A CONTRIBUTION TO THE STUDY OF Ti-6Al-4V TURNING

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Abstract. . *The aeronautical and aerospace industry, took place to the changes happened in the last years in the aerial transport of mass and with the development of new products, it requires a larger avaiability of new materials of the which amount of enough information is had for its processing. The proposal of this work is the study of the behavior in machining, but specifically for the turning of the Ti-6Al-4V alloy, for so much they will be study the wear mechanisms was existing in the tools, the relationship between roughness and cutting parameters used, besides the effect in the different forms of cutting fluid application during the machining operation: dry or wet condition. During the tests the mainly objective was to determine the behavior of different cutting tools, they will be appraised the variation of the roughness of the workpieces surface, the tool wear and material deposition in the rake face of the cutting tool, which can be make by the macroscopic surface observation, shows the deposited material in rake face of cutting tool throght the X-ray observation (EDS mapping).*

Keywords*: machining, titanium, wear, roughness, coolant.*

1. INTRODUCTION

Titanium alloys are very used in the aeronautical industry, mainly because their exotic properties such as high resistance/density relation, fatigue resistance, corrosion resistance in high temperature, etc. The alpha/beta, Ti-6Al-4V (Ti-6-4) alloy, Ti-6Al-6V-2Sn (Ti-6-6-2) and Ti-6Al-2Sn-4Zr-6Mo (Ti-6-2-4-6) are very used in advanced industrial equipment production, in energy generation and transport. They have been widely used will be dental and orthopedic implants is the last two decades (Moreira, 2002).

The machining of the titanium alloy is difficulty basically due to its high chemical reaction with mostly of tool materials and its low thermal conductivity (about 7,3 W/m K) generating high temperature in chip/tool/workpiece interface which favors the wear mechanisms occur, (Bhaumik et al., 1995). Approximately 80% of the heat generated is restrained in tool and 20% in the chip (Ezugwu and Wang, 1997).

According to Zoya and Krishnamurthy (2000), during the machining of titanium alloy, tool wear progress rapidly because of the high cutting temperature and strong adhesion between the tool and the work material, owing to their high chemical reactivity**.** Some specific studies in tool failure modes and wear mechanisms when machining titanium alloy were carried out (Ezugwu and Wang, 1997). Due to the low modulus of elasticity of the titanium the tool is subject to a pulsation load (spring back) during the machining causing attrition and vibration. The Ti-6Al-4V alloy presents a low thermal conductivity with most of the heat generated during the machining it is retained in the tool. The combination of pulsing loads and high temperature accelerates the tool wear mechanisms, these factors contribute to its low tool life.

In machining, three different types of chip formation can be observed: continuous chips, segmented chips and broken chips (very small) if extreme cutting conditions are used. Ti-6Al-4V forms segmented chips for a wide range of cutting parameters (Bäker et al., 2001; Komanduri and Reed, 1983). Serious vibrations ploughs often find due its chip segmentation is a limitation that restrict material removal rates and, consequently, productivity.

The cemented carbide (WC/Co) does no represents the best cutting tool for machining of Ti-6Al-4V, but represents the more common cutting tool in the shop-floor mainly due to its lower cost. The high chemical reactivity of titanium alloy results in diffusion and excessive crater wear during machining (Ribeiro et al., 2003). The cutting length (*lc*) is defined as the length of the removed slice and can be calculated by the equation (1), were (*d*) is a workpiece diameter (mm); (l_f) is the workpiece length (mm); and (f) is the feed rate used (mm/rev):

$$l_c = \frac{\pi \cdot d \cdot l_f}{1000 \cdot f} \quad (1)$$

In the Ti-6Al-4V alloy machining cost is related to the short tool life, in cutting length (*lc*) terms and the growth of its applications in some areas of engineering stimulates the carrying out of some analyses on the optimization of its machining conditions. Inside of the production processes, the machining belongs to a group of processes that, takes more in consideration the dimensional precision and the surface finishing. The machining parameters that influence the final surface, are mainly workpiece material, tool geometry and cutting parameters. The surface quality can be used as a parameter of study of these materials.

2. EXPERIMENTAL PROCEDURE

2.1 Materials

The machining tests were accomplished through external cylindrical turning using a titanium alloy (Ti-6Al-4V) workpiece, these had been machining in a CNC lathe model CENTUR - 30D ROMI. The cutting tools used in the experimental trials are as it follows: cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm. The cooling environments employed were wet and dry conditions. The characteristics of the tested tools are showed in Table 1.

Table 1. Characteristics of cutting tools used in the tests

ISO CODE	Coating	Tool code
VBMT110304 MF GC1025	coating (TiAlN)	**PVD**
VBMT110304 PF CT5015	uncoated (Cermet)	**Cermet**
VBMT110204 UF H13A	uncoated	**UF**
VBMT110304 KF H13A	uncoated	**KF**
VCGX110204 AL 1810	coating (diamond)	**1810**

In the tests was used a high performance fluid, developed specifically for machining operations of ferrous metals and aluminum alloys. This fluid consists of micro emulsion of 5-10% concentration; in the case a 10% concentration was used. It contains in its composition a mixture of mineral oils, esters, boric amides, antifoaming and biocides. Its commercial name is "QUAKERAL 370".

3. RESULTS AND DISCUSSIONS

By observing the tests carried through for Moreira (2002), in which it was used some conditions of cutting speed, varying between 55 and 110 m/min, using **UF** grade in dry machining conditions only, to taken account into of the cost/benefice the best resulted was 110 m/min. Taking as starting point these test, was fixed the cutting speed in 110 m/min and having used some cutting tool grade in wet and dry machining conditions. In the Fig 1 is observed that **UF** grade, in wet machining condition, presented the best ones resulted, taking as reference the flank wear, limited in 0,6 mm, with a life of 1500 m and 0,75 μm roughness (Fig.3). Using the same grade, however, in dry machining condition (Fig. 2), the best ones had been also resulted, was 0,6 mm of flank wear with tool life of 850 m and 1 μm of roughness (Fig. 4). The results of the investigation that in dry machining condition using cutting tool **1810** presented the lesser levels of flank wear, 0,4 mm, for a tool life of 2000 m with roughness levels of the order of 3 μm and cutting length of the order of 1750 m, with further increase of the roughness reaching maximum values of 3,5 μm. Regard to the others tested tools, it is observed low values when compared with the previously tested and cited. It can be said that the performance of the performance of the others tools had been extremely inferior as for the flank wear and finishing.

The follow graphics allow to observe that the performance of others tested tools (**PVD**, **Cermet** and **KF** grades) there is not in the same level of the **UF** and **1810** grades, mainly due to the high chemical reactivity of titanium alloy with these tool materials (**PVD** coating and **Cermet** matrix), regard to the **KF** its deficiency was in the break-chip own to machining steel and similar alloys.

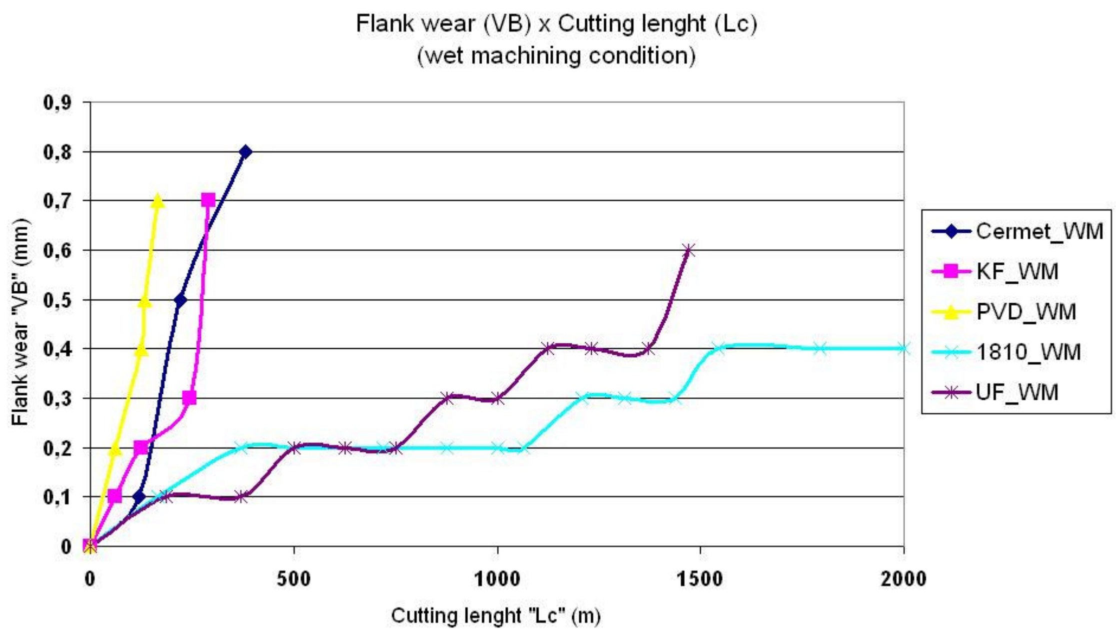


Figure 1. Flank wear (VB) X Cutting length for different tools in wet machining condition.

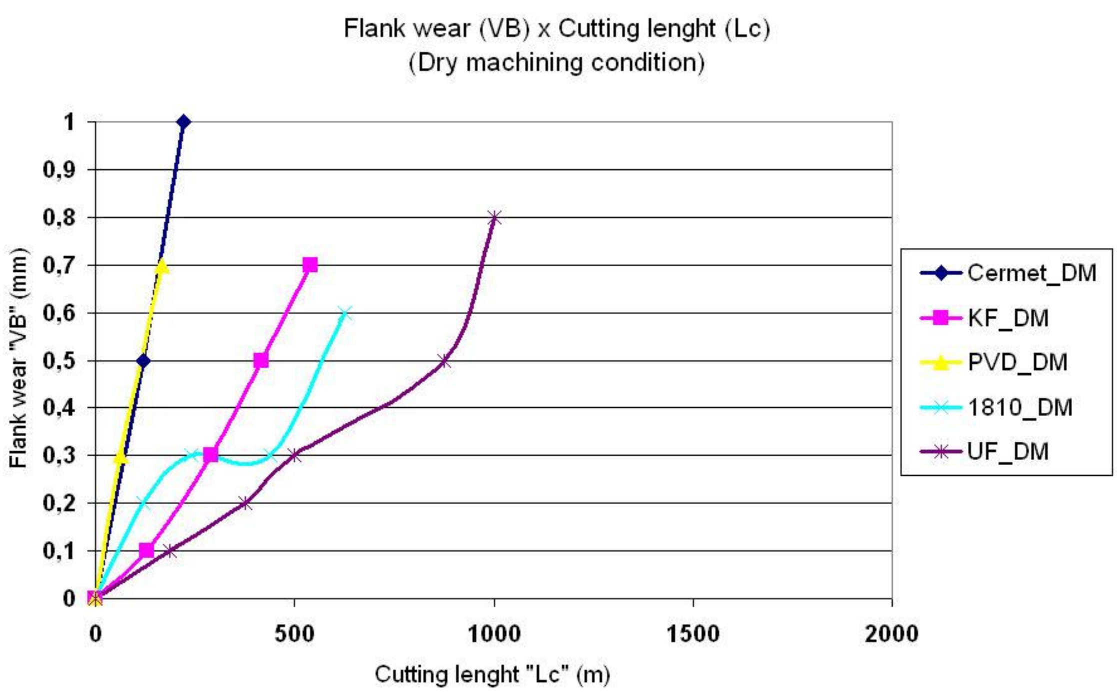


Figure 2. Flank wear (VB) X Cutting length for different tools in dry machining condition.

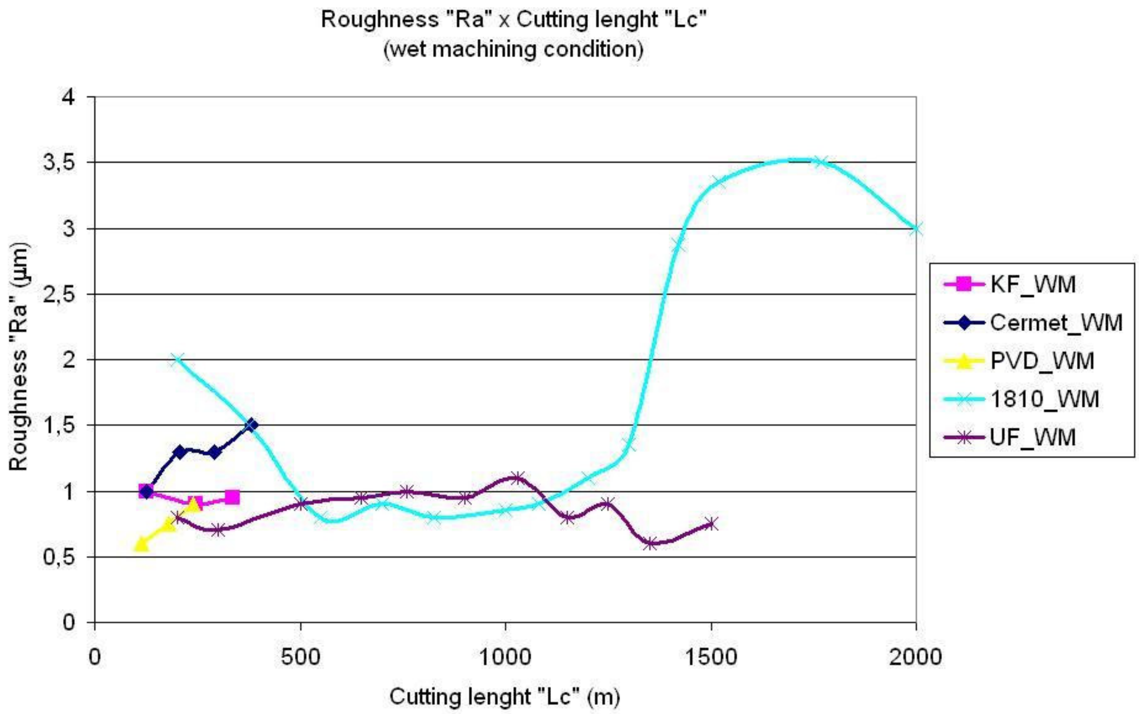


Figure 3. Roughness (Ra) X Cutting length for different tools in wet machining condition.

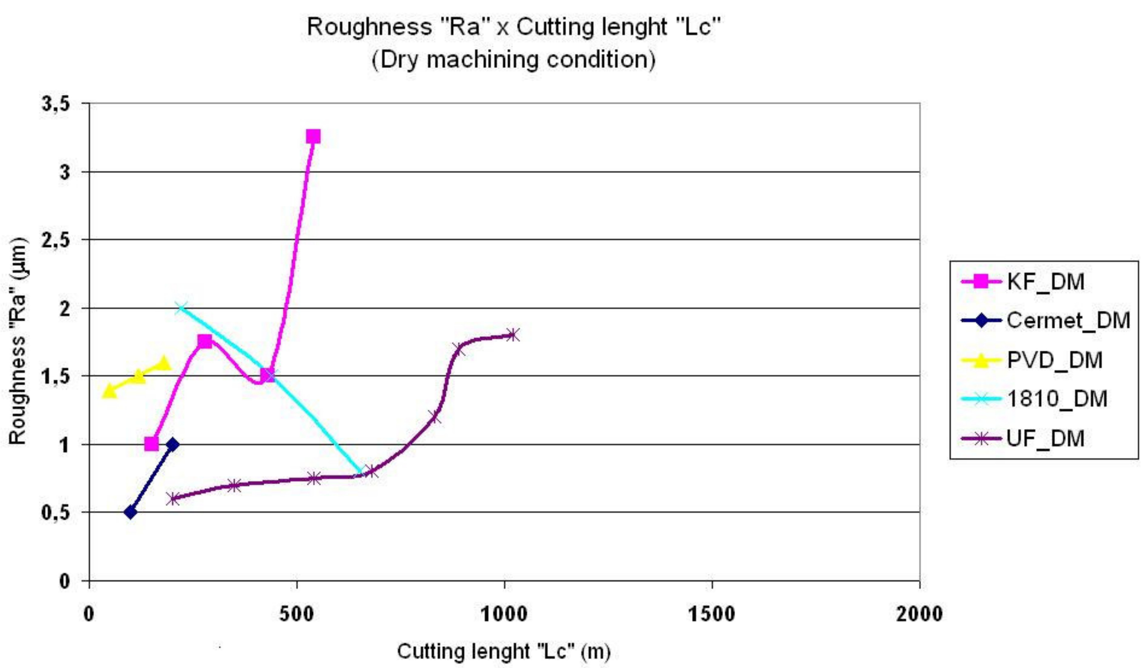
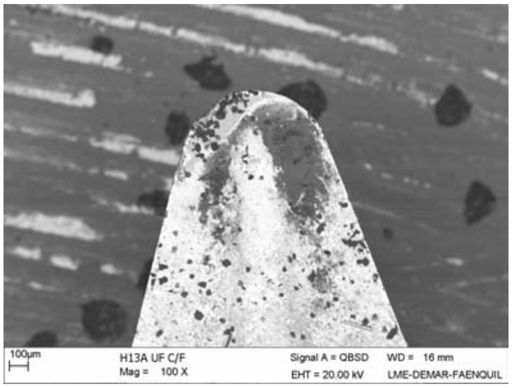
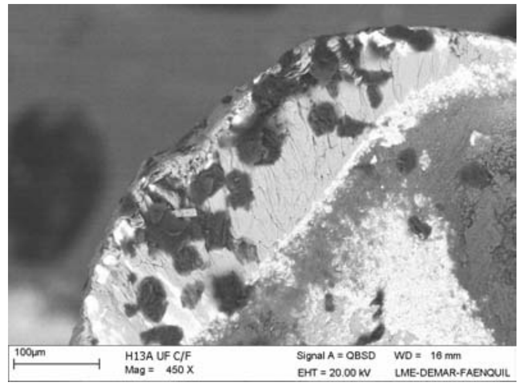


Figure 4. Roughness (Ra) X Cutting length for different tools in dry machining condition.

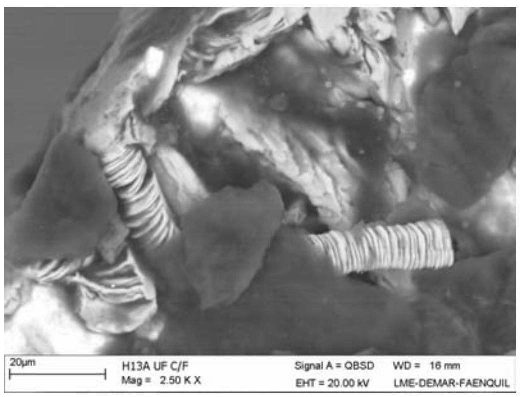
In Fig. 5a is shown to a general roughness pattern of cutting (**UF**) with the deterioration and wear in the rake face of cutting tool, Fig 5b, what also in promotes the flank wear increase. Some specific details on tool wear have been observed in microscopical analysis more shows the chip adhesion in tool surface, Fig 5c. In addition to notching and flank wear some tool also encountered catastrophic failure and thermal crack, Fig 5d.



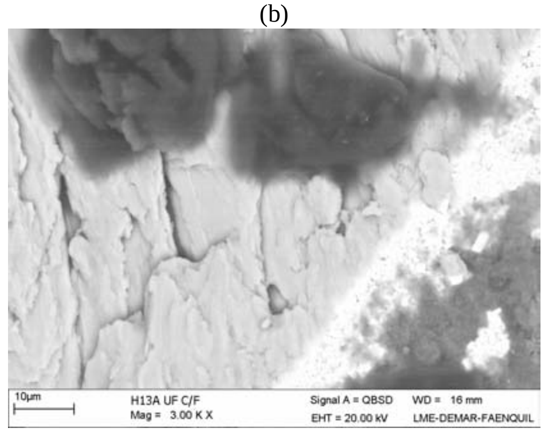
(a)



(b)



(c)



(d)

Figure 5. Different magnification of **UF** cutting tool in wet machining: turning (cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm).

During the machining, a great quantity of chip have been widely deposited in the tool rake face of (Fig. 6), which did not can be considered as BUE because high cutting speed was used. It is occur due the reactivity titanium alloy with WC/Co cemented carbide under high pressure and temperature in this process, the microstructure of tool material and grain can be change of the microstructural aspects and original properties of the metal matrix, for example, new individual phase formed with titanium alloy, it is favorable due the diffusion mechanisms.

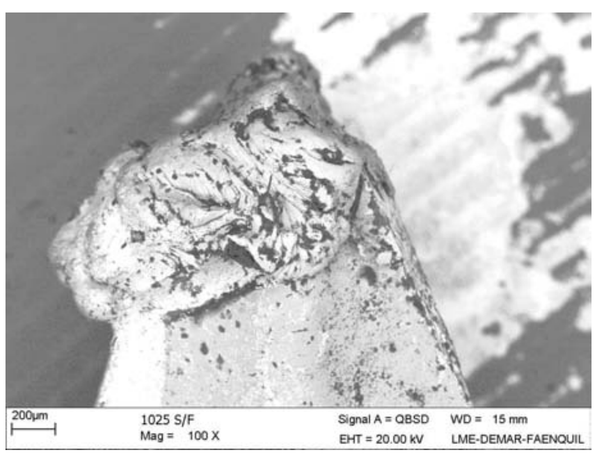


Figure 6. Tested cutting tool (**PVD** grade), which present a great chip adhesion in rake face by dry machining condition (cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm).

The macroscopic surface observation, fig 7a, show deposited material in rake face of **PVD** grade tool in dry machining condition, in the x-ray observation (EDS mapping), fig 7b, 7c and 7d, the clear points shows titanium, vanadium and aluminum adhesion in tool surface respectively.

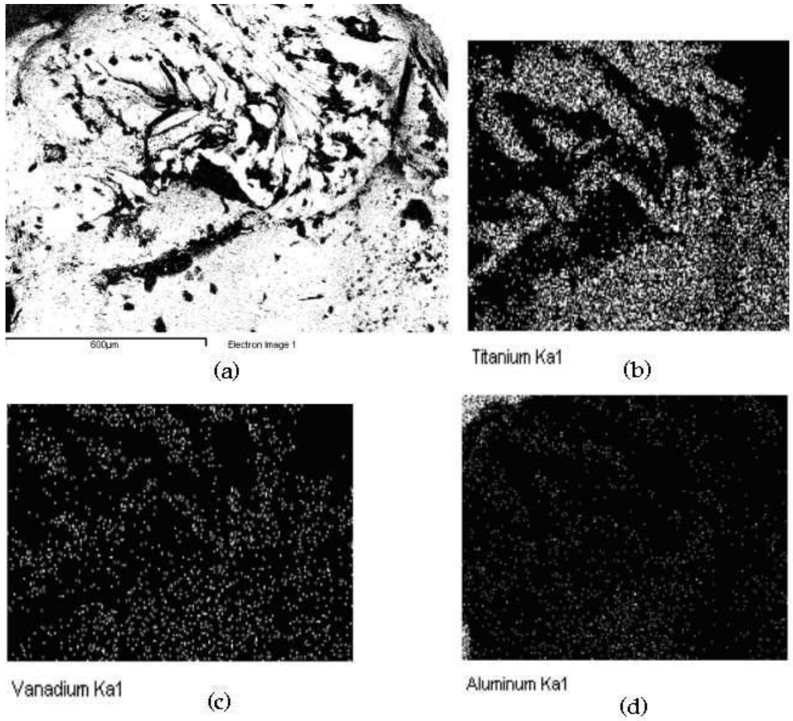


Figure 7. EDS analysis in rake face of **PVD** grade tool in dry machining (cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm): (a) chosen region, (b) titanium presence, (c) vanadium and (d) aluminum.

The predominant tool failure mode in 1810 tool grade in wet machining condition, was the notch wear (fig 8.a), also observed it a small development of flank wear, what it was common in all the tests, however, in lesser levels (0,4 mm). However very satisfactory the reached consuming, observes the abrasive wear, sufficiently operating in the edge and opposing surface to the cutting, Figs 8b and 8c, which had to the abrasive effect of the chip. The Fig 8d, shows details of microstructure tool surface.

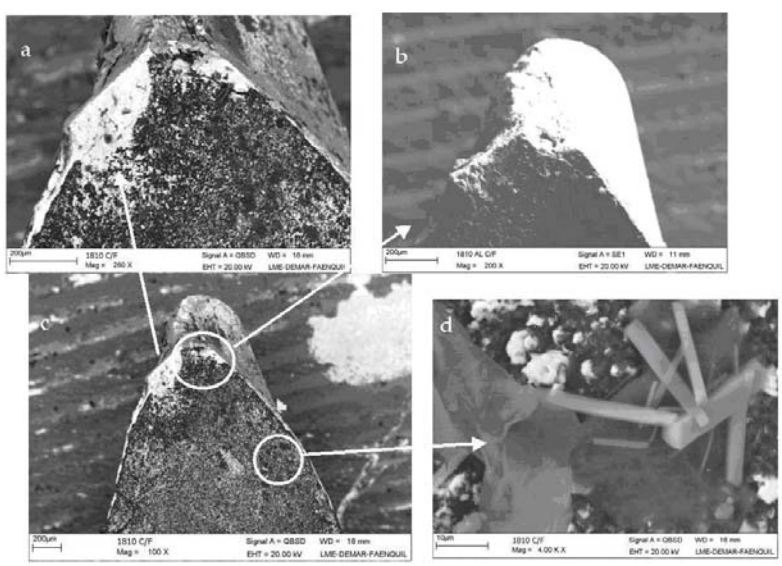


Figure 8. Different regions of **1810** grade tool after test in wet machining condition (cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm): (a) cutting edge, (b) nose radius and (d) rake face.

Sintered carbides are polycrystalline mixture materials based on the compounds of C, they usually contain 2 or 3 components, called α, β and γ phases. The first consist of WC grains compound. The crystals of WC are trigonal symmetry. The β phase, called binding material is based in Co. Finally, the composition of γ phases, called solid solution, is varied, for example (Ti, W)C.

The carbide sintered microstructure containing mixed carbides (WC) and binding (Co). Fig 9 shows the results of the EDS mapping analysis in the rake face of **1810** grade tool in wet machining condition. Carbon, tungsten, cobalt and titanium are particles of α, β and γ phases. Aluminum, vanadium and titanium particles occur due to chip adhesion.

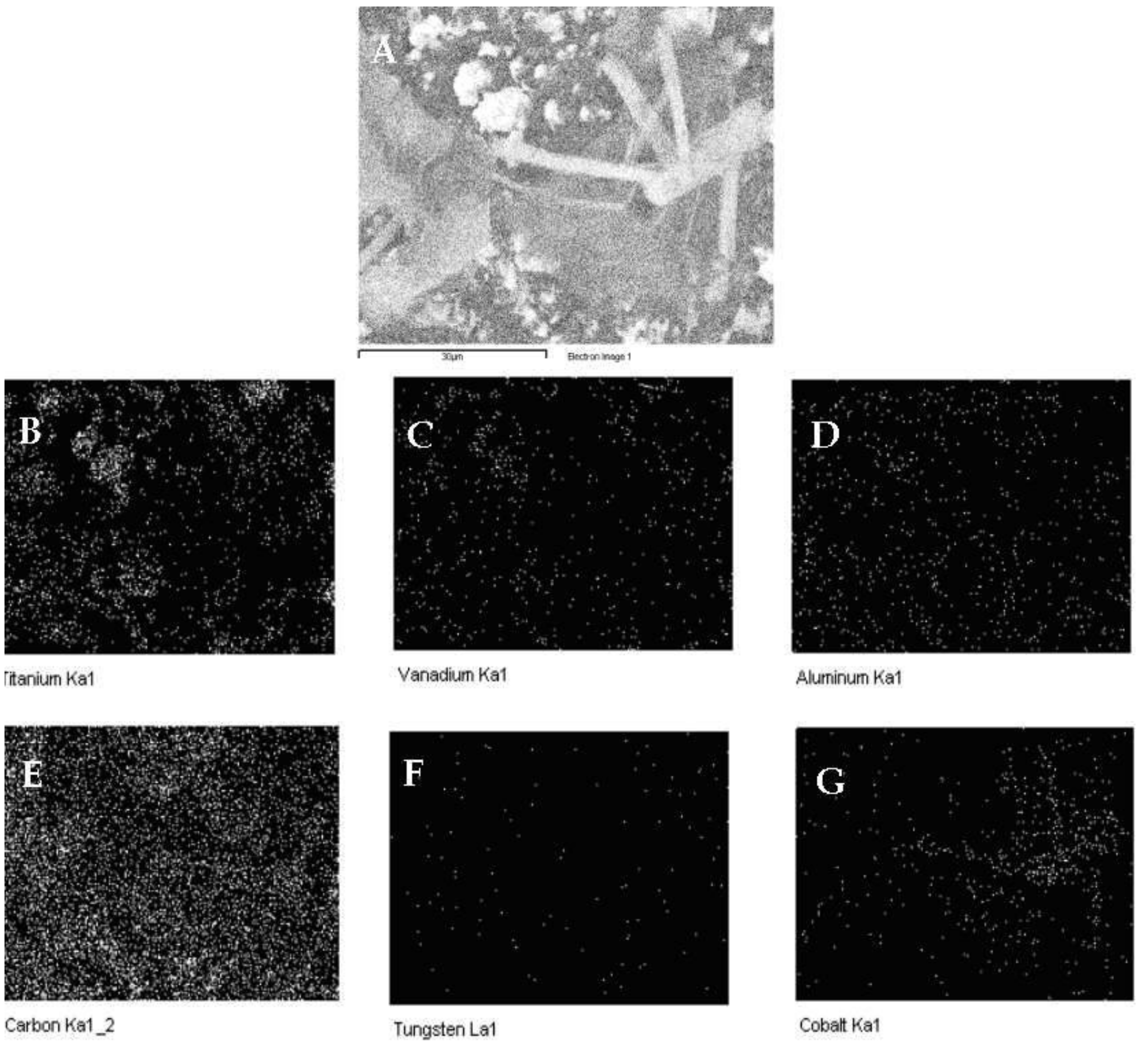
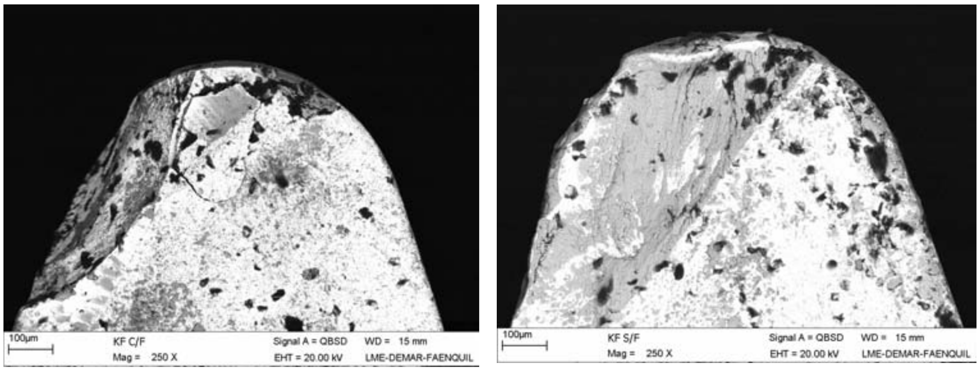


Figure 9. EDS analysis of **1810** grade tool after test in wet machining condition: (a) chosen region, (b) titanium presence, (c) vanadium, (d) aluminum (e), Carbon, (f) tungsten and (g) cobalt.

When machining titanium alloy, the tool material and cutting fluid application, did not have a considerable influence in the too failure modes. In general, the cutting edge was deformed during machining. The figs. 10, shows the cutting edge in two conditions, flooding cutting fluid (10.a) and dry machining (10.b) and thus, can be observed a severe abrasion wear and chipping of the cutting edge.



(a) (b)

Figure 10. Images for **KF** grade tools (cutting speed of 110 m/min, feed rate of 0,1 mm/rev. and cutting depth of 0,5 mm) in wet machining condition (a) and dry condition (b).

4. CONCLUSIONS

When machining Ti-6Al-4V with different cutting tools and various cutting conditions it was observed that the **1810** and **UF** grades showed the best performance in all the conditions investigated, where low wear rate or high cutting length in were obtained compared to other cutting tools. An exception should be made logically to the **1810** tools, which in some cases presented catastrophic failures. However these failures occur probably due to its geometry, which at first were developed for the machining of aluminum parts, what it make its cutting edge very fragile.

The roughness results confirm the results of the wear, because it was influenced directly by the same ones, it is interesting to notice, however that among the tested tools the **UF** grade tool it presented during all the tests a better acting with low roughness values, it fits to increase that **KF** grade tool was the only tested tool composed of the same material that **UF**, however with a different chip-break, which was not shown effective in the titanium alloy machining.

Through the EDS analysis can be observed the great interaction between cutting tool and chip formed, which can be promotes the occurrence of certain wear mechanisms based in diffusion, but its occurrence only can be proved through specifics diffusion tests, as well as diffusion-pair, for example.

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