Tool wear analysis and improvement of cutting conditions using the high-pressure water-jet assistance when machining the Ti17 titanium alloy

Y. Ayed [a,*], G. Germain [a], A. Ammar [a], B. Furet [b]

[a] *Arts et Métiers ParisTech, LAMPA, 2 bd du Ronceray, 49035 Angers Cedex, France*
[b] *IUT Nantes, IRCCyN, 2 av. du Professeur Jean Rouxel, 44475 Carqefou, France*

A B S T R A C T

This paper presents experimental results concerning the machinability of the titanium alloy Ti17 with and without high-pressure water jet assistance (HPWJA) using uncoated WC/Co tools. For this purpose, the influence of the cutting speed and the water jet pressure on the evolution of tool wear and cutting forces have been investigated. The cutting speed has been varied between 50 m/min and 100 m/min and the water jet pressure has been varied from 50 bar to 250 bar. The optimum water jet pressure has been determined, leading to an increase in tool life of approximately 9 times. Compared to conventional lubrication, an increase of about 30% in productivity can be obtained.

Keywords:
Tool wear
Tool life
High pressure
Cutting forces
Titanium alloy

1. Introduction

Titanium alloys have been widely studied due to their remarkable properties, notably their strength/density ratio which presents interesting advantages in the aviation and aerospace fields. However, the machining of these alloys is particularly challenging, which has a direct impact on productivity, surface integrity and tool life.

The high chemical reactivity and the low thermal conductivity of these alloys present favourable conditions for tool wear. In addition, the high temperature in the cutting zone and the high cutting forces accentuate the evolution of the wear. According to [16], there is a critical temperature at which the degradation of the cutting tool is accelerated. This is around 740 °C, 760 °C and 900 °C for WC/Co, PCD and CBN respectively. This limits the choice of cutting tool materials and coatings. Regardless of the type of machined material, the tool must fulfil a number of characteristics to have better wear resistance:

- Maintain good mechanical properties at high temperatures (hardness, rigidity and tenacity).
- Have a high chemical inertia to resist the high chemical affinity of some alloys.
- Have an adapted cutting geometry.

According to [11,19–21] the uncoated tungsten carbide WC/Co seems to be a good choice for the machining of titanium alloys.

High-pressure water jet assistance presents an efficient solution to decelerate tool wear and to enhance tool life. Using this technique, the increase in tool life for titanium alloys varies between 185% [3] and 460% and it can reach 780% when machining Inconel 718 [8,15]. In addition, HPWJA allows, among other things, to effectively lubricate the cutting zone and thus to reduce the temperature in the tool by more than 40% [13]. Furthermore, the fragmentation of chips is ensured. The study of orthogonal cutting with high pressure coolant assistance [12] showed that chip breaking is controlled by the nozzle diameter used and the pressure of the water jet.

The effect of the lubricant type has been tested by [17]. The study is based on the comparison of the performance of the water-soluble oil and the neat oil during the high-pressure cooling assisted machining of Ti–6Al–4V. The respective tool life for the conventional lubrication, neat oil and water-soluble oil are 4 min, 5 min and 14 min (V_c = 100 m/min, f = 0.2 mm/rev, P = 100 bar, d_{nozzle} = 0.8 mm). The influence of the direction of the lubricant jet and flow rate has been the object of the study carried out by [7] for the turning of AISI 1045 steel. When the fluid was applied on

* Corresponding author.
E-mail address: yessine.ayed@ensam.eu (Y. Ayed).

Table 1
Chemical composition and mechanical properties of Ti17.

Chemical composition (%)						Mechanical properties		
Ti	Al	Mo	Cr	Zr	Sn	σ_{UTS} (MPa)	$\sigma_{p0.2\%}$ (MPa)	A%
82.5	5.16	4.08	4.06	2.01	2.06	1110	1020	5

the rake and the flank faces of the tool, the best results have been obtained. It has been mentioned that the lubricant jet accelerates crater wear by pulling-out the adherent layers.

The turning of Ti–6Al–4V at high cutting speeds using PCD inserts has been tested by [5,10]. The study showed that an improvement of the tool life of up to 9 to 21 times could be obtained. Different grades of CBN tools have been used when machining Ti–6Al–4V [9]. They seem to be sensitive to coolant pressure, the improvement of tool life can reach 150%.

The explanation of tool wear mechanisms when machining titanium alloys [1] and nickel-based alloys has been the subject of other studies [2,6,22].

The present study provides a contribution to the optimization of this process when machining Ti17 titanium alloy. It is based on a wide range of experimental tests and a well-informed study of the tool wear mechanisms.

2. Material and experimental setup

2.1. Material presentation

The studied material is the Ti17 titanium alloy (Ti–5Al–2Sn–4Mo–2Zr–4Cr); its chemical composition and its mechanical properties are summarized in Table 1.

At room temperature, the Ti17 alloy is composed of an α phase and a β phase. The transus temperature is located at 880 °C; above this temperature, only the β phase exists. The α phase exists in different morphologies: α grain boundary (α_{GB}), α Widmanstätten grain boundary (α_{WGB}) and α_{WI} morphology [18]. The microstructure of the material is presented in Fig. 1.

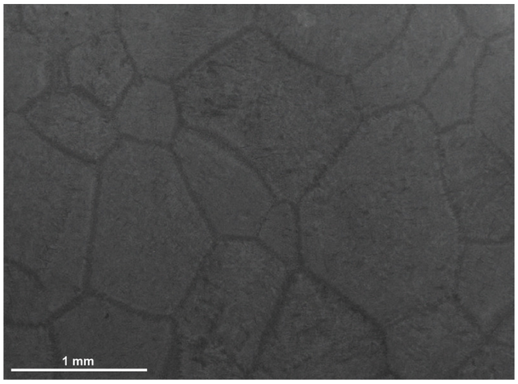


Fig. 1. Microstructure of Ti17.

2.2. Experimental setup

In order to determine the V_{Cmin} (minimum cutting speed), preliminary tests based on the "Pr E 66-520-4" standard have been done. The cutting speed has been varied from 5 m/min to 90 m/min. At the end of these tests, the cutting speed of 50 m/min was selected. After this phase, tool wear experiments were undertaken at different cutting speeds and with different lubrication pressures. The tool used in all tests is the Secco JetStream PCLNR 2525M12. The purpose of these tests was to evaluate the effectiveness of HPWJA under the following conditions:

Table 2
Water jet pressure and flow rate.

Pressure (bar)	50	100	150	200	250
Flow rate (l/min)	9	15	20	23	26

Table 3
Geometrical parameters of the cutting tool and the cutting parameters.

Tool geometry	
Nose radius r_ϵ (mm)	1.2
Edge radius r_β (μm)	30
Rake angle (°)	7
Flank angle (°)	6
Cutting edge angle (°)	95
Cutting parameters	
Cutting speed V_C (m/min)	50; 61; 75; 81; 88; 100
Depth of cut a_p (mm)	1.5
Feed rate f (mm/rev)	0.1

- Cutting speed V_C (m/min): 50; 75; 61; 81; 88 and 100.
- Water jet pressure and flow rate (Table 2).

All machining operations have been carried out with a "LEADWELL LTC25iL" CNC lathe (Fig. 2). A high-pressure pump has been used to supply the high-pressure jet (400 bar, 38 l/min). The pump tank is filled with 200 L of lubricant consisting of 95% water and 5% soluble oil. The experimental setup is illustrated by Fig. 3

The depth of cut and the feed rate were maintained constant (1.5 mm and 0.1 mm/rev respectively). For each test, a new uncoated tungsten carbide (H13A) tool insert was used. The measurement of the three cutting force components was done using a Kistler 9257B dynamometer. The geometrical parameters of the tool and the cutting parameters are summarized in Table 3.

(a) (b)

Fig. 2. (a) High-pressure pump, (b) CNC lathe.

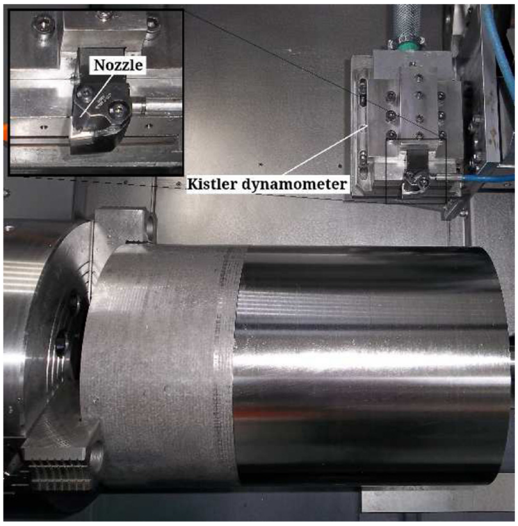


Fig. 3. Experimental setup.

Tool wear has been followed and controlled by using a stereo binocular microscope and a scanning electron microscope, by monitoring the cutting forces. Over 270 measurements related to the 20 tests have been carried out. At the beginning of the experimental work, a series of repeatability tests were performed. The same types of wear was observed and the measurement error of the flank wear is estimated to be 0.02 mm. Fig. 4 shows the main wear types.

3. Tool wear tests at $V_C = 50$ m/min

For the initial cutting speed of 50 m/min, three lubrication types were selected: conventional lubrication (Conv-Lub), and two high-pressure lubrication conditions ($P = 100$ bar and $P = 250$ bar). Fig. 5 shows the evolution of flank wear (VB) as a function of the machining time. For the total duration of the test (30 min), flank wear does not exceed 0.26 mm. It can also be noted that with HPWJA (250 bar), the evolution of flank wear is stable in the beginning of the test. However, towards the end of the test, its evolution becomes very rapid. Moreover, with a pressure of 100 bar, the flank wear is still less than 0.2 mm [1]. Hence, it would be interesting to test other lubrication pressures to investigate their effect on tool wear.

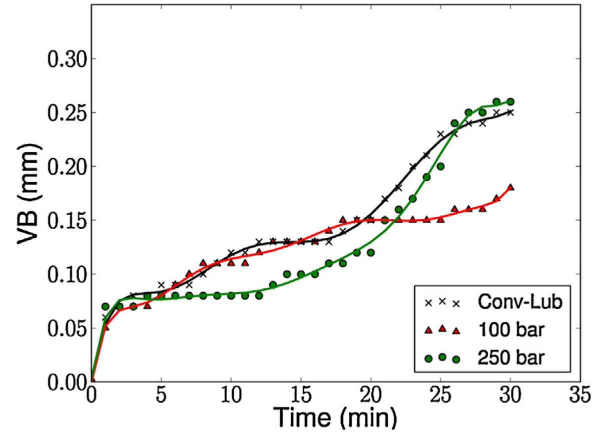


Fig. 5. Flank wear evolution, $V_C = 50$ m/min.

Fig. 6 shows the SEM images of the tool rake face at the end of the three trials. For the conventional lubrication condition, layers of deposits and a large notch have been noticed on the cutting edge (Fig. 6(a)).

Bahatt et al. [2] explains that the combination of the high contact pressure between the tool and the chip, coupled with the high cutting temperature, causes welding to occur between the surface of the chip and the rake face. Devillez et al. [6] proposes the same explanation.

Childs [4] shows that the sticking between the chip and the carbide grains is due to diffusion between the chip and the tool. Thus, an increase in the cutting temperature promotes the diffusion between the tool and the chip. It is true that the adherent layers could protect the tool. However, when the formation of these layers reaches a saturation state, they are pulled-out. When this happens, they are detached along with fragments of the tool, thus causing adhesive wear [6,22].

However, with the high-pressure lubrication, a crater is visible on the tool rake face (Fig. 6(b) and (c)). Furthermore, the build-up of the adherent layers has been reduced due to the action of the lubricant jet. In fact, The lubricant jet pulls out the adherent layers leading to the acceleration of the crater wear [1,7]. However, under these conditions the evolution of the flank wear remains low compared to conventional lubrication. Over time, this will weaken

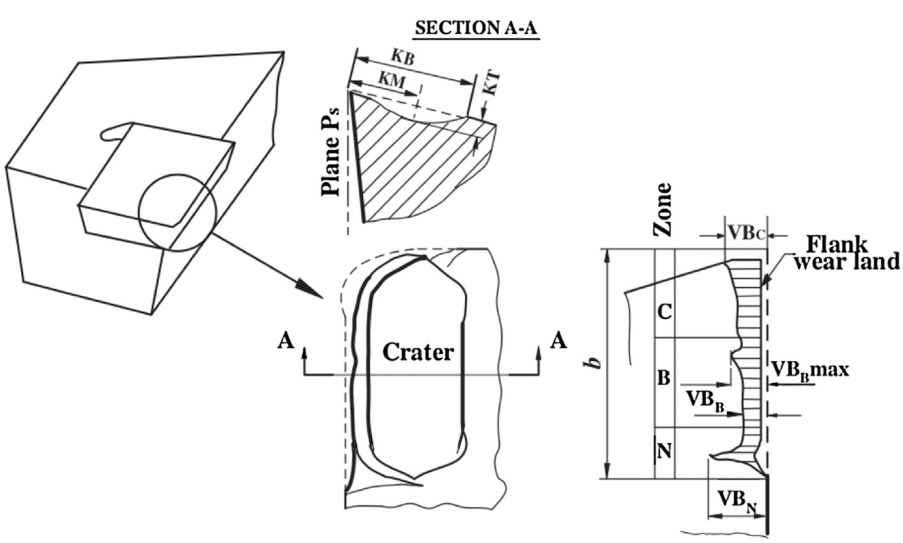
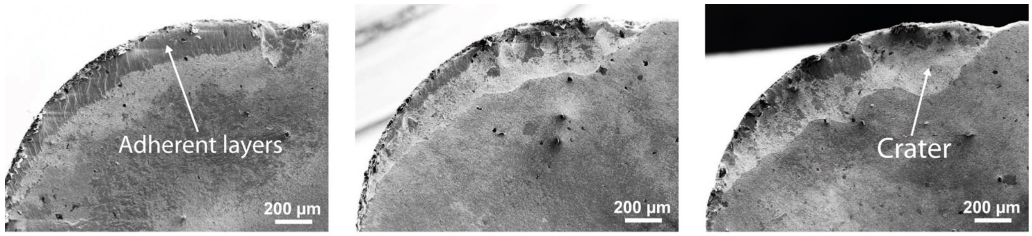


Fig. 4. Types of wear [14].



(a) (b) (c)

Fig. 6. Crater wear, (a) conventional lubrication, (b) 100 bar, (c) 250 bar.

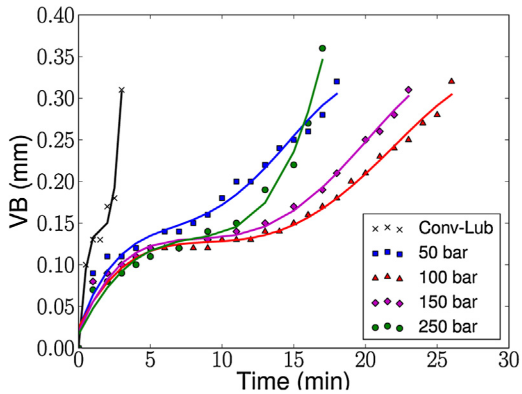


Fig. 7. Flank wear evolution, $V_C = 75$ m/min.

the tool insert. The cutting edge will eventually collapse under the action of the cutting forces.

Increasing the pressure of the water jet causes faster tearing away of the deposed layers leading to the acceleration of the crater wear. Hence, the optimal pressure should be determined which, firstly, cools the tool and allows access to the cutting area (a pressure of 50 bar seems to be insufficient in this case). Secondly, it reduces the flank wear (a pressure of 100 bar gives the best results).

Still, this does not affect the global tool life. In fact, tool wear is more severe with conventional lubrication due to the higher cutting temperature and the higher friction coefficient compared to HPWJA. Under these conditions, the wear rate is higher than in HPWJA due to the activation of many wear mechanisms. In fact with conventional lubrication the combination of high cutting forces and high temperature causes the rapid collapse of the cutting edge, especially for high cutting speeds.

4. Tool wear tests at $V_C = 75$ m/min

For these tests the cutting speed was increased by 50% relative to the reference cutting speed of 50 m/min. Fig. 7 shows the evolution of flank wear for the five lubrication conditions. For the conventional lubrication condition, tool wear increases very quickly and the tool life does not exceed 3 min. However, with high-pressure lubrication, tool life has been greatly improved. Indeed, the best performance has been recorded at 100 bar.

Table 4 summarizes the results of the wear tests. It can be noticed that tool life has been multiplied by 8 fort the pressure of 100 bar. However, increasing the pressure beyond 100 bar does not improve the results.

Table 4
Tool life at $V_C = 75$ m/min.

	Conv-Lub	50 bar	100 bar	150 bar	250 bar
Tool life (min)	3	18	26	23	16

The formation and the evolution of notch wear have also been noted. When the notch wear exceeds 0.21 mm, burrs are formed on the workpiece. Fig. 8 shows the evolution of notch wear (VBn). In fact, it gives the mean values and provides a global estimation over the machining time.

The variation of the cutting and the axial forces, for different lubrication conditions, are plotted in Fig. 9. It shows that F_a and F_C increase as a function of machining time and consequently the tool wear. Furthermore, for an increase of 0.3 mm of flank wear, the variation of the axial force ΔF_a reaches 350 N while the variation of the cutting force ΔF_C exceeds 100 N. It was also noted that the evolution of the axial and the cutting forces follows the evolution of flank wear, the same trends are noticed. Furthermore, when the axial force exceeds 600 N, the corresponding flank wear is about 0.3 mm for all tests. So, the axial force is more sensitive to flank wear than the cutting force. Fig. 10 shows the evolution of the axial force as a function of the flank wear for different lubrication conditions.

Globally, the use of high-pressure assistance significantly increases the tool life. However, when the jet pressure exceeds 100 bar, the tool life begins to decrease (compared to its value at 100 bar), and the surface of the workpiece is affected by scratches. These scratches are most likely caused by the impact of fragmented chips. Moreover, when the pressure increases, the chips are broken into smaller pieces and projected at higher speeds. This may intensify the scratches on the surface of the workpiece.

It is necessary to note that this phenomenon is observed in the context of this study on the Ti17 alloy. However, this might not be the case for other alloys and materials.

5. Tool wear tests at $V_C = 88$ m/min

For this series of tests, the cutting speed is increased by 75% relative to the reference cutting speed. Fig. 11 shows the evolution of

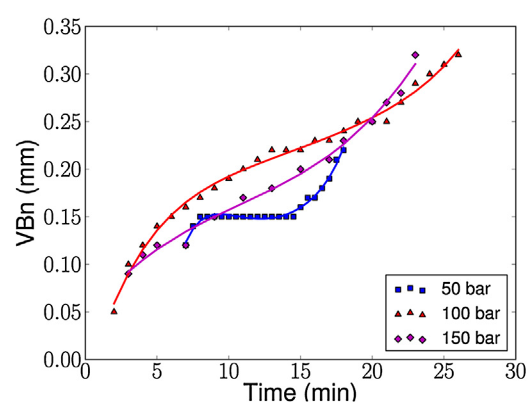


Fig. 8. Notch wear evolution, $V_C = 75$ m/min.

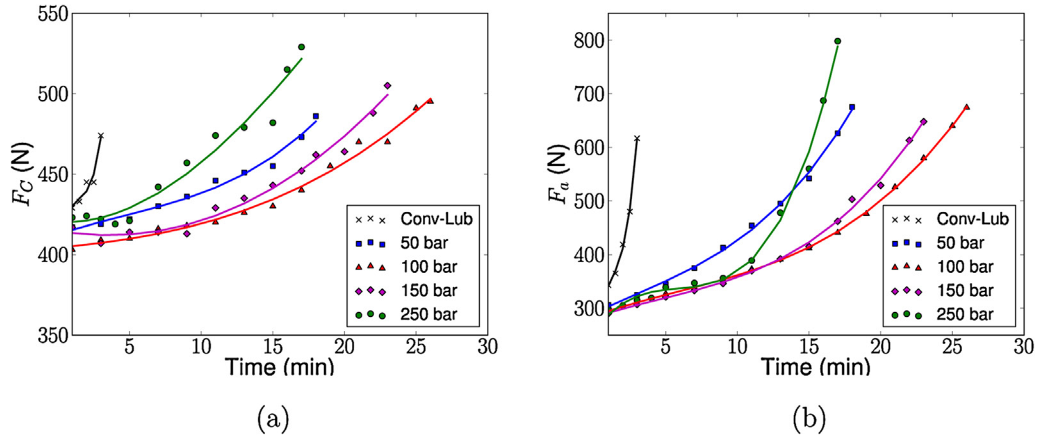


Fig. 9. Evolution of the axial and the cutting forces.

Table 5
Tool life at V_C = 88 m/min.

	Conv-Lub	50 bar	100 bar	150 bar	250 bar
Tool life (min)	1	6	9	8.5	9

flank wear for the different conditions. With conventional lubrication, the Ti17 alloy is not machinable at this cutting speed because the tool life is about 1 min. In fact, the flank wear evolves linearly reaching 0.45 mm in only 90 s. However, with high-pressure assistance the tool life has been increased significantly with values up to 9 min and with a linear evolution of the flank wear. Indeed, the curves do not exhibit the catastrophic evolution of wear.

Fig. 12 shows the rake and flank faces of the tool at the end of the wear tests. With Conventional lubrication, the cutting edge has completely collapsed. Indeed, tool wear seems to be very severe. In contrast, with HPWJA, tool wear is more regular.

Table 5 shows the effect of the high-pressure water jet assistance on increasing the tool life. With a pressure of 50-bar, tool life is multiplied by 6 and with the pressure of 100 bar it is multiplied by 9. According to the flank wear curves, increasing the pressure seems to have no effect beyond 100 bar. However, as for the cutting speed of 75 m/min, scratches have been observed on the workpiece. They are more intense and accompanied by the welding of chip fragments on the workpiece.

As it has been previously noted, under the action of the water jet, chips are fragmented into very small fragments which do not exceed 3 mm, some of which are recycled by passing between the cutting edge and the workpiece. These could be welded on the workpiece, as shown in Fig. 13.

The analysis of the cutting force evolution during the machining time shows the existence of peaks. These peaks may correspond to the phenomenon of chips recycling. The change in cutting force ΔF can reach 50 N. Fig. 14(a) and (b) respectively shows the evolution of the cutting force after 5 min and 9 min of high-pressure water jet assisted machining. Furthermore, from these curves, it can be noted that the frequency of force peaks has been increased. Hence, it can be concluded that the chip recycling frequency has also been increased. The approximate number of these peaks has been multiplied by two.

Flank wear could be accelerated with the phenomenon of chip recycling which could also explain the curves of Figs. 5 and 7.

6. Tool wear tests at V_C = 100 m/min

For this series of experiments, the cutting speed has been doubled compared to the reference cutting speed. According to Fig. 15, tool life does not exceed 4.5 min even with high-pressure water jet assistance. Thus, it can be deduced that the effectiveness of the assistance has been greatly reduced. In fact, the lubricant jet cannot dissipate the heat generated in the cutting zone and the wear continues to evolve.

However, compared with conventional lubrication, Table 16 shows that the tool life can be multiplied by 9 with a pressure of 100 bar. With conventional lubrication, the tool lasts only a few seconds before collapsing. As has already been noticed, for pressures exceeding 100 bar, the surface of the workpiece is affected by scratches and welded fragments of chips.

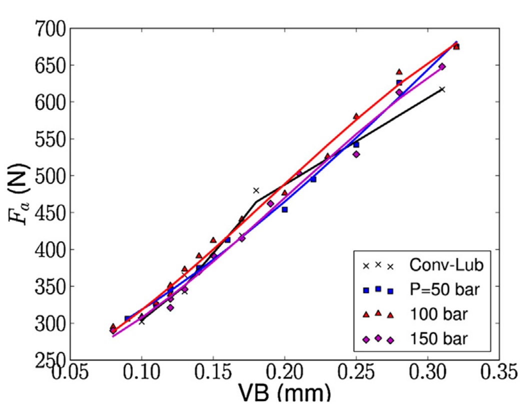


Fig. 10. Evolution of the axial force as a function of flank wear (V_C = 75 m/min).

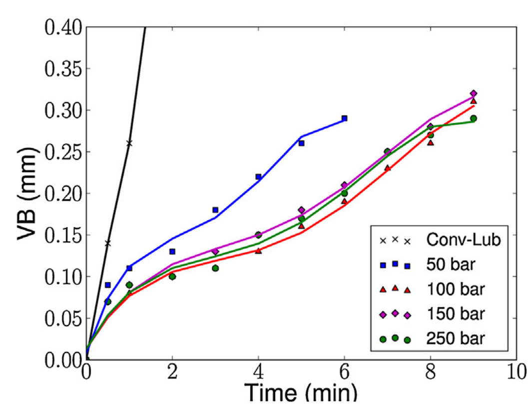


Fig. 11. Flank wear evolution, V_C = 88 m/min.

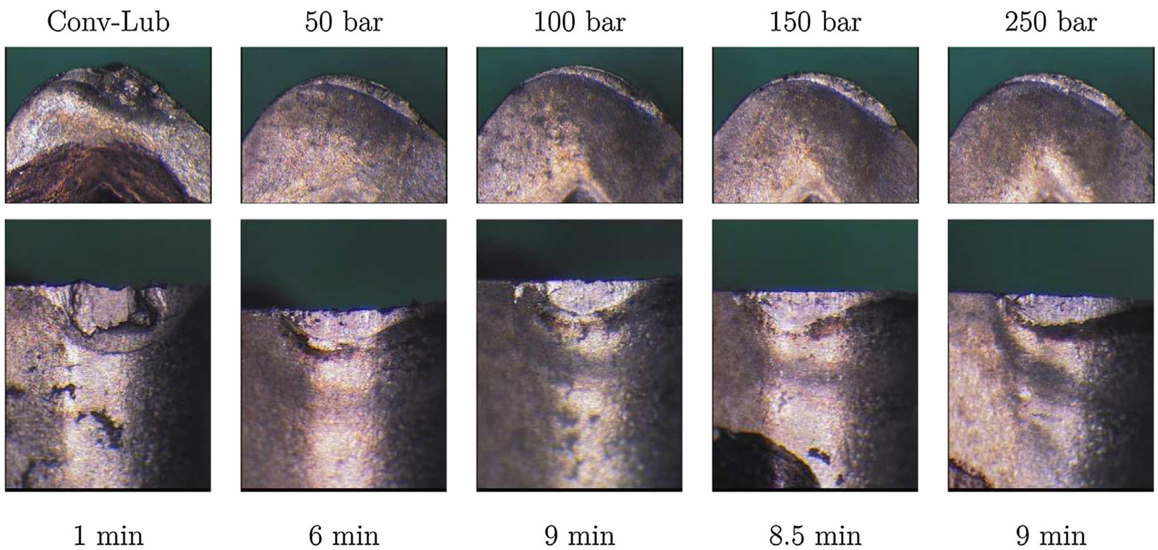


Fig. 12. Flank and crater wear at the end of tool life, $V_C = 88$ m/min.

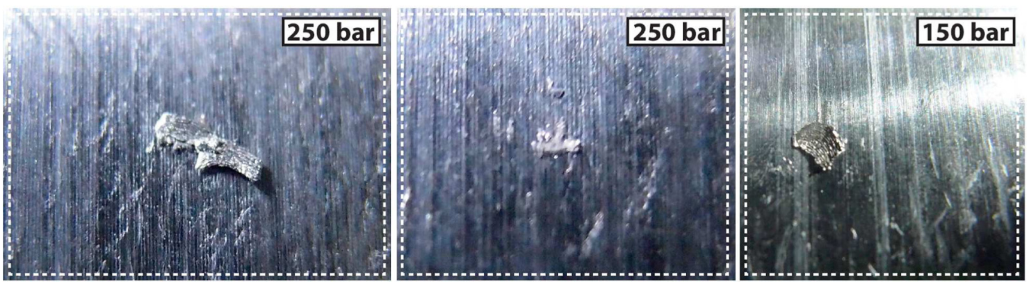


Fig. 13. Scratches and welded chip fragments on the surface of the workpiece (150 bar and 250 bar).

7. Discussion

Fig. 17 summarizes the results obtained for the cutting speeds of 75 m/min, 88 m/min and 100 m/min. The first finding is that tool life drops rapidly when cutting speed increases. This is because the increase of the cutting speed causes an increase of the cutting power and so the dissipation of heat in the workpiece as well as the tool. The additional generation of heat causes a temperature rise in the cutting zone. Thereafter, the wear mechanisms which are activated at high temperatures dominate, thus accelerating tool wear.

In the case of conventional lubrication, wear takes place very quickly and causes the collapse of the cutting edge after a few minutes ($V_C = 75$ m/min), or after a few seconds ($V_C = 100$ m/min). The high-pressure water jet allows the continuous cooling of the cutting area. However, the effectiveness of the assistance decreases as the cutting speed becomes more important. Certainly, high-pressure water jet assistance can increase the tool life greatly compared to the conventional lubrication, but it reaches its limits for high cutting speeds.

In the range of cutting speeds in which assistance has certain advantages and is still effective, an optimum pressure can be

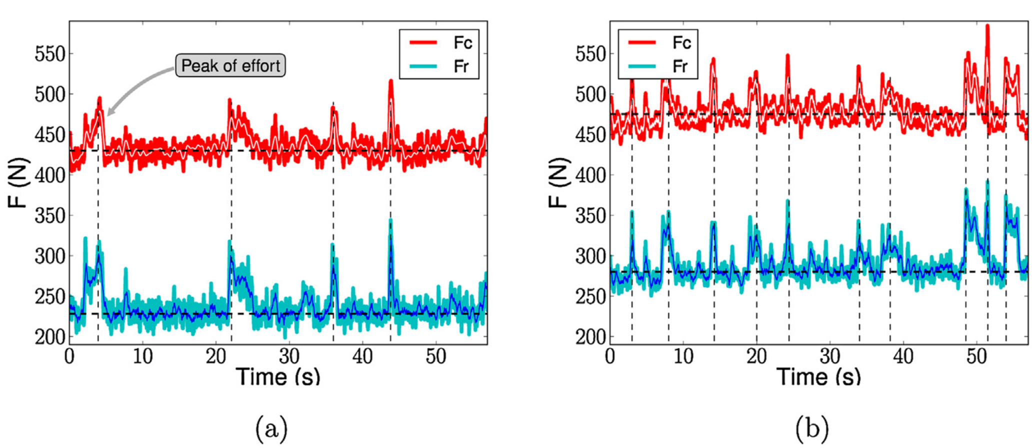


Fig. 14. Evolution of the cutting and axial forces at 250 bar (a) between 5 min and 6 min, (b) between 9 min and 10 min.

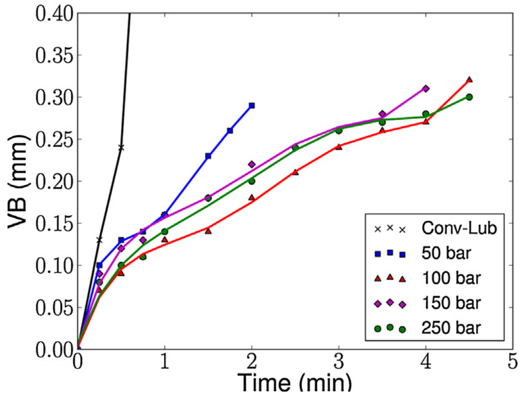


Fig. 15. Flank wear evolution, $V_C = 100$ m/min.

	Conv-Lub	50 bar	100 bar	150 bar	250 bar
Tool life (min)	0.5 (30s)	2	4.5	4	4

Fig. 16. Tool life at $V_C = 100$ m/min.

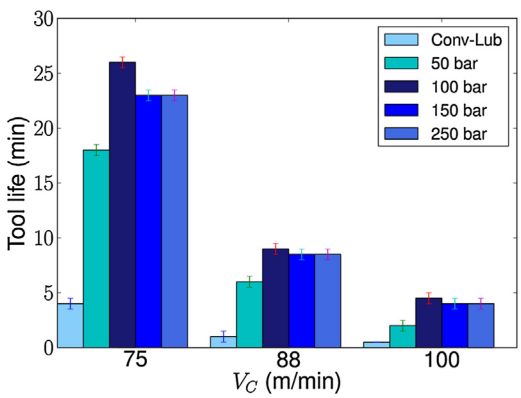


Fig. 17. Variation of the tool life in function of the cutting speed and the lubricant jet pressure.

determined. Indeed, increasing the lubricant jet pressure allows the convection coefficient to increase and so decreases the temperature in the cutting zone. This could present a barrier to some wear mechanisms, thus increasing tool life. In the case of Ti17, the best results have been obtained at 100 bar. Moreover, the analysis of the cutting force and the workpiece surface has allowed the detection of force peaks, scratches and welded chips for the highest pressures used

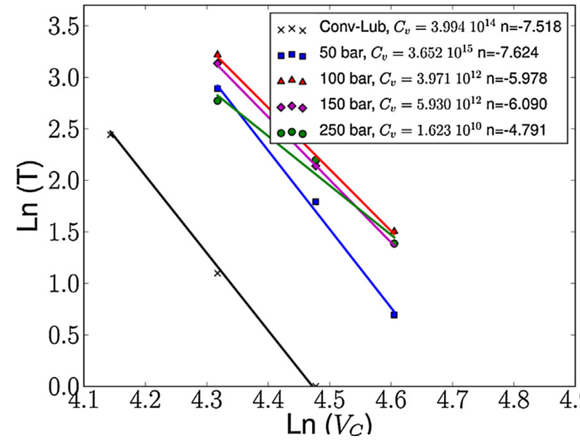


Fig. 18. Identification of the Taylor law.

in this study. All these elements have made it possible to identify the pressure of 100 bar as the optimum pressure.

8. Determination of the maximum cutting speed for *T* = 15 min

In this part of the study, the maximum tool life has been fixed at 15 min (i.e. the value commonly used in industry). The main objective is to determine the maximum cutting speed that can ensure the 15 min of machining using conventional and high-pressure lubrication. For this purpose, the Taylor law coefficients (Eq. (1)) have been identified. Fig. 18 shows the obtained results.

$$T = C_v {V_c}^n \quad (1)$$

For the conventional and HP (100 bar) conditions, the analytical calculation of the cutting speeds gives respectively 61.06 m/min and 81.40 m/min.

Following this calculation, two tests at $V_C = 61$ m/min and at $V_C = 81$ m/min have been carried out. Fig. 19(a) shows the tool wear evolution for these tests. It can be seen that the results of analytical calculations are confirmed.

For conventional lubrication condition after run-in and stabilization phases, the wear increases significantly; indeed, it goes from 0.16 to 0.3 between 12 min and 16 min ($\Delta V_B = 0.14$ mm). However, in the case of water jet assistance (100 bar), wear increases linearly from the sixth minute. It goes from 0.23 to 0.31 between 11 min and 15 min ($\Delta V_B = 0.08$ mm). Moreover, it can be noticed that the evolution of wear in the case of HP assistance is more controlled and presents a linear evolution. By contrast, for the conventional machining, wear is rapidly accelerated from 10 min of

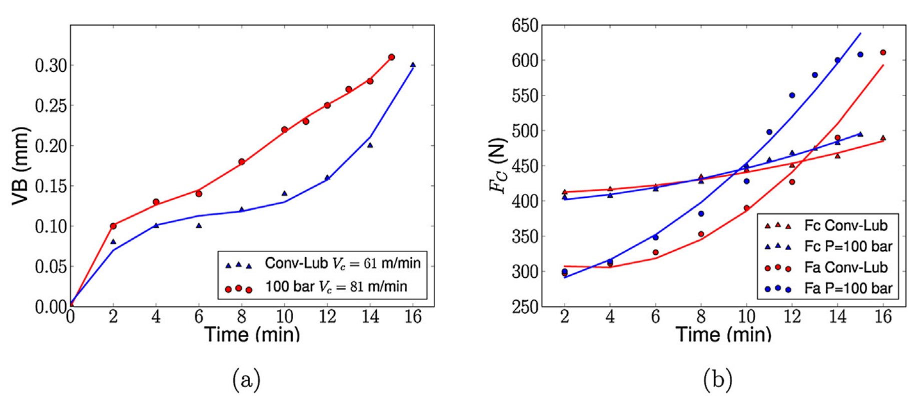


Fig. 19. Evolution of the flank wear and the cutting force for $V_C = 61$ m/min in conventional lubrication and $V_C = 81$ m/min at 100 bar.

machining, which results in a catastrophic tool wear. So, even if the two configurations have the same tool life, HP assistance provides better wear control.

Fig. 19(b) shows the evolution of the cutting and the axial forces. For the cutting force, its evolution is the same for both lubrication conditions. The evolution of the axial force seems to follow the evolution of wear. These observations confirm that the axial force of 600 N is a sign of flank wear of 0.3 mm.

For a tool life of 15 min, the transition from $V_C = 61$ m/min (conventional lubrication) to $V_C = 81$ m/min (100 bar) signifies an increase in productivity of about 32 %. Tool life remains between 9 min and 15 min for the cutting speeds of up to 88 m/min. In this range, Ti17 is not machinable with conventional lubrication.

9. Conclusion

This study is focused on the influence of pressure and cutting speed on the effectiveness of the high-pressure water jet assistance. The lubricant pressure has been varied from 50 bar to 250 bar and the cutting speed from 50 m/min to 100 m/min.

The effect of HP assistance is clearly discernible. In fact, experimental tests have shown that tool life can be increased up to 9 times with a pressure of 100 bar. Moreover, beyond a certain cutting speed the material is no longer machinable with conventional lubrication. However, using HP assistance, it is possible to continue machining and even to increase the cutting speed. For the same tool life of 15 min, the cutting speed can be increased by 30% using HP assistance. The efficiency of water jet assistance decreases with increasing cutting speed.

The influence of wear on the evolution of the cutting forces has been studied. It has been noted that a certain value of the axial force presents a sign of flank wear (0.3 mm).

It has been remarked that, for pressures beyond 100 bar, scratches on the surface of the workpiece have been noticed. Moreover, welded fragments of chips have been observed on the machined surface, which can be the result of chips recycling phenomenon.

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