PERFORMANCE OF COOLING/LUBRICATION CONDITIONS IN THE ROUGH MILLING OF THE 15-5 PH STAINLESS STEEL

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Abstract. *Among the construction materials used in the aerospace industry are the precipitation hardened (PH) martensitic stainless steel. However, most of the machining of stainless steels researches are carried out on the austenitic type. With the objective of preventing metallurgical changes in the part being manufactured, the machining is usually done with the aid of cutting fluid that, as it is well known, is harmful to the milling tool life. This work verifies the performance of the rough milling operation of the PH 15-5 martensitic stainless steel under three cooling/lubrication conditions. The tool used was an insert endmill with 2 cutting edges and 19.05 mm of diameter. The cutting fluids were emulsions of vegetable base and of mineral base in the concentrations of 7 and 12% brix. The input variables of this study were: the cooling/lubrication condition, the cemented carbide grade and the cutting speed. The evaluation parameters were tool life and tool wear. The results demonstrated that the cooling/lubrication conditions have strong influence in the tool life and in the evolution of the wear. The condition without fluid provided the longest tool life and the use of cutting fluid accelerated tool wear regardless the cemented carbide grade and cutting speed used.*

***Keywords**: rough milling, stainless steel, carbide tools, tool wear and cutting fluid*

1. Introduction

The aerospace industry has as characteristic the production of parts starting from solid plates. Although this procedure guarantees components of high quality, the material volume to be removed is high, demanding long time of machining. According to Bossert (1995), machining is the main cost factor in the manufacturing of parts. Stainless steels are considered difficult to machine, because they are characterized by a "plastic" behavior during the cutting, with tendency to form long chips, which adhere to the tool rake face and frequently form built-up edge. Therefore, it may result in reduced tool life and inadequate surface finish (mainly in the machining of austenitic type) (Diniz, 2001). To obtain economic tool life and appropriated surface quality, machining of these steels is usually made with the aid of cutting fluid. As most of the machining researches are carried out using the austenitic stainless steel, the feasibility of using fluid in the machining of other types of stainless steels is not well established. In the aerospace industry, the most used stainless steel is the precipitation hardened martensitic type. It is chosen due to its high mechanical resistance (close to the martensitics steels) and good ductility (close to the austenitics) (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). Most of the parts of the aerospace industry have milled surfaces. In this case, the use of fluid can be analyzed under two points of view. It is known that in most milling operations, the usage of fluid reduce tool life due to its contribution to the increase of temperature variation, which causes cracks in the cutting edge (De Melo, 2000). On the other hand, according to some aerospace industries the parts are usually machined with the aid of fluids to prevent any metallurgical damage that the material may suffer due to the heat generated. This damage may spoil the performance of the part in service, which would be disastrous. This work verifies the performance of the rough milling operation of the PH 15-5 martensitic stainless steel under three cooling/lubrication conditions.

2. Materials and methods

2.1. Materials and equipments

The workpiece material was the 15-5 precipitation hardened martensitic stainless steel in dimensions 355 mm of length x 205 mm of width x 75 mm of height. The hardness of the material was of 31 ± 1 HRc.

The tool used in the experiments was an end mill with indexable inserts with 19.05 mm (3/4 inches) of diameter with 2 cutting edges. The mill has 2 channels which allow the cutting fluid to pass through the interior of the mill, making possible the application of the fluid directed to the rake surface of each insert.

The cemented carbide inserts used in the experiments have as substrate WC plus Co and are coated with TiAlN (deposited for PVD process - Physical Deposition Vapor) and nose radius of 0,4 mm. Two cemented carbide grades were used, an ISO M30 - M40 and another ISO M20 - M40.

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

The flank tool wear measurements were carried out at various machining intervals using a stereoscope microscope (with maximum magnification of 50 times) connected to an image acquisition system composed of CCD camera and a computer with image acquisition software with measurement resources (Global software Lab Image). To facilitate the measurement of the cutting edges of the mill, a divider device was incorporated to the stereoscopic which allows the clamping of the tool through its tool holder. With the turn of the divider, the two cutting edges can be located for measurement of the wear.

2.2. Experimental methodology

Down milling was made with passes executed in the longitudinal direction of the workpiece. After certain number of consecutive milling passes the measurement of the flank wear was accomplished. The number of passes varied in function of the application or not of the emulsion. When the machining was accomplished without the application of emulsion (dry cutting), the usual number of consecutive passes was 5 and, in the case of the application of emulsion, the usual number of passes was 2. This procedure was necessary due to the fact that tool life with emulsion was much shorter than tool life when the cutting was carried out without fluid. The measurement of the flank wear was made in each one of the cutting edges. With the wear measured, the tool was assembled again in the machine-tool for the milling of a new set of passes. This procedure was repeated up to the point the tool reached its criterion of tool life (maximum flank wear V_{Bmax} = 0.3 mm).

3. Experimental planning

Three 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 of 120 and 140 m/min were employed based on the results of preliminary experiments.

Cemented carbide tool grade - the performance of the tool is very dependent of the chosen grade. Depending of the characteristics of the stainless steel, a grade recommended by the tool manufacturer can not present the expected results. Two cemented carbide grades was chosen: a grade with higher toughness (ISO M30 - M40) with larger WC grain size (> 1 micron) and a grade with intermediary properties (ISO M20 - M40 – intermediary toughness and hot hardness) with grain size smaller than 1 micron. To facilitate the identification of cemented carbide grade the nomenclature of the manufacturer was used. In this way, ISO M30-M40 grade corresponds to the 2030 grade and ISO M20-M40 grade to 2005 grade.

Cooling/lubrication condition - Normally cutting fluid in the milling is not used. However, the machinig without fluid could soon modify the workpiece microstructure below the surface. It is important to remember that the studied steel is used in the aerospace industry, which has a very demanding quality control. 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. Three forms of emulsion applications were tested: without fluid or dry (D); with fluid application externally to the tool (EF), with flow rate of 45 l/min and with fluid injected internally to the mill (IF), with flow rate of 25 l/min. Related to the type and concentration of emulsions, two emulsions had been used: one of vegetable base (VE) and another one of mineral base (ME). For both, the concentrations used were 7% and 12% brix.

The experiments were divided in two stages. The first one aimed to identify which cemented carbide grade suited for this operation under different cooling/lubrication conditions and cutting speeds. In this stage just the vegetable emulsion in the concentration of 7% was used. Therefore, this first stage of the experiments had three input variables (cutting speed in 2 levels, cemented carbide grade in 2 levels and cooling/lubrication condition 3 levels, totalizing 12 experimental conditions). Table 1 shows the experimental matrix of this stage. Each condition of experiment was made twice. The order of the experiments was randomly chosen.

Table1. Matrix of experiments of the first stage

Cutting speed [m/min]	Cemented carbide grade	Cooling/lubrication condition		
		Dry (D)	External Fluid (EF)	Internal Fluid (IF)
120	2030	120_2030_D	120_2030_EF	120_2030_IF
	2005	120_2005_D	120_2005_EF	120_2005_IF
140	2030	140_2030_D	140_2030_EF	140_2030_IF
	2005	140_2005_D	140_2005_EF	140_2005_FI

After accomplished the first stage and it was concluded that 2005 (ISO M30 - M40) grade presented the longest tool life, this grade became a constant in the second stage. In this stage the input variables were type and concentration of the emulsion (the exception was the vegetable emulsion in the concentration of 7% that already had been tested in the first stage), cutting speed and form of application of the emulsion. The combination of these variables generated a second matrix of experiments, presented in Tab. 2.

Table 2. Matrix of experiments of the second stage

Type and concentration of the emulsion	Cutting speed [m/min]	Form of the application of the emulsion	
		External Fluid (EF)	Internal Fluid (IF)
Vegetable Emulsion (VE) 12%	120	VE_12%_120_EF	VE_12%_120_IF
	140	VE_12%_140_EF	VE_12%_140_IF
Mineral Emulsion (ME) 7%	120	ME_7%_120_EF	ME_7%_120_IF
	140	ME_7%_140_EF	ME_7%_140_IF
Mineral Emulsion (ME) 12%	120	ME_12%_120_EF	ME_12%_120_IF
	140	ME_12%_140_EF	ME_12%_140_IF

The performance of the milling was evaluated through the tool life. The tool life was measured through the effective cutting time that the tool provided under the various machining conditions tested. The criterion of end tool life was the maximum flank wear of 0,3 mm.

The evolution of the wear throughout each experiment was monitored to allow the elaboration of the curves of wear behavior.

With intention to search for explanations for the differences of tool life and the differences in the curves of wear evolution among all the conditions tested, it was necessary to identify the predominant mechanisms of wear. To reach this objective, photographs of scanning electron microscope and analyses of EDS (Energy Disperse Spectroscope) on the worn edges were taken.

The parameters that had been kept constant during all the experimentation had been: radial depth of cut -13,33 mm (70% of the diameter of the mill); axial depth of cut - 4 mm; feed per tooth - 0,12 mm.

4. Results and Discussion

4.1. Tool life

Tool life values represented by effective cutting time showed in Figs. 1-3 is a result of average two life recorded under the same machinig 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 (in some conditions it did not have dispersion, therefore the life for the two experiments of the same condition coincided).

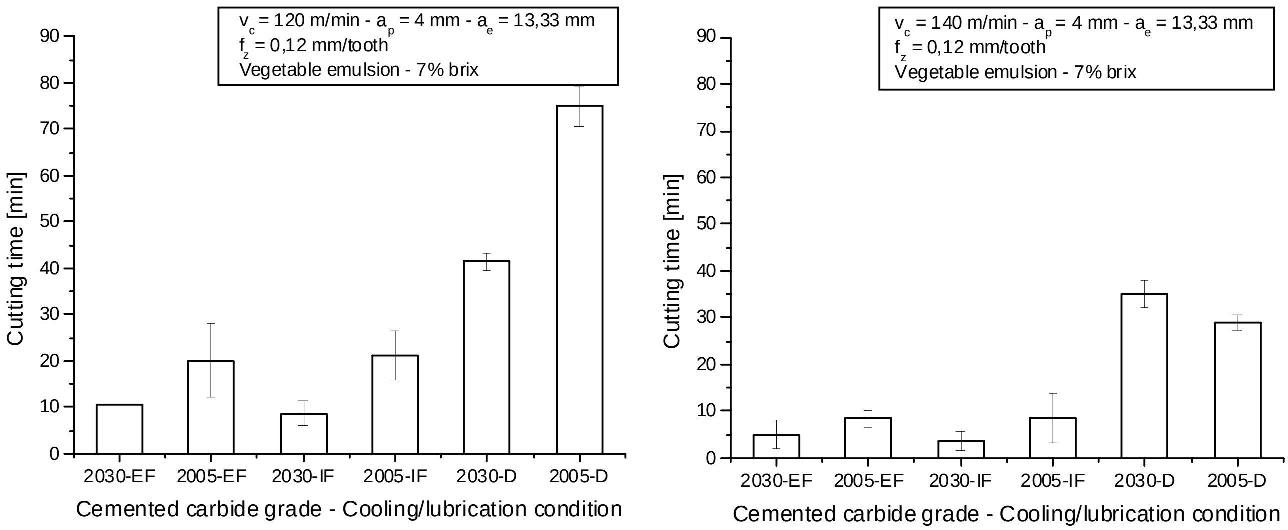
The results of the first stage of the experimentation had shown that the life of the tool was influenced by all input variables. Fig. 1a presents the results of tool life (in cutting time) versus cooling/lubrication condition combined with cemented carbide grade for the cutting speed of 120 m/min and the Fig. 1b presents a similar graph for the cutting speed of 140m/min.

It can be seen in figures 1a and 1b that application of cutting fluid, either externally or internally the mill, diminishes tool life when compared with the condition without fluid for the same cemented carbide grade and same cutting speed. It is clear from Fig. 1a e 1b that tool wear is accelerated when vegetable emulsion (concentration of 7%) is employed..

Analyzing the performance of carbide grades, it can be seen in the figures that 2005 grade presented longer life than 2030 grade in the great majority of the experiments when compared under the same cooling/lubrication conditions and cutting speeds. The only exception occurred for the cutting speed of 140 m/min and cooling/lubrication condition without fluid, where 2030 grade was superior. An analysis of variance (ANOVA) test confirmed, with 95% of confidence, that the 2005 cemented carbide grade was superior than 2030 grade. The better performance of 2005 grade occurred due to the good general conditions of the operation (rigidity of the machine-tool, good clamping of the workpiece, tool holder with enough rigidity and absence of interrupted surfaces in the workpiece). Under these conditions, it could be expected that a more wear resistant tool would have longer tool life. The 2030 grade would have the advantage of being tougher, what would help this grade to resist better to the mechanical and thermal shocks, characteristics of the milling process. However, 2005 grade possess the WC grain size smaller than 1μm, what improves the toughness of the tool without loss of the hardness. In this way, 2005 grade also has a good toughness. For the second stage of the experimentation 2005 grade was the only used.

The increase of the cutting speed influenced negatively the tool life in all the comparable conditions (same cooling/lubrication condition and cemented carbide grade), as it was expected.

Just the cooling/lubrication condition without fluid was capable to provide 30 minutes of machining, which could be considered the minimum tool life acceptable. The use of the vegetable emulsion in the 7% concentration was not capable to provide an acceptable tool life, mainly for the cutting speed of 140 m/min. However, a question still remain: "A change in the concentration of this emulsion or another type of emulsion could produce a better result?" The answer for this question was searched in the second stage of the experiments.



(a) Cutting speed 120 m/min

(b) Cutting speed 140 m/min

Figure 1. Tool life for the first stage of the experiments under three cooling/lubrication conditions and two cemented carbide grades.

The raise of the concentration of the vegetable emulsion for 12% reduced even more tool life, regardless cutting speed, as can be seen in Fig. 2 and Fig. 3. In the same figures, it can be observed that the substitution of the vegetable emulsion for a mineral emulsion also revealed inadequate, since the tool life it generated was even shorter than that obtained with vegetable emulsion, regardless the concentration. This occurred due to the bigger cooling capacity the mineral emulsion. The cooling curves for each emulsion had been built through an experiment where a heated probe (with an internal thermocouple) was plunged in a container containing the emulsion. The acquisition of the temperature was made during one determined period of time made possible the construct of cooling curves. It could not be said that this kind of experiment could simulate the dynamics of a machining operation, however, a qualitative comparison between the cooling curves of the emulsions can be made with the objective to identify tendency of behavior. These curves are not shown here due to lack of space.

In opposition to the vegetable emulsion, the increase of the concentration to 12% for the mineral emulsion improved tool life compared with 7% concentration for the cutting speed of 120 m/min. For the cutting speed of 140 m/min the mineral emulsion concentration did not influence tool life.

The machining without cutting fluid continued being the best option to maximize tool life.

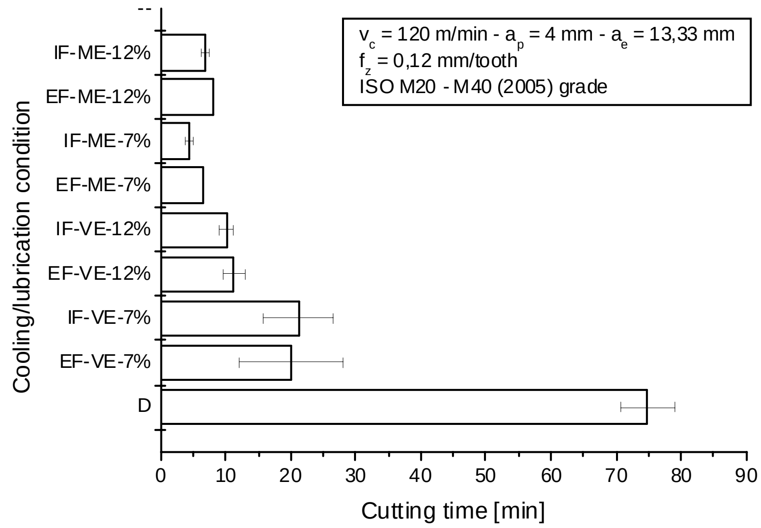


Figure 2. Tool life for cutting speed of 120 m/min under all cooling/lubrication conditions in the second stage of the experiments.

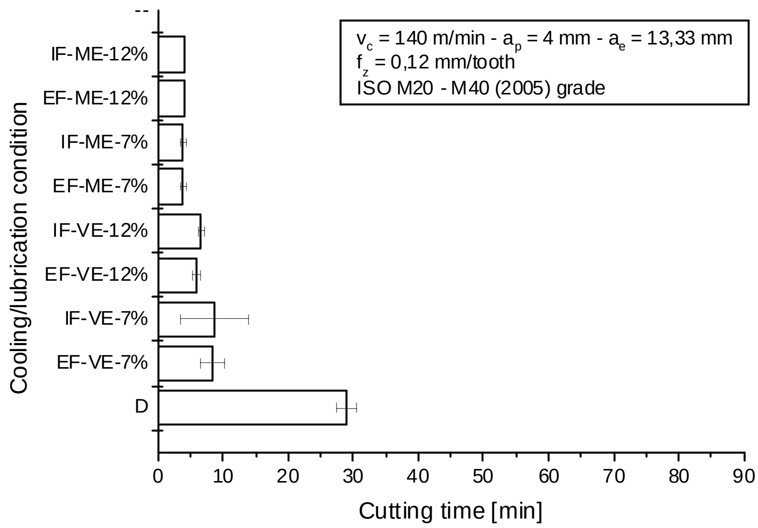


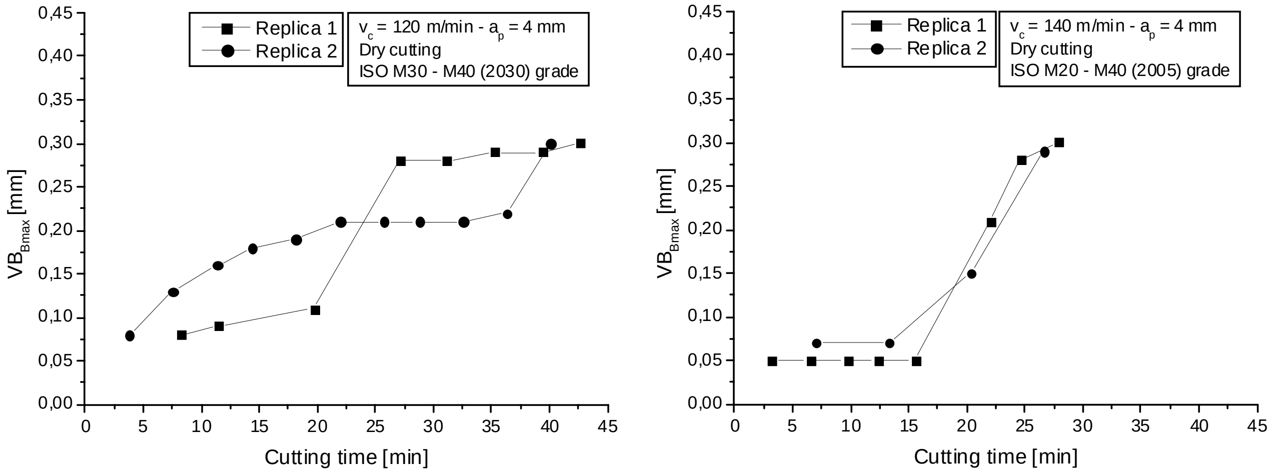
Figure 3. Tool life for cutting speed of 140 m/min under all cooling/lubrication conditions in the second stage of the experiments.

4.2 Tool wear behavior

It can be observed in figures 4 and 5 that the wear evolution during the experiments followed two similar behavior standards, with some differences. For the machining without fluid, in the majority of the cases, the initial rate of wear growth was lower than the wear rate of the machining with the application of emulsion. Fig. 4 shows this wear behavior for milling without fluid. In the graph of the Fig. 4a, each replica showed distinct behaviors. Replica 2 presents a rate of wear growth constant until half of tool life, followed by a stability in the wear rate and with sudden increase of the wear in the end of the life. This behavior occurred in the minority of the cases. The most common behavior was like replica 1 of the same figure, where the wear starts with a small rate, passes through an abrupt rise and the end of tool life was reached with a small wear rate. The two replicas shown in figure 4b present similar behaviors. The wear growth rate was null in the beginning, passes for a sudden rise, which leads to the life end or to a wear very close to the end of tool life. It was also observed that the final wear slightly exceeded the criterion of end life (maximum flank wear of 0,3 mm). Figure 5 presents other two graphs that characterize the behavior of the wear for the milling with the application of emulsion. The graphs of Fig. 5a and Fig. 5b present very similar behaviors. The initial rate of wear was very small and, suddenly, the rate grew abruptly. In these graphs, it can be observed that the final wear exceeds by far the tool life criterion. In some situations, the final wear was well above of the maximum wear presented in the Fig. 5a and Fig. 5b, causing the chipping of the edge. This behavior occurred regardless the cutting speed and cemented carbide grade.

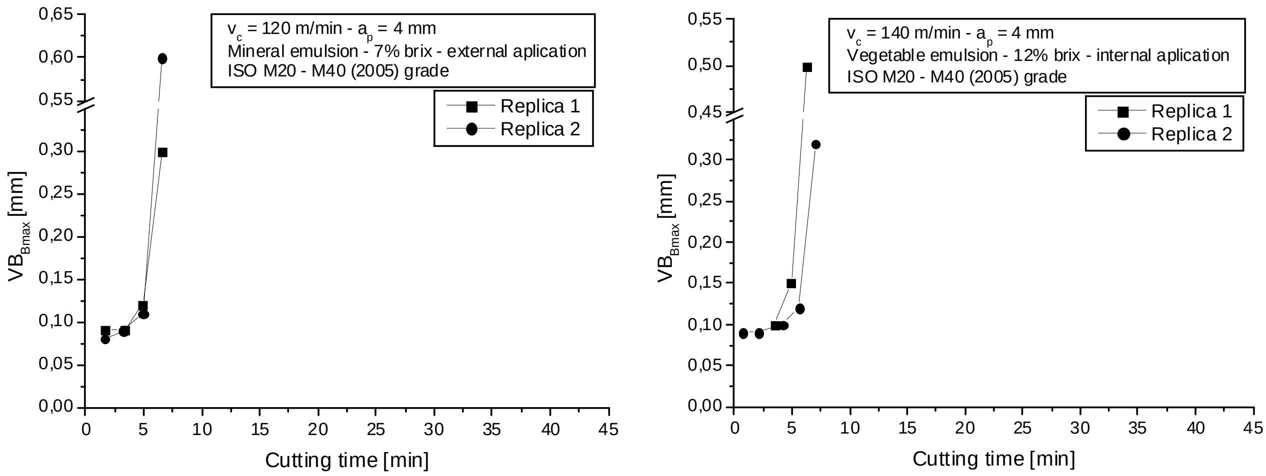
In a general qualitative analysis, it can be said that the behavior of the wear curves followed the same standard. In the majority of the experiments accomplished, the wear has a continuous growth until little more than the half of the tool life. The end of the life was marked, in the majority of the cases, for a sudden raise of the wear. This occurred regardless the cutting speed, cemented carbide grade and cooling/lubrication condition.

This abrupt form of ending tool life, makes difficult to affirm with some security which tool life should be expected for one given condition or which would be the right moment for the exchange of the inserts in a production environment.



(a) Cutting speed 120 m/min (b) Cutting speed 140 m/min

Figure 4. Tool wear behavior for experiments without application of emulsion (dry cutting).



(a) Cutting speed 120 m/min (b) Cutting speed 140 m/min

Figure 5. Tool wear behavior for experiments with application of emulsion.

4.3. Tool wear mechanism

When machining without fluid, the wear was marked by the presence of the mechanism of abrasive wear with much adhesion of the workpiece material in the worn edge, as it is shown in Fig. 6. These characteristics of wear had been observed regardless the cutting speed and the cemented carbide grade.

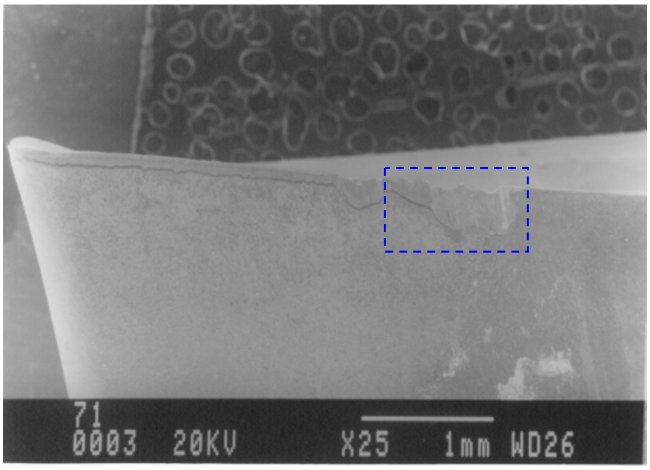
Figure 6a shows that an uniform wear occurred until close to the end of the contact workpiece-tool, where the wear becomes more intense. In all the worn edge occurred the adhesion of workpiece material.

In the region of larger wear, Fig. 6b, the adhesion covered completely the tool substrate. The analysis of EDS, made inside of the area delimited for the indicative rectangle in this same figure, confirms that the workpiece material predominates in this region.

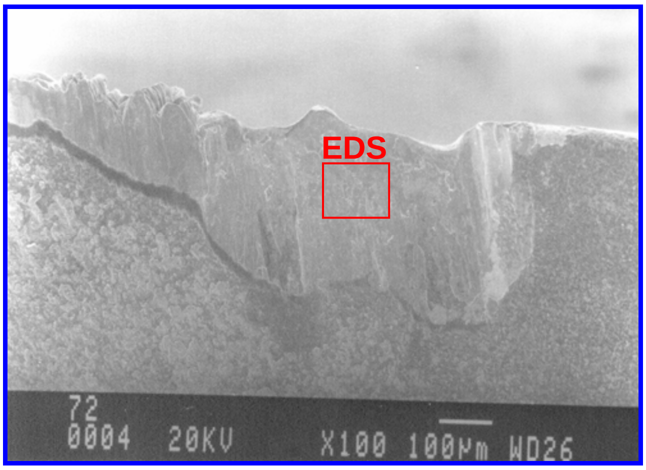
When the machining was accomplished with the application of emulsion, the cutting edge suffered a wear much higher, Fig. 7, regardless the type of emulsion or the application form. It can be noticed that some adhesion of the workpiece material occurred and, in a large part of the worn edge the substrate was exposed.

I can be noticed in fig. 7a that the great loss of material from tool was concentrated in the nose radius region and that, in the rest of the edge, only the flank of the tool suffered a soft and homogeneous wear, without accented loss of material. Figure 7b shows a magnification of the nose radius region, in which it can be observed that there were particles of the workpiece material adhered in the inferior part of the wear. In the superior part of the wear the tool substrate was completely exposed.

In the remaining portion of the worn edge, the edge radius was destroyed and a very fine adhesion of the workpiece material in the flank of the tool occurred, Fig. 7c.

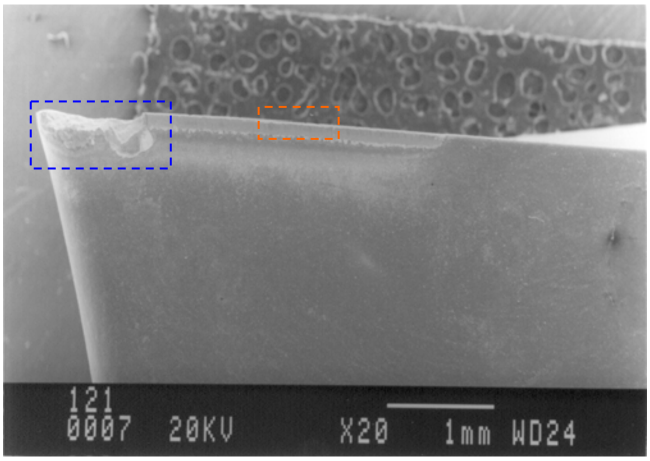


(a) General view. Magnification 25x.

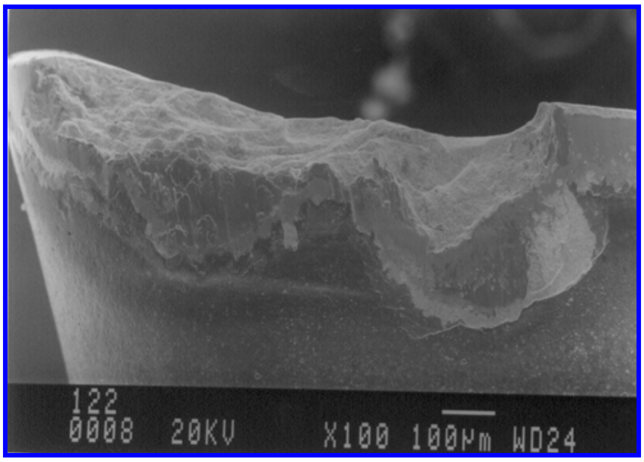


(b) Magnification of the region inside blue rectangle from picture (a). Magnification 100x.

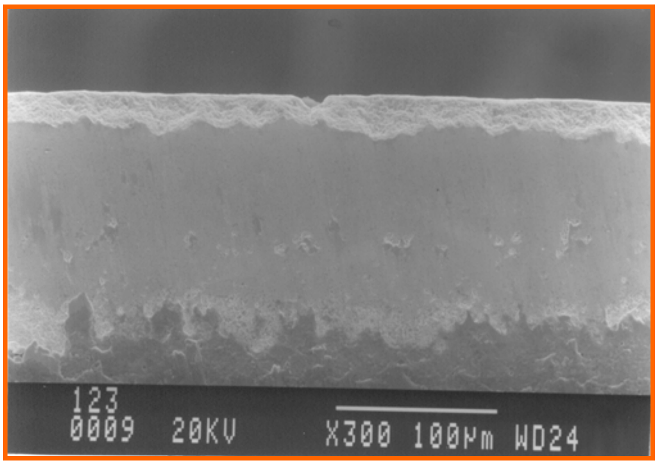
Figure 6. Sequence of pictures from SEM for cutting speed 140 m/min, cemented carbide grade 2005 and cooling/lubrication condition without fluid.



(a) General view. Magnification 25x.



Magnification of the region inside blue rectangle from picture (a). Magnification 100x.



Magnification of the region inside orange rectangle from picture (a). Magnification 300x.

Figure 7. Sequence of pictures from SEM for cutting speed 120 m/min, cemented carbide grade 2030 and cooling/lubrication condition with vegetable emulsion in the concentration of 7% with internal application.

The wear mechanisms do not depend on the cutting speed and on the cemented carbide grade. For these two parameters, only a variation in the intensity of the wear occurred, but it did not occur a change of wear mechanism.

Based on various analysis on worn tools, the following explanation for the wear mechanisms in these tools can be drawn. The change of the wear mechanism occurred in function of the cooling/lubrication conditions used. For the milling without cutting fluid the wear mechanism was abrasive with adhesion of the workpiece material along the worn edge. This adhesion occurred, in the majority of the cases, of homogeneous form. In some worn edges it was possible to observe particles of material adhered on it (on the edge radius). When the emulsion was applied (regardless the type and concentration) the wear was much more severe with great removal of particles of the tool substrate (great compared with the size of the wear). This process of particle removal had begun with the arising of small points where the substrate "was eroded" and, as the machining continued, these points of erosion grew and joined with the neighboring points forming a worn surface. The loss of the initial geometry of the tool contributed to increase the area of contact of the region of the edge radius and, consequently, it raised also the intensity of the mechanical shock in each new interaction between tool and workpiece. This shock facilitated the formation of cracks in the cutting edge, which facilitated the process of particle removal from the tool. These cracks also have in its formation a contribution of the thermal shock inherent of the process of milling and increased by the application of the emulsion. In the machining with emulsion also adhesion of workpiece material occurred. The adhesion occurred only in part of the worn edge and for greater particles compared to the size of the wear.

The adhesion is more homogeneous in the machining without fluid because the workpiece material in the cutting zone presented a relatively high temperature, what makes easier its plastic strain. In the case of the machining with emulsion, the temperature of the part in the region of chip formation is relatively low, what makes difficult the plastic strain of the workpiece material and the adhesion of the material occurs in a very well limited region, due to pure compression. The adhesion of the workpiece material always occurred on the exposed substrate and it was never observed a case where the adhesion occurred on the tool coating.

Conclusions

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

1. The cutting without fluid always generated longer tool lives when compared with the cutting with flood of emulsion, regardless the cutting speed and cemented carbide grade used.
2. The cemented carbide grade 2005 (ISO M20 - M40) presented better results compared to the grade 2030 (ISO M30 - M40) in terms of tool life, due to its higher hot hardness and good toughness.
3. In dry cutting, a strong adhesion between workpiece material and tool flank surface always occurred and abrasive wear was always present.
4. In cutting with abundant fluid the main wear mechanism was the removal of tool particles caused by the adhesion of workpiece material on the tool wear land.
5. The end of tool life was sudden in the majority of the cases.

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