INFLUENCE OF THE CUTTING FLUID CONDITIONS IN FINISH MILLING OF 15-5PH STAINLESS STEEL

Fernando Teixeira Filho
Federal Center of Technological Education of Minas Gerais – CEFET-MG
Campus VIII - Varginha
Rua Presidente Antônio Carlos, 356.
37.002-000 – Varginha – MG
fernandotf@varginha.cefetmg.br

Anselmo Eduardo Diniz
Department of Fabrication Engineering
The State University of Campinas – UNICAMP
R. Mendeleiev, s/n
Cidade Universitária "Zeferino Vaz" Barão Geraldo
13.083-970 – Campinas – SP
anselmo@fem.unicamp.br

Aldo Braghini Júnior
Federal Technological University of Paraná – UTFPR
Avenida Monteiro Lobato, km 04, s/n. Jardim Pitangui
84.016-210 – Ponta Grossa - PR
aldo@pg.cefetpr.br

Abstract. *The preciptation hardenable stainless presents high mechanical strength and corrosion resistance, having a wide application field, specially in the aerospace industry. The present work evaluated the influence of cutting fluids in the 15-5PH martensitic stainless steel milling, using carbide tool, TiAlN coated. Experiments were carried out for finishing operation, varying the carbide tool class (M20-M40 and M30-M40), the cutting speed (100 and 120 m/min), the lubri-cooling conditions (without cutting fluid, internal and external emulsion apllication) and the emulsion concentration (7% and 12%). Tool wear, power consumption and workpiece roughness were measured. The analysis of the results allowed to conclude that the machining without cutting fluid gave longer tool life than with emulsion application, regardless the cemented carbide grade and cutting speed used. The results also demonstraded that the cooling/lubrication conditions have strong influence in the tool life and in the evolution of the wear.*

Keywords*: stainless steel, milling, 15-5PH, cutting fluids.*

1. INTRODUCTION

Due to anti-corrosive and resistance characteristics, stainless steels are frequently used in the food, chemical, oil and aerospace industries. The aerospace industry has as characteristcs the production of parts starting from a 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. This may result in reduced tool life and inadequate surface finish, mainly in the machining of austenitic type (Diniz et al., 2001). To obtain economic tool life and appropriate surface quality, machining of these steels is usually made with the aid of cutting fluid. 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 steels (Arisoy, 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 the fluid can be anlyzed under two points of view. Is is known that in most milling operations the use of the fluid harms the tool life due to its contribution to the increase of temperature variation, which causes cracks in the cutting edge (De Melo et al., 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. The main goal of this work is verifies the performance of the finish milling of the 15-5 precipitation hardened martensitic satainless steel under diferentes cooling/lubrication conditions.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

The workpieces was made of 15-5PH stainless steel and had hardness varying from 30 to 32 HRc. The dimensions of the workpiece were 355 mm length x 205 mm width x 75 mm height. The experiments were carried out in a Mori Seiki vertical machining center, model SV-40, with a spindle of 22 kW.

The tool was an end mill with three cutting edges and a diameter of 19,05 mm. The inserts used had 0,8 mm of nose radius. 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 in the experiments have as substrate WC plus Co and are coated with TiAlN, deposited for PVD process.

To the experimental planning, three input variables were selected:

Cutting speed – two cutting speed of 120 and 140 m/min were employed, based on the results of preliminary experiments.

Cemented carbide grades – ISO M30-M40 and M20-M40, both coated with TiAlN deposited by PVD process. There was a difference in the tungsten carbide (WC) particles size of the substrate. They were sub-micrometric in the M20-M40 grade. To facilitate the identification, the manufacturer's nomenclature of the grades will be used in this work. Therefore, the ISO grade M30-M40 corresponds to the grade IN2030 and the ISO grade M20-M40 to the grade IN2005.

The cooling/lubrication condition – without fluid, called dry cutting, and an emulsion applied external and internally to the mill.

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 in 3 levels, totalizing 12 experimental conditions). Table 1 shows the experimental matrix of this stage. Each condition of the experiment was made twice. The order of the experiments was randomly chosen.

Table 1. Matrix of the experiments of the first stage.

Cutting speed v_c (m/min)	Cemented carbide grade	Cooling/lubrication condition		
		Dry (D)	External Fluid (EF)	Internal Fluid (IF)
100	IN2030	100 2030 D	100 2030 EF	100 2030 IF
	IN2005	100 2005 D	100 2005 EF	100 2005 IF
120	IN2030	120 2030 D	120 2030 EF	120 2030 IF
	IN2005	120 2005 D	120 2005 EF	120 2005 IF

After accomplished the first stage and it was concluded that IN2005 grade (ISO M20-M40) presented the longest tool life, this grade became a constant in the second stage. In this stage the concentration of the cutting fluid was 12%, the cemented carbide grade was IN2005 and the application of the emulsion was internal and external to the tool.

The out put variables were tool life, tool wear and roughness of the workpiece. The depth of cut (a_p = 1,0 mm), feed (f_z = 0,08 mm/tooth) and radial depth of cutting (a_e = 13,33 mm, corresponding to a 70% of the diameter of the mill) were kept constant in all experiments.

The rule to determine the end of the tool life in the experiments was the maximum flank wear of 0,2 mm, that is a typical value for finish operations. All the experiments were carried out using down milling in the longitudinal direction of the workpiece. They were milled in a series of five passes and, at the end of the fifth, the machining was interrupted for the mesasurement of the tool wear. The measurement of the maximum flank was made in each of the cutting edges. Once the wear was measured, the tool was set up again in the machine tool for the milling of a new series of five passes, in the end of the which the measurement procedure of the wear was repeated, until the maximum flank wear of 0,2 mm was reached.

The Ra roughness measurement was made when the whole surface of the workpiece was machined. The measures were made in the area of the workpiece machined by the first pass (new cutting edge), by the fifth pass and, in the sequence, of 5 in 5 passes up to the end of the expermiment. Three measurements, using a cutoff of 0,8 mm, of roughness were taken in each measurement area.

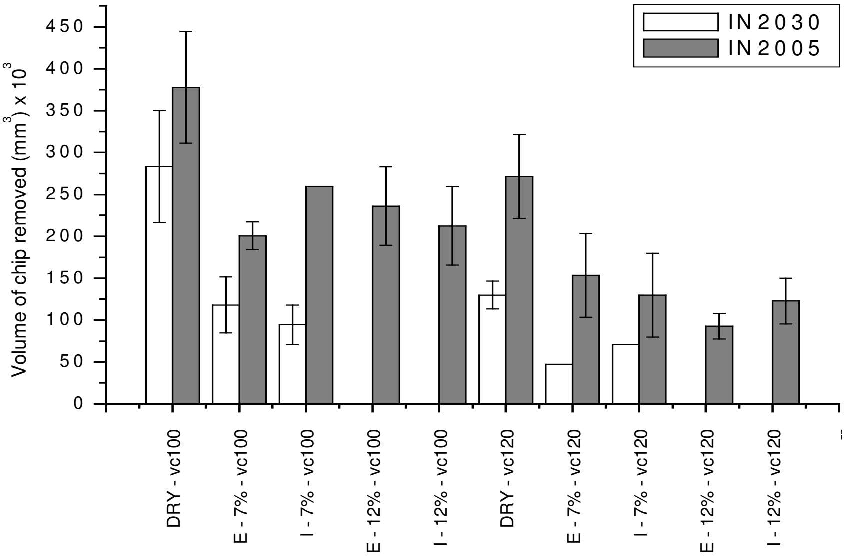
At the end of the experiments, the worm inserts were analysed in Scanning Electron Micorscope (SEM), with the aid of the Energy Disperse Spectroscope (EDS) to characterize the type of wear.

3. RESULTS AND DISCUSSION

3.1. Tool life

Figure 1 shows the results of tool life (in volume of chip removed) for all the conditions experimented in this work. The tool life is a result of average two life 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. In some conditions it did not have dispersion, therefore the life for the two experiments of the same condition coincided.

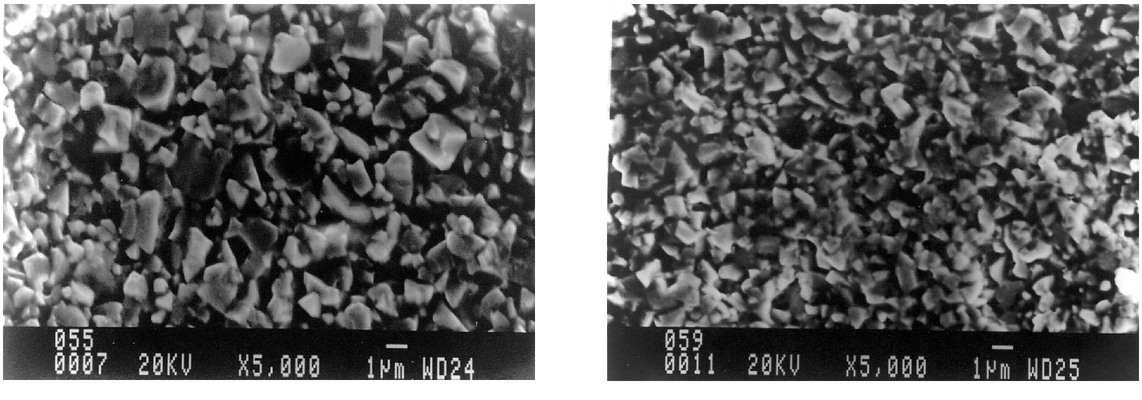
Material: 15-5PH (UNS 15500) stainless steel, hardness 35 HRC. **Cutting tool:** Cemented carbide grade ISO M30-M40 (IN2030), PVD TiAlN and ISO M20-M40 (IN2005), PVD TiAlN. **Insert:** APKT080304R. **Cutting parameters:** a_p=1,0 mm; a_e=13,3 mm; f_z=0,08(0,04) mm/insert. Using v_c=100 m/min: v_f=401(200) mm/min, n=1670 rpm. Using v_c=120 m/min: v_f=481(240) mm/min, n=2005 rpm. **Cutting fluid**: vegetable emulsion, concentration 7%e 12%. **Application of cutting fluid:** external e internal.



DRY – without cutting fluid	**E** – External application of cutting fluid (emulsion)
vc100 – cutting speed 100 m/min	**I** – Internal application of cutting fluid (emulsion)
vc120 – cutting speed 120 m/min	**7% –** concentration of 7%
	12% – concentration of 12%

Figure 1. Tool life, in terms of volume of chip removed, versus cooling/lubrication conditions for all conditions experimented in the finish milling operation.

It can be observed in Figure 1 that the cemented carbide IN2005 grade always presented longer life than the IN2030 grade. The most wear resistant grade presented the best performance. In part this result can be attributed to the good rigidity of the machine-tool, good fixation of the workpiece and tool and to the absence of interrupted surfaces in the workpiece. This good conditons minimized vibration and, so, avoided situations that favored chipping. Besides, the IN2005 grade has smaller size of tungsten carbide particles, which confers more toughness to this grade. Figure 2 shows the grain size of the cemented carbide used in the experiments



a) Cemented carbide M30-M40 (IN2030) grade. b) Cemented carbide M20-M40 (IN2005) grade.

Figura 2 – Pictures showing the grain size of the cemented carbide grade used in the experiments, magnification of 5.000x.

It also can be observed in figure 1 how the action of the cutting fluid was harmful for tool life, regardless the cutting speed and the cemented carbide grade. It can bee seen in this figure that the 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 the figure 1 that tool wear is accelerated when vegetable emulsion is employed.

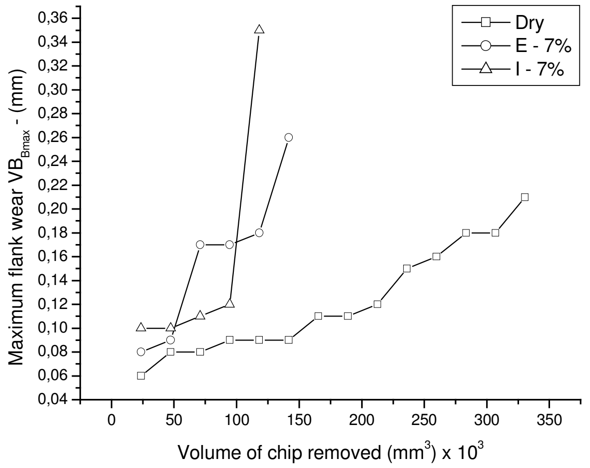
The increase of the cutting speed influenced negatively the tool life in all the comparable conditions (same cooling/lubrication condition and cemented carbide grade), as it was expected. The increase of the cutting speed increase the heat generation and the wear of the tool is accelerated.

Comparing the concentration of the vegetable emulsion (7% and 12%) and considering the standard deviation, it is not possible to affirm which condition presented the better performance.

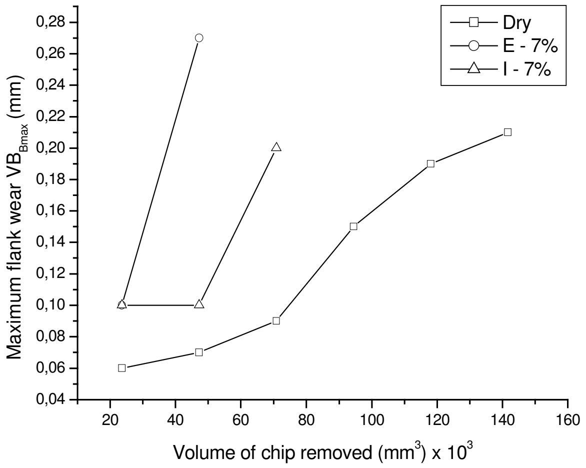
3.2. Flank wear

Figure 3 shows the behavior of the maximum flank wear of the tools used in the experiments. The curves represent the better performance of the tool for two replicas executed in each one of the conditons experimented. In others words, it was taken for each conditon the replica that presented the largest volume of chip removed.

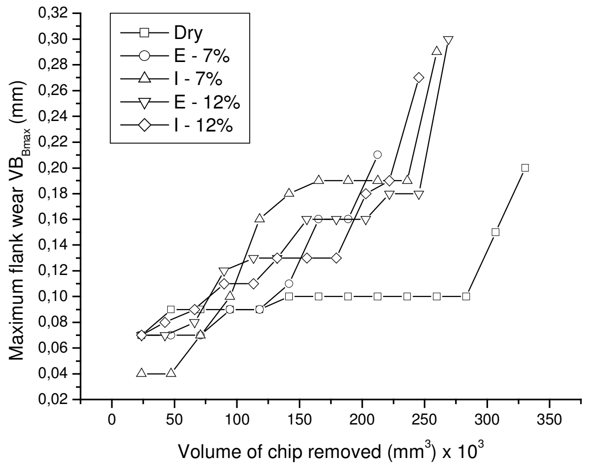
Material: 15-5PH (UNS 15500) stainless steel, hardness 35 HRC. **Cutting tool:** Cemented carbide grade ISO M30-M40 (IN2030), PVD TiAlN and ISO M20-M40 (IN2005), PVD TiAlN. **Insert:** APKT080304R. **Cutting parameters:** a_p=1,0 mm; a_e=13,3 mm; f_z=0,08(0,04) mm/insert. Using v_c=100 m/min: v_f=401(200) mm/min, n=1670 rpm. Using v_c=120 m/min: v_f=481(240) mm/min, n=2005 rpm. **Cutting fluid**: vegetable emulsion, concentration 7%e 12%. **Application of cutting fluid:** external e internal.



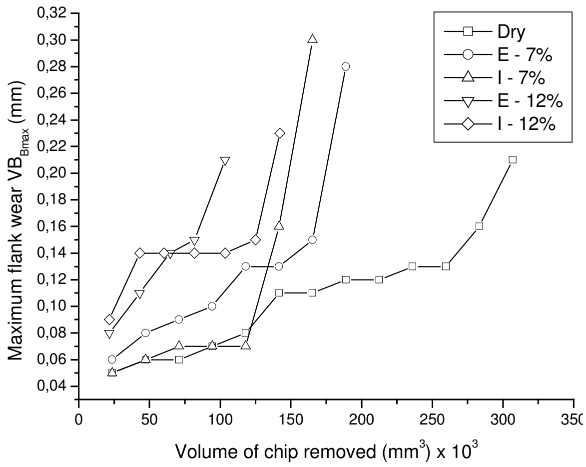
a) Cemented carbide IN2030, v_c = 100 m/min



b) Cemented carbide IN2030, v_c = 120 m/min.



c) Cemented carbide IN2005, v_c = 100 m/min



d) Cemented carbide IN2005, v_c = 120 m/min

Dry – without cutting fluid
E – External application of cutting fluid (emulsion)
I – Internal application of cutting fluid (emulsion)
7% – concentration of 7%
12% – concentration of 12%

Figura 3 – Behavior of the maximum flank wear VB_{Bmax} for the replicas that presented better performance.

It can be observed in all the graphics of the Figure 3 that, when dry cutting was used, the slope of the wear was roughly constant and, after certain period of cutting time it changed abruptly, overcoming the value established for the end of tool life.

It can be seen in the graphics of the figure 3 that the use of cutting fluid accelerated tool wear. The IN2030 cemented carbide grade presented quicker wear than IN2005 grade, comparing figure 3a an figure 3c. When compared Fig. 3b with Fig. 3d it can be observed that the increase of the cutting speed increased the difference of performance between the grades. It can be seen that the IN2030 grade presented a very quick wear growth, while when the IN2005 grade was used the growth of the wear was smooth. However, the sudden increase of tool wear close to the end of the tool life ocurred again for both grades.

The combination of cutting fluid and cutting speed of 120 m/min was very harmful to the IN2030 grade (Figure 3b). Tool life for this condition was the shortest of all experiments, and the value of the wear was very high. The result for grade IN2005 was not much better in this set of conditions.

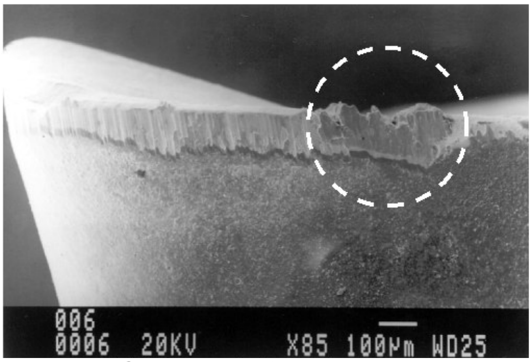
The abrupt growth of the maximum flank wear observed in many combinations of the input variable makes difficult a reliable forecast of the tool life, what is quite undesirable.

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 continous 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 and cooling/lubrication condition.

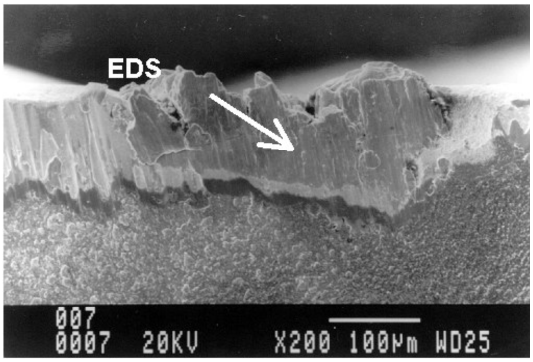
3.3. SEM and EDS Analyses

Figure 4 shows the pictures taken in the SEM of the worm cutting edge used in machining without cutting fluid and IN2030 cemented carbide grade and cutting speed of 100 m/min.

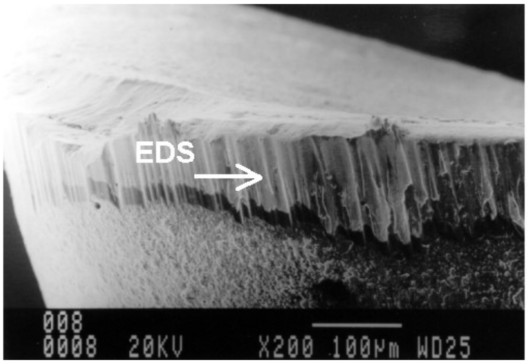
Material: stainless steel 15-5PH (UNS 15500), hardness 35 HRC. **Cutting tool:** cemented carbide grade M30-M40 (IN2030), PVD TiAlN. **Insert:** APKT080304R. **Cutting parameters:** v_c=100 m/min; a_p=1,0 mm; a_e=13,3 mm; v_f=401(200) mm/min; f_z=0,08(0,04) mm/insert; n=1670 rpm. **Cooling/lubrication condition:** without cutting fluid (dry).



a) General view of the cutting edge.



b) Magnification of the region indicated in figure a).



c) Magnification of the left region on the figure a).

Chemical Elements, weight (%)						
Element	W	Co	Fe	Cr	Al	Ti
EDS figure (b)	0,00	2,66	79,93	17,23	0,00	0,18
EDS figure (c)	53,08	7,43	28,94	10,14	0,00	0,41

d) EDS analyses of the regions indicated in the figures (b) and (c).

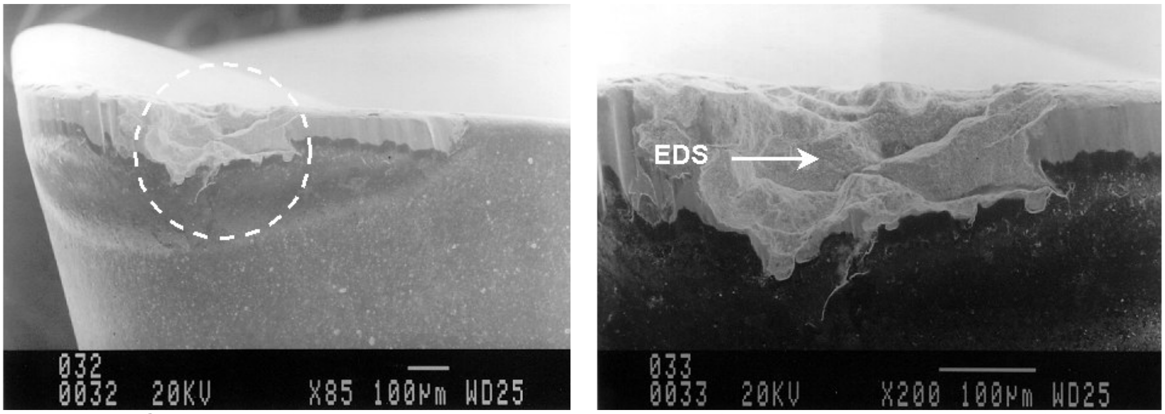
Figure 4 – Pictures from SEM showing workpiece material adhered to worm edge (end of tool life) for the condition: vc 100 m/min, dry cutting and IN2030 grade.

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. 4. These characteristics of the wear had been observed regardless the cutting speed and the cemented carbide grades. Figure 4a 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 the workpiece material. In the region showed by the figure 4b the adhesion covered completely the tool substrate. The analysis of EDS (figure 4d), made in the area indicated by the arrow, confirms that the workpiece material predominates in this region. The marks in the cutting direction in Figure 4c shows that abrasive wear was an important mechanism of tool wear in this condition. Based on the pictures in Figure 4, it can be observed that the main elements of the workpiece material were present on the worn edge, but the amount of it varied along the edge.

The heat generated during the dry machining reduced the mechanical resistance of the volume of workpiece material in front of the edge, increasing its ductility in such a way that the material adhesion on the tool wear land was facilitated. As soon as the cutting edge left the workpiece in one revolution, the edge entered in contact with the air, which has much lower cooling capacity than an emulsion. Thus, the temperature of the adhered material on the tool did not decrease so much, keeping its mechanical resistance low. In the following edge-workpiece interaction, the adhered material on the cutting edge met a workpiece material with lower resistance, facilitating the plastic strain of both. Due to the high plasticity of the workpiece material in the region which interacted with the tool, the abrasion wear mechanism prevalled. The plasticity of the workpiece material in this area was such that allowed the action of the workpiece material hard particles on the tool, with consequent removal of microscopic tool particles together with particles of the adhered material. After this, the worn area of the tool was again coated with the workpiece material. In this case, it was observed that the flank wear was more homogeneous than when cutting fluid was used and, in most cases, the area of the edge radius presented a wear minimized by the adhered material. The sudden growth of the flank wear showed on Figure 3 may be consequence of the weakening of the edge caused by the wear, what increased the wear rate. As the flank wear grew, the coating layer was being removed and the substrate was more exposed to the contact with the adhered material and, therefore, exposed to the wear process. There was a moment when the exposure of the substrate was very high and, so, flank wear grew quickly.

Figure 5 shows the pictures taken in the SEM of the worm cutting edge used in machining with cutting fluid and IN2005 cemented carbide grade and cutting speed of 120 m/min.

Material: 15-5PH (UNS 15500) stainless steel, hardness 35 HRC. **Cutting tool:** cemented carbide grade M20-M40 (IN2005), PVD TiAlN. **Insert:** APKT080304R. **Cutting parameters*:*** v_c=120 m/min; a_p=1,0 mm; a_e=13,3 mm; v_f=481(240) mm/min; f_z=0,08(0,04) mm/insert; n=2005 rpm. **Cooling/lubrication condition:** vegetable emulsion, external application.



a) General view of the cutting edge. *b) Magnification of the region indicated in figure (a).*

Chemical Elements, weight (%)							
Elements	W	Co	Cr	Fe	Ni	Al	Ti
EDS fig. (b)	69,10	11,19	4,49	14,12	0,84	0,00	0,26

c) EDS of the region indicated by the arrow in the figure (b).

Figura 5 – Pictures from SEM showing cutting fluid effects on the cutting edge for the condition: vc 120 m/min, vegetable emulsion and IN2005 grade.

The increase of cutting speed for the machining with cutting fluid harmed a lot the performance of the cutting tool. In the figure 5a it can be seen that the flank wear was not uniform and existed a central area where the wear was very severe. Figure 5b shows a magnification of this area, in which it can be observed that large particles from the tool were pulled up. The use of cutting fluid together with the high cutting speed made the wear mechanism much more severe. EDS analysis showed in figure 5c showed a presence in great amount of tungsten and cobalt (elements from tool substrate) and a smaller amount of iron, chromium and nickel (elements from workpiece). There uas still workpiece material adhered on the worn edge, however the amount of it was smaller.

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 ocurrred, in the majority of the cases, of homogeneous form. 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 particles 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 facilitaded 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 great 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.

3. CONCLUSIONS

Based on the results obtained in this work, some conclusions can be drawn for the finish milling of 15-5PH stainless steel with cemented carbide inserts:

- The cutting without fluid always generated larger tool lives when compared with the cutting with flood of emulsion, regardless the cutting speed and cemented carbide grade used.

- The cemented carbide grade IN2005 (ISO M20-M40) always presented better results compared to the grade IN2030 (ISO M30-M40) with relationship to the tool life, due to its higher hot hardness and toughness.

- In dry cutting a strong adhesion between workpiece material and tool flank surface always occurred and abrasive wear was always present.

- 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.

3. ACKNOWLEDGEMENTS

To the companies Blaser Swisslube, Embraer, Ingersoll Cutting Tools and to Iscar for the colaboration during the execution of this work. To Fapesp for the scholarship conceded.

4. REFERENCES

Bossert, M., 1995, "Machining stainless alloys", Advanced Materials & Processes, n. 7, p. 43-44.

Diniz, A. E. et al., 2001, "Tecnologia da Usinagem dos Metais", 3. ed., São Paulo: Artliber, 248 p.

Arisoy, F. C. et al., 2003, "Failure of a 17-4 PH stainless steel sailboat propeller shaft", Engineering Failure Analysis, v. 10, p. 711-717.

Brucker, R., 1995, "Precipitation-hardening alloys", Advanced Materials & Processes, v. 12, p.25-27.

Meyrick, G., 2002, "Physical Metallurgy of Steel, Section 6, Special Steels", Available in: www.engr.sjsu/cme/cmcourses/MatE152/Others/necleationandgrowth2.pdf. Access in 06/05/2003.

ASM Handbook, 1997, Machining, v. 16, p.681-707.

De Melo, A. C., et al., 2000, "Estudo da formação de trincas de origem térmica no fresamento", In: Congresso Nacional de Engenharia Mecânica 2000, Natal. Anais. Natal,RN.

5. RESPONSIBILITY NOTICE

The authors are the only responsibles for the printed material included in this paper.