7% – 160 m/min

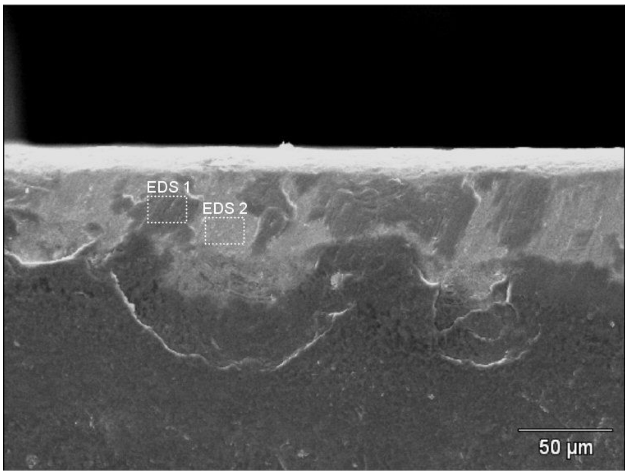
(e) VE – 12% – 160 m/min

(f) ME – 12% – 160 m/min

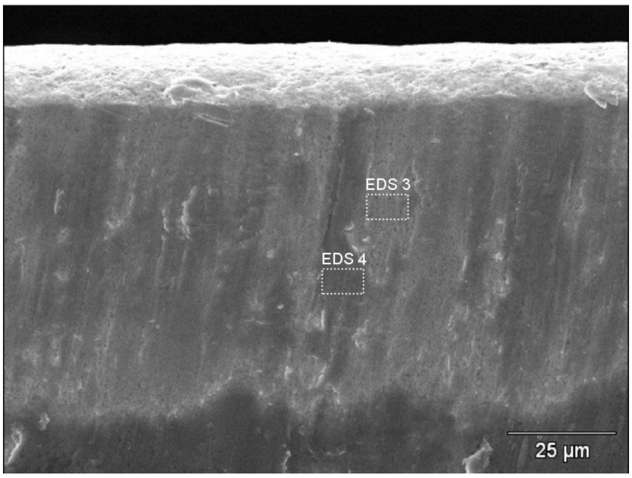
Figure 3. Pattern of the maximum flank wear under the combination of the input variables: cutting speed, type and concentration of emulsion.



(a) General view of the worn edge. The center of the drill is at the left of this picture (25x)



(b) Close-up view A of the Fig. 3(a) (350x)



(c) Close-up view B of the Fig. 3(a) (800x)

Figure 4. Sequence of MEV pictures of a worn edge of a central insert for cutting speed of 160 m/min, vegetable based emulsion in the concentration of 7%.

It can be seen on Fig. 4(b) and Fig. 4(c) that the edge radius was preserved. The wear consumed just the tool flank.

An example of worn edge for peripheral insert can be seen in the sequence of MEV pictures of Fig. 5. Fig. 5(a) shows that, for the peripheral insert, a homogeneous wear also occurred in the whole worn edge, without notch formation. There was some loss of tool material located in the area of the radius point (detail E of Fig. 5(a), amplified in Fig. 5(d)).

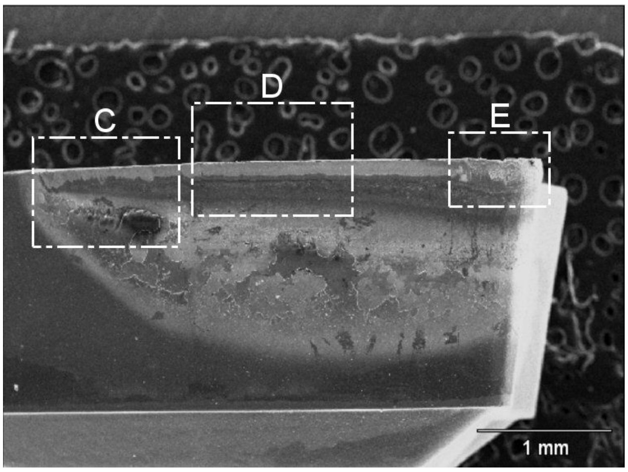
The left area of the worn edge, detail C in Fig. 5(a), can be observed in Fig. 5(b). It can be seen the existence of some areas where workpiece material is present and most of the worn edge has the substrate exposed. The EDS analysis confirms the material adhesion in the most internal area (EDS 5) and the non adhesion in the most external area of this picture (EDS 6).

The central area of the worn edge does not present any indication of workpiece material adhesion, Fig. 5(c), detail D in the Fig. 5(a). The analysis of EDS done in two different areas from this figure did not detect the significant presence of chemical elements from the workpiece material, (EDS 7 and EDS8).

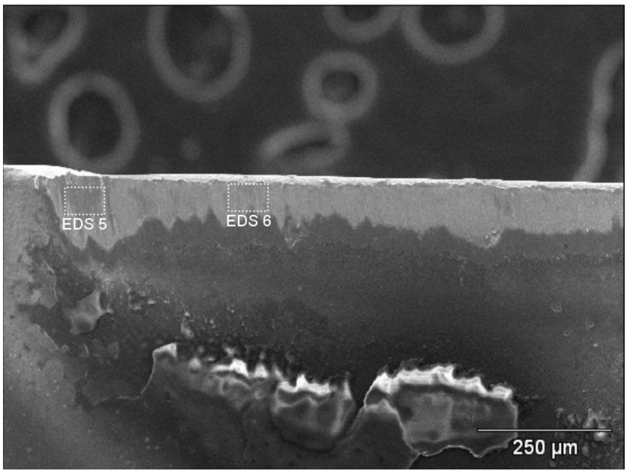
In the area of the radius point it is noticed a great adhesion, Fig. 5(d), where certainly the radius edge was already gone. This adhesion was more intense for v_c = 160 m/min.

The phenomena observed in the Fig. 5 was similar in all peripheral inserts, regardless of the cutting speed, fluid type and concentration. The intensity of the adhesion and the position of the same in the worn edge varied slightly in function of the machining conditions.

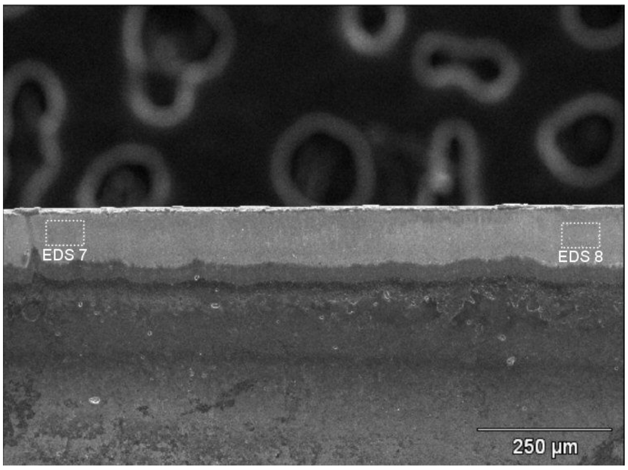
There is not any SEM picture which showed workpiece material adhesion on the tool coating. All the adhesion occurred on the tool substrate. This may mean that adhesion occurred just after the coating had been removed by other kind of tool wear.



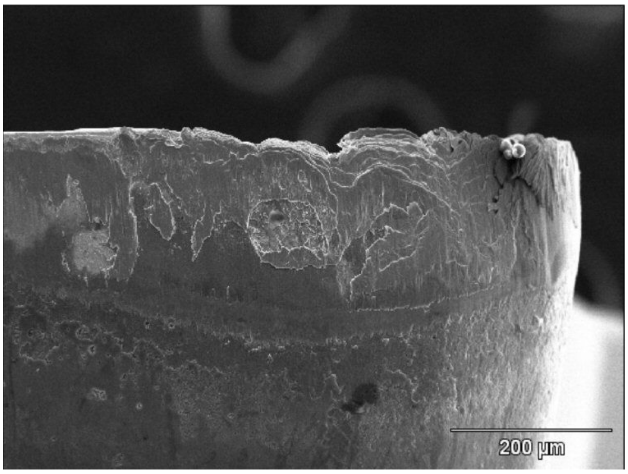
(a) General view of the worn edge. The periphery of the drill is at the right of this picture (25x)



(b) Close-up view C of the Fig. 5(a) (100x)



(c) Close-up view D of the Fig. 5(a) (100x)



(d) Close-up view E of the Fig. 5(a) (150x)

Figure 5. Sequence of MEV pictures of a worn edge of a peripheral insert for cutting speed of 160 m/min, mineral based emulsion in the concentration of 7%.

The adhesion in the tool flank is present due to the "extrusion" of the chip between the workpiece and the cutting edge (where the rake angle is negative). The chip material just above the radius edge is heavily compressed due to the high normal stresses of this region and, due to its high ductility, it reaches the condition to this extrusion to occur.

The observations realized in the SEM pictures and EDS analysis indicate that the wear mechanism present in the experiments was adhesive with removal of micro particles of the tool. When the tool penetrates the workpiece to machine the hole, there was a very intense contact between the tool flank face (full of adhered material) and the bottom of the hole being drilling. This contact created high friction between these surfaces hardening the layer of adhered material. Along the machining this adhered layer was frequently replaced by a fresh layer due to dynamic of the interaction between tool and workpiece. In this removal, the layer of adhered material pulls away micro particles of the tool, causing the wear.

The vegetable based emulsion in the concentration of 12% delayed the wear mechanism due to the sum of two factors: the addictives were in enough concentration to promote a lubricating effect capable to decrease the friction of the tool (full of adhered material) against workpiece; and this emulsion has the lowest cooling capacity among all the fluids used (Fig. 6) what made tool temperature to be the highest one and, so, causing the workpiece material to become more plastic. This effect decreased the mechanical resistance of the material, decreasing the capacity of the adhered material to remove tool particles.

An experiment was carried out to measure the cooling capacity of the fluids used in this work. This experiment is usually used to build the cooling curves of oils used in quenching. The cooling curves for all emulsions and concentrations used are showed in Fig. 6. The cooling curve of the water was used as reference. In this figure it can be observed that a different pattern exists among the water, the mineral based emulsion (ME) and the vegetable based emulsion (VE). The water cooled more quickly, followed by the mineral based emulsion and finally by vegetable based emulsion. It is also noticed that the variation of the concentration for each emulsion presented little influence on the respective cooling curves.

The fact of the mineral based emulsion to have a pattern closer to the water than the vegetable based emulsion indicates that the cooling capacity of the mineral based emulsion of was larger than to vegetable based emulsion.

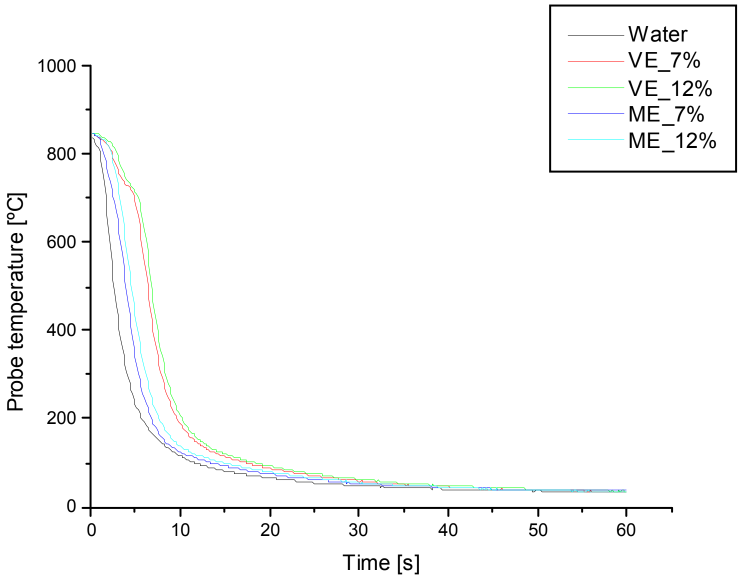


Figure 6. Cooling curves for the emulsions used in the experimentation and for the water.

4.4. Dimensional dispersion of the hole

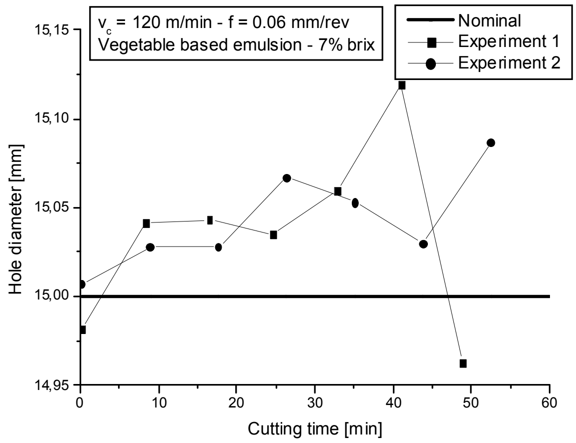
Fig. 7 shows the diameters of all the holes measured in all experiments. In this figure is also shown a line with the nominal measure of the drill diameter. This figure shows that almost all the experimental conditions with v_c = 160 m/min (Fig. 6(c-f)) produced holes with less than 0.1 mm of dimensional variation above the nominal diameter of the drill. The exception was the condition which used mineral based emulsion in the concentration of 7% (Fig. 6(d)), which presented one point of each experiment slightly above the diameter of 15.1 mm. For v_c = 120 m/min (Fig. 6(a-b)), most of the measured points were below the 15.1 mm, with few exceptions.

For the condition v_c = 120 m/min and vegetable based emulsion with 7% concentration (Fig. 6(a)), one hole was smaller than the nominal drill diameter. For this speed 120 m/min it was difficulty to extract the chip from the hole. Therefore, the chip rubbed strongly against the wall of the hole, leaving adhered particles on it. This adhesion was sufficiently strong to deposit chip material on the hole wall, causing hole diameter to be smaller than the drill diameter.

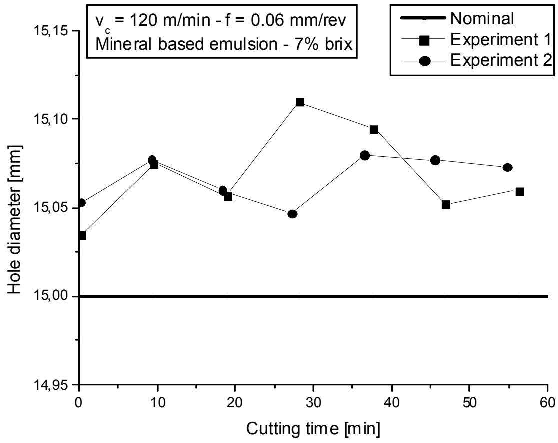
5. CONCLUSIONS

Based on the results obtained in this work, some conclusions can be drawn:

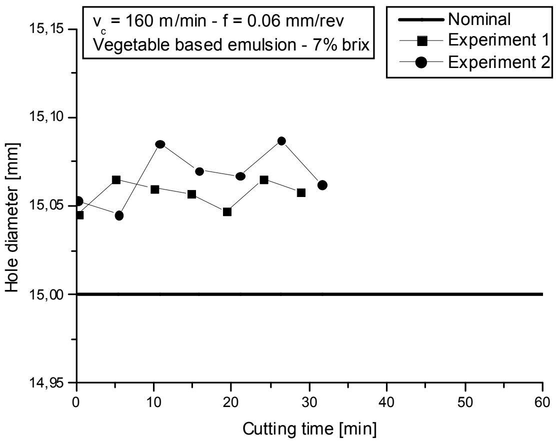
- The results of tool life showed that for the concentration of 7% (regardless the emulsion type) the elevation of cutting speed meant life reduction. The increase of the concentration of the emulsion produced results dependents of the emulsion type.
- For the cutting speeds of 120 m/min and 160 m/min in the concentration of 7% the mineral based emulsion presented slightly superior performance than vegetable based emulsion in terms of tool life. The vegetable based emulsion was very superior than the mineral based emulsion in the condition where the cutting speed was 160 m/min and the concentration 12%.
- The wear curves showed that, in the majority of the experiments, the wear growth was continuous, without long spaces of stability or sudden elevations.
- For the concentration of 7% it was noticed that the cutting speed or the emulsion type did not present any significant influence on the maximum flank wear curves. For the concentration of 12% the pattern of the wear curve was a function of the emulsion type.
- The wear mechanism of adhesion of workpiece material with removal of micro particles of the tool material occurred for all experimentation. The SEM pictures showed that adhesion of the workpiece material was always on the tool coating substrate, never on the tool coating.
- The dispersion of the hole diameters did not overcame 0.1 mm above the nominal drill diameter in most of the measurements. It was not observed any influence of the emulsion type and concentration in the dispersion of the diameter.



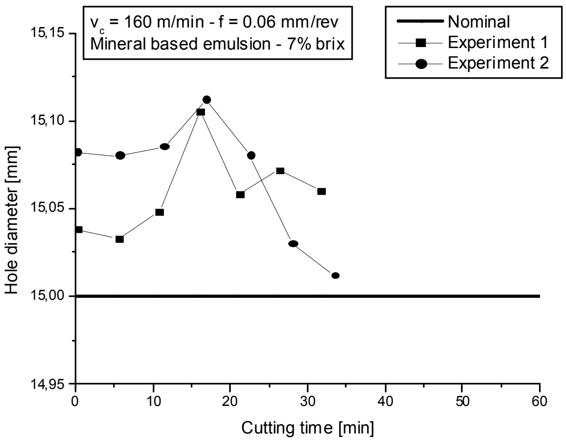
(a) VE – 7% – 120 m/min



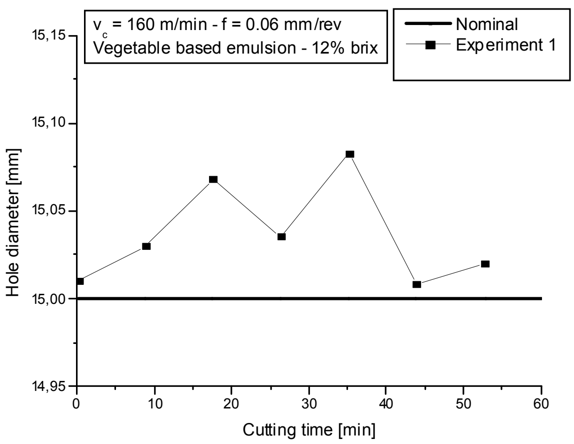
(b) ME – 7% – 120 m/min



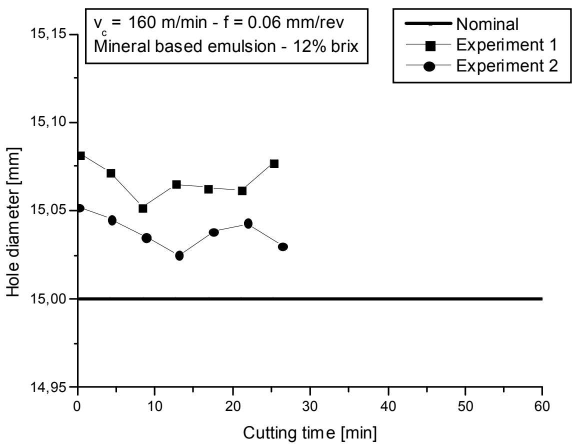
(c) VE – 7% – 160 m/min



(d) ME – 7% – 160 m/min



(e) VE – 12% – 160 m/min



(f) ME – 12% – 160 m/min

Figure 7. Dimensional dispersion of the machining hole under the combination of the input variables: cutting speed, type and concentration of emulsion.

6. ACKNOWLEDGEMENTS

To the companies Blaser Swisslube, Embraer and Sandvik Coromant for the collaboration during the execution of this work.

To FAPESP for the scholarship conceded.

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