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MILLING OF TITANIUM ALLOY: CUTTING FORCES AND TOOL LIVES

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Abstract. *Titanium alloys are important for many applications in engineering because of their excellent characteristics. On the other hand, these alloys are known as difficult to machine materials because of their unique combination of properties, such as high strength at elevated temperatures, low thermal conductivity, high chemical reactivity with almost all tool materials and low modulus of elasticity (which favors vibration). The purpose of this work was to study the influence of the tool holder material (steel and carbide) and the cutting speed on tool lives and machining forces. Modal analysis of tool holders and workpiece were carried out in order to verify the natural frequency of these systems. EDS analysis of worn tools were also conducted, allowing the evaluation of wear mechanisms. Results showed that both tool holders have similar frequency response functions for the considered L/D ratio, with close machining performance. ANOVA showed cutting speed is the main factor affecting tool life. Attrition was the main wear mechanism in all tests.*

Keywords: *Milling, Titanium, Tool wear.*

1. INTRODUCTION

Titanium alloys exhibit excellent properties, such as high strength-to-weight ratio, which is maintained even at high temperatures, and good resistance to corrosion, what makes them adequate to the manufacturing of several components in aerospace industry, also playing an important role in chemical, petrochemical and biomedical industries. However, these materials have a high cost when compared to other metals, mainly because of difficulties with the extraction process and problems during manufacturing (Boyer *et al.*, 1994).

Titanium and its alloys are considered difficult to machine materials due to some inherent material properties, such as high strength at high temperatures, low thermal conductivity, high reactivity with almost all tool materials and low Young modulus (which favors vibration). Because of such characteristics, these materials are usually machined with cutting speeds below 30 m/min for HSS tools and 60 m/min for carbide tools, which results in low productivity (Ezugwu and Wang, 2007).

Titanium alloys exhibit low thermal conductivity (7,3 W/m.K), almost 86% lower than the thermal conductivity of AISI 1045 steel (50,7 W/m.K). According to Rahman *et al.*(2003), almost 80% of the heat generated during titanium machining is dissipated through cutting tool, accelerating thermal activated wear mechanisms.

Because of its poor thermal properties, titanium chips are typically segmented (saw-tooth), formed by narrow bands of intensely sheared material separated by broader zones lightly sheared. These intensely sheared bands are called adiabatic shear bands (Trent and Wright, 2000). According to Sun *et al.* (2009), adiabatic shear results in a cyclic variation of cutting forces causing vibration. This vibration limits the material removal rate also reducing tool life.

Ti-6Al-4V alloy may be found in range of Young modulus from 100 to 130 GPa (Boyer *et al.*, 1994). This relatively low Young modulus may cause chatter vibrations and problems with workpiece deflection (Machado and Wallbank, 1990). The low Young modulus causes higher fluctuation of chip thickness, generating high levels of chatter vibration, leading to microchipping of the cutting edge and early tool breakage (Ezugwu and Wang, 2007).

Due to the high tendency of vibration titanium machining presents (mainly in interrupted cutting operations, as milling process), to achieve high productivity it is important to maintain tool and/or workpiece vibration under control. Several techniques have been developed to reduce vibration. Among them are those based on the selection of cutting parameters that guarantee stable cutting and those based on modifying the system machine tool/tool/workpiece/fixation device system (Quintana and Ciurana, 2011).

The main goal of this work was to test two different tool holder materials (steel and cemented carbide) with different cutting speeds and to evaluate its effect on tool life, tool wear mechanisms and cutting forces.

2. MATERIALS AND METHODS

2.1 Equipments

The machining tests were carried out in a 3-axis CNC vertical machining center (22 kW power and maximum rotation spindle of 12.000 rpm).

Tool wear evolution was monitored using a stereo-microscope with 50x maximum magnification equipped with a camera and processing image software. After machining tests, worn tools were analyzed in a scanning electron microscope (SEM) with an energy dispersive x-ray spectrometer (EDS), which allows identification of chemical elements on the tool and helps understanding wear mechanisms.

The components of the cutting force were measured with a 3 components stationary piezoelectric dynamometer connected to a signal conditioner and a computer equipped with an A/D data acquisition board and a signal processing software. Modal analyses of the cutting tools were performed with a set of accelerometers, impact hummer and a dynamic signal analyser.

2.2 Materials

The workpiece was a recrystallized plate of Ti-6Al-4V alloy. The machining tests were done with two indexable insert milling cutter of 16 mm maximum diameter, a steel toolholder (maker’s code R300-016A20L-08L) and a cemented carbide body (maker’s code 393.T-16 08 110) with a steel head (maker’s code R300-016T08-08L). The tool overhang was 85 mm in both cases. The cutting tools were round shape cemented tungsten carbide inserts (maker’s code R300-0828E-MM) coated with TiCN/Al_2O_3/TiN (ISO S30 grade). Cutting fluid was a water miscible vegetable-based oil (Vasco 1000®) in a concentration of 8% applied externally at 45 l/min.

2.3 Experimental planning

The machining test followed a 2^2 factorial planning. The input levels were the toolholder material and the cutting speed. Response variables analyzed were tool life and tool wear mechanisms. Cutting force was also measured.

2.4 Experimental procedures

Before the machining tests, modal analysis of toolholders was carried out in order to verify the natural frequency of these systems. With the tools fixed in the machining tool, an accelerometer was stuck on the toolholder tip and an impact hummer excited the system. The frequency response function (FRF) of the toolholders was then obtained by the dynamic signal analyser. The sampling frequency selected was 20 kHz and the sign was filter by a digital low-pass filter of 8 kHz, following Nyquist theorem (Harris and Piersol, 2002).

Table 1 shows the cutting parameters selected for the milling tests, where v_c is the cutting speed, f_z feed per tooth, z number of teeth, a_e radial depth of cut and a_p axial depth of cut. The cutting strategy applied to all tests was down-milling parallel passes.

Table 1. Milling parameters (based on Sandvik Coromant, 2007)

Test	v_c (m/min)	Toolholder material	f_z (mm/tooth)	z (teeth)	a_p (mm)	a_e (mm)
A	65	Steel	0,1	2	1	9,3
B		Cemented carbide				
C	78	Steel				
D		Cemented carbide				

During the machining operation, the tests were paused every three minutes and the tool flank wear was measured with the stereo-microscope. The milling tests were performed until the end of tool life, determined by maximum flank wear of 0.2 mm (chosen to guarantee good surface finishing and also to avoid waste of workpiece material). In order to provide statistical reliability, all the machining tests were replied.

The SEM analysis with the EDS resource provided a semi-quantitative parameter to identify the presence or absence of coating material (Ti, Al), tool substrate (W, Co) and workpiece material (Ti, Al, V) adhered to the flank face of worn inserts.

The cutting forces of new and worn inserts were measured with a similar plate of the same workpiece material fixed on the stationary dynamometer and machined under the same cutting parameters. The sampling frequency selected was

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10 kHz and the signal was filtered by an analogical low-pass filter of 3 kHz, also following Nyquist theorem (Harris and Piersol, 2002).

The cutting forces were calculated by the Eq (1), adapted from Altintas (2000), where F_t is the tangential component (or cutting force) of the machining force, F_x and F_y are the x-axis direction and y-axis direction components (respectively) measured by the stationary dynamometer, and φ is the instantaneous contact angle:

$$F_t = F_x \cos(\varphi) - F_y \sin(\varphi) \tag{1}$$

With $0 \le \varphi < \dfrac{2\pi}{z}$

3. RESULTS AND DISCUSSION

Figure 1 shows the frequency response function of both tool holders.

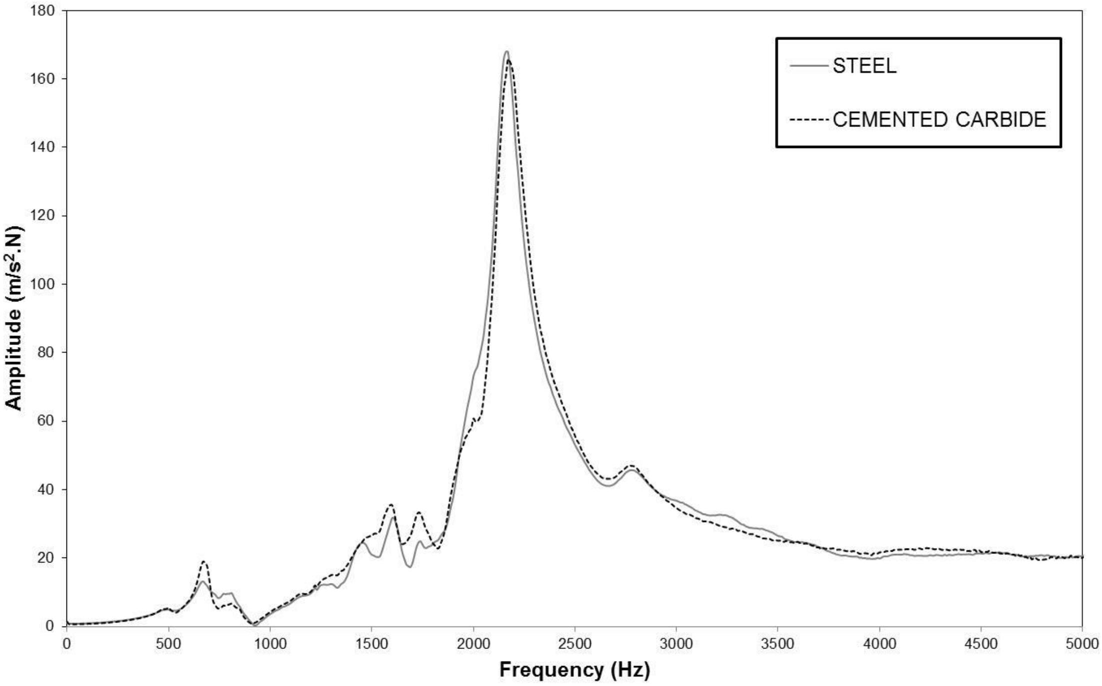


Figure 1. Frequency response function of the tool holders

It can be noticed that the considered toolholders have similar FRFs, with almost equal natural frequencies, given by the position of the peaks. This suggests that both toolholders may have the same dynamic behavior during the machining process, which was verified by the tool life and cutting forces measurements.

As it can be seen in Fig. 2, no differences can be noticed among tool lives for the machining tests with cutting speed of 65 m/min. However, a slight difference occurs for the higher cutting speed (78 m/min) with the cemented carbide exhibiting better performance. Besides, results show that the increase in the cutting speed causes a reduction of tool life, which was an expected result, since cutting speed is the machining parameter that has the highest influence on tool life (Diniz *et al*, 2006).

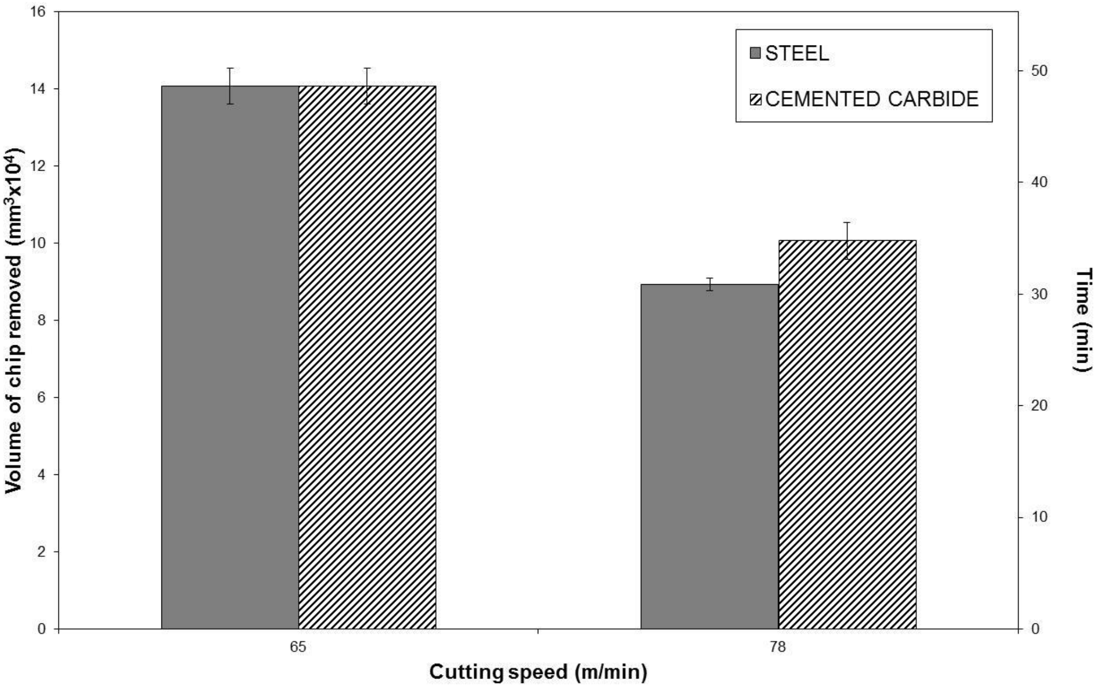


Figure 2. Tool lives expressed in terms of volume of chip removed and cutting time.

For a better understanding of the influence of the input variables on tool life, it was performed the analysis of the variance of the results. Figure 3 contains the Pareto's chart of the standardized effects for tool life for a level of confidence of 95%.

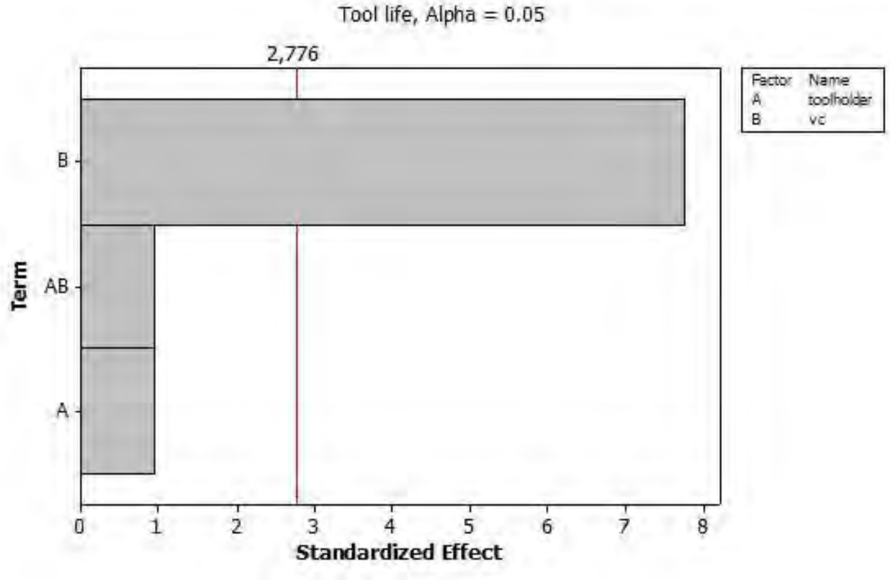
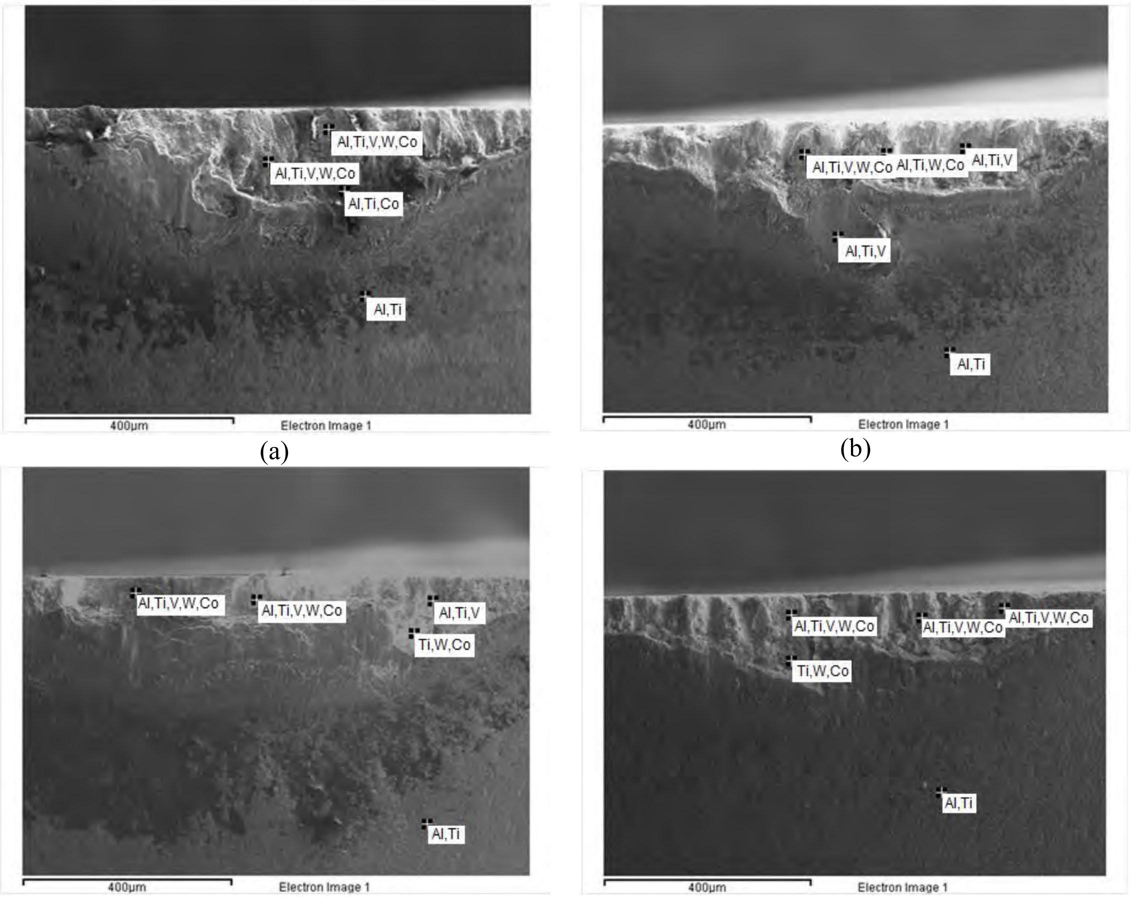


Figure 3. Pareto chart of the standardized effects.

Pareto's chart indicates that the main input variable affecting tool life when considering the group of experiments performed is the cutting speed. The toolholder material and its interaction with the cutting speed did not show significant influence on tool life. This result may be explained by the similar dynamic behavior of the toolholders, verified by the modal analysis of the toolholder/machine tool system.

Figure 4 presents the SEM images and the EDS analysis of the worn tools. In all tests there was adhesion of the workpiece material on the worn flank face of the inserts, which can be verified by the presence of Ti, Al and V (that composes only the workpiece material). It was also noticed micro chipping of the cutting edge, characterized by the irregular worn surface. This suggests that the main wear mechanism was attrition, which consists on the adhesion of the workpiece material in the flank face, followed by the removal of microscopic size fragments of the tool (Trent and Wright, 2000). According to Trent and Wright (2000) and also found by Antonialli *et al* (2010), attrition wear is intensified when there is vibration due to the lack of stiffness of the system. Antonialli *et al* (2010) found that when there is vibration in the natural frequency band, the tool life is short due to the cutting edge breakage. On the other hand, when there is high vibration energy in frequencies below the natural frequency, attrition is favored and becomes the main wear mechanism.



(a) (b)

(c) (d)

Figure 4. SEM images and EDS analysis of the worn tools for $v_c = 65$ m/min, (a) Steel toolholder and (b) Cemented carbide toolholder, and for for $v_c = 78$ m/min, (c) Steel toolholder and (d) Cemented carbide toolholder.

Figure 5 shows the average of the cutting force peaks in ten tool rotations with fresh and worn inserts (maximum flank wear of 0.2 mm). The x-axis and y-axis components of the machining force were transformed in cutting force (F_t) following Eq (1).

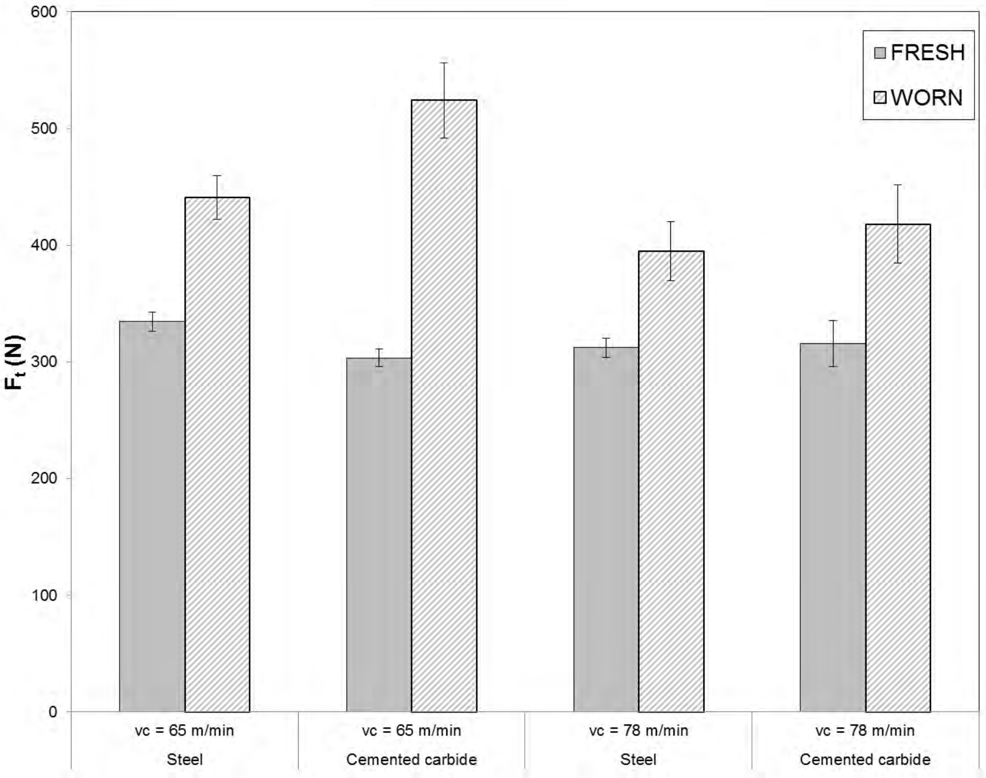


Figure 5. Average of the maximum cutting force of new and worn inserts.

No considerable difference can be seen between both toolholders and even between different cutting speeds. Diniz *et al* (2006) affirm that when the cutting speed is high enough to avoid build-up edge, cutting speed has low influence in the cutting pressure, thus its variation do not change the cutting force, since it do not affect cutting pressure and chip thickness. On the other hand, an increase in the cutting force occurs for the worn tools. This happens because when tool wear increases, it may change the tool edge shape leading to an increase of the cutting pressure.

4. CONCLUSIONS

After the results and discussions, the following conclusions can be pointed:

- Commercially available steel and cemented carbide toolholders exhibit similar frequency response functions, which suggest they have close dynamic behavior.
- Statistical analysis showed that cutting speed was the only input variable affecting tool life.
- There was intense adhesion of the workpiece material on the tool flank face. Attrition was the main wear mechanism in all tests. Micro chipping of the cutting edge was also found.
- Cutting force was affected only by the increase of tool wear.

5. AKNOWLEDMENTS

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7. RESPONSIBILITY NOTICE

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