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Impact of supply conditions of liquid nitrogen on tool wear and surface integrity when machining the Ti-6Al-4V titanium alloy

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Abstract Cryogenic-assisted machining has already shown its advantages on the process and the machining parameters have been analysed. However, part of the coolant jet characteristics as the pressure and flow rate have not been completely studied and optimized. Hence, the main objective of this study is to investigate the impact of these parameters on tool wear and surface integrity when machining the titanium alloy Ti-6Al-4V. Several nozzle diameters have been therefore employed in order to vary the pressure and the flow rate. A new nozzle holder has been developed to ensure the replacement of these calibrated nozzles of different diameters. The machining tests have allowed to draw attention to the impact of the pressure and the flow rate of the liquid nitrogen jet not only on tool life but also on surface integrity. Indeed, the increase of flow rate and pressure increases tool life. Moreover, surface integrity has been greatly improved notably at the highest pressure and the highest flow rate.

Keywords Tool wear · Cryogenic-assisted machining · Liquid nitrogen · Titanium alloy

1 Introduction

Titanium alloys present very interesting assets in the aerospace, marine, and biomedical fields especially due to their excellent mechanical characteristics, their corrosion resistance, and their low density. However, the machining of these alloys is particularly challenging [1, 2]. This is mainly due to their good mechanical properties (resulting in high cutting forces), their very high chemical reactivity (resulting in high cutting forces) with most cutting materials. The temperatures reached in the cutting zone are very high and accelerate certain wear phenomena, which greatly reduce the tool life. All these constraints limit the range of possible cutting conditions. The tool must therefore be strongly cooled. Among the solutions that have been developed to overcome these problems is machining assistance such as laser-assisted machining [3–6], high pressure lubrication-assisted machining [7–11], and cryogenic assisted machining, the subject of this study.

The cryogenic cooling consists of injecting a low temperature liquefied gas (liquid nitrogen or CO_2) into the cutting zone, which improves the dissipation of the heat generated in this area, causing the temperature to drop. This reduction in temperature reduces the effect of certain wear mechanisms, increases tool life, and may improve the surface integrity [12–14]. In addition, machining with cryogenic assistance is similar to a dry machining in that the chips are not contaminated by the cutting fluid, simplifying recycling. The entire lubrication processing chain, which is very expensive, can thus be removed. Hence, this type of assistance has a significant ecological, environmental, and economic impacts.

In the few recent years, cryogenic assistance has became an interesting and a growing field of research. Hong et al. [14, 15] compared different cryogenic cooling strategies; it has been evidenced that the cryogenic cooling allows a remarkable increase of tool life. However, cutting forces become higher due to the increase of material strength and hardness. A significant reduction of the cutting temperature

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and an improved tool life have been obtained when machining AISI 4140, Inconel, Tantalum, silicon nitride ceramic, and titanium [13, 16, 17]. Venugopal et al. [18, 19] showed that tool life has been enhanced from 7 min under dry machining to 24 min under cryogenic cooling; the use of the cryogenic cooling results in a reduction of tool wear on both crater and flank faces. According to studies carried out by Dhar et al. [20] and Khan et al. [21], cryogenic cooling presents various advantages when machining AISI 4037 and 304L stainless steel. Indeed, better surface finish and a considerable increase of tool life (four times) are obtained. It has been noted that cryogenic assistance is more effective at high cutting speeds and high feed rates. Bicek et al. [22] reported that cryogenic assistance enhance tool life of about 370% when machining AISI 52100 bearing steel. The residual stresses become 300–400% more compressive and the white layer is supressed. The turning of AISI 304 stainless steel using the MQL+cryogenic cooling results in doubling tool life according to Pereira et al [23]. The machining of Ti-6Al-4V using the liquid nitrogen lubrication seems to give good results compared to the conventional machining [24, 25]; the cutting temperature decreases of about 60% and tool wear is significantly reduced. Shokrani et al. [26] reported that the cryogenic cooling has improved surface roughness when machining Ti-6Al-4V titanium alloy. According to Jerold and Kumar [27], the cryogenic cooling using liquid CO_2 is more effective at high cutting speeds and feed rates. Machai and Biermann [28] demonstrated that tool life can be increased over two times when machining Ti-10V-2Fe-3Al titanium alloy. They have also remarked that the chemical reactivity of this β titanium alloy is not affected by the liquid CO_2 cooling. The cryogenic turning of ZK60 Mg alloy permits a reduction in cutting temperature of about 60% and the improvement of the micro-hardness of the machined surface by about 40% [29]. The study carried out by Bordin et al. [30, 31] showed that cryogenic assistance allows a significant increase in tool life when machining additive manufactured Ti6Al4V alloy. However, the adhesive wear remains the main tool wear mechanism. Krolczyk et al. [32] and Maruda et al. [33] discussed the environmentally friendly cutting processes (dry, MQCL and MQCL+EP/AW) and their impacts on cutting forces, surface roughness, and tool wear. An interesting investigation carried out by Iturbe et al. [34] has demonstrated that tool life decreases when machining Inconel 718 using the cryogenic+MQL assistance. As reported by the authors, this is due to a deep hardened layer formed under the action of the cryogenic liquid. These constatations are in agreement with the results found by Tebaldo et al. [35].

Most of these studies were focused on the impact of the cryogenic assistance on tool life, surface integrity, and cutting temperature. They have been conducted using standard tools and without taking into account lubrication parameters. The objective of this study is therefore to investigate the impact of the flow rate and the pressure of the cryogenic fluid on tool life, wear mechanisms, and surface integrity.

2 Experimental setup

Turning tests have been carried out on Leadwell LTC25iL (2500 rev/min, 24kw) CNC lathe. The liquid nitrogen has been conditioned in a 180 liter ranger and it has been supplied to the tool through thermally insulated pipes. The dimensions of the Ti-6Al-4V workpiece are respectively $D = 180$ mm and $L = 250$ mm. Due to the high chemical reactivity of titanium alloys, uncoated H13A carbide inserts have been used (CCMT 12-04-08KM). The evolution of tool wear has been tracked using a stereo microscope and a scanning electron microscope (SEM) according to the standard 3685:1993. The critical value of the flank wear V_B is set to 0.3 mm. In addition, in order to investigate tool wear mechanisms, energy-dispersive X-ray spectroscopy (EDS) analysis has been carried out. Concerning the surface integrity, it has been checked out basing on X-ray diffraction and surface roughness measurement. Finally, the cutting forces have been measured using a measuring chain composed of a Kistler 9257B piezoelectric dynamometer, a HBM CD600 charge amplifier and a HBM MX440A 24 bit A/D converter. The experimental setup is illustrated by

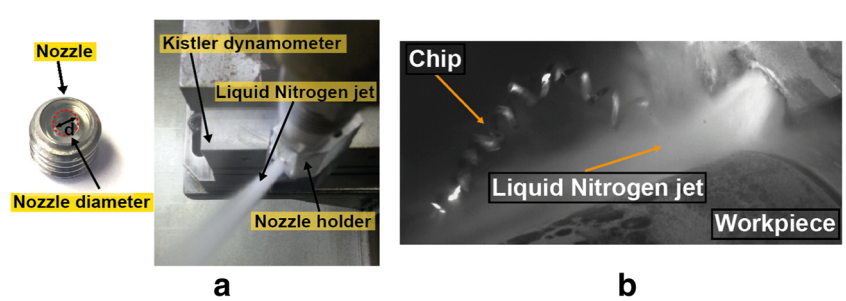

Fig. 1 **a** Experimental setup. **b** High-speed camera acquisition

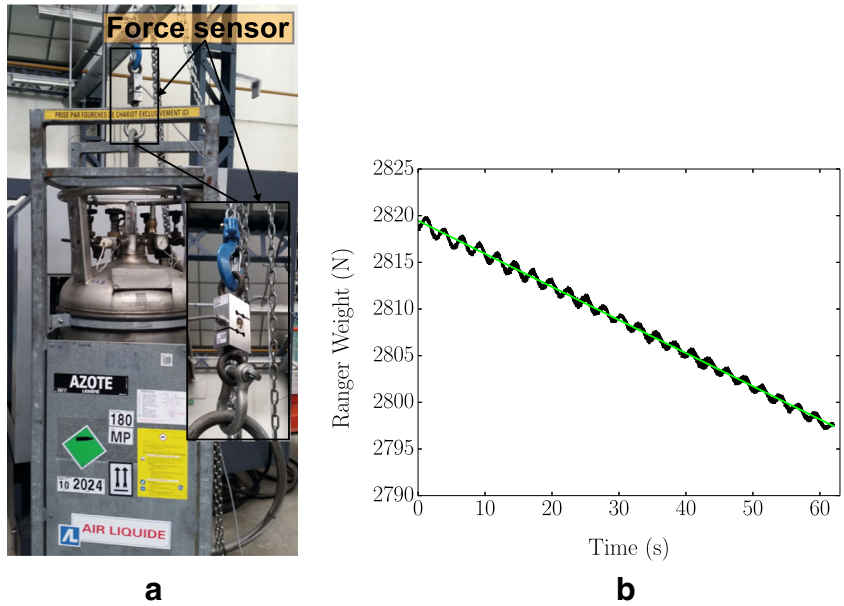

Fig. 2 **a** Mass flow rate measurement setup. **b** Example of LN2 ranger weight measurement during a calibration procedure

Fig. 1. It shows the force dynamometer, the nozzle, the nozzle holder, and a picture of the machining operation using a high-speed camera.

The employed cutting conditions are listed below:

- Cutting speed V_c 80 m/min
- Depth of cut a_p 1 mm
- Feed rate f 0.2 mm/rev
- Nose radius 1.2 mm
- Rake angle 7°
- Cutting edge angle 95°
- Flank angle 6°

In order to measure the mass flow rate, the liquid nitrogen ranger has been suspended and attached to a HBM S9M/5KN load cell. Indeed, the loss of weight at the level of the ranger makes it possible to calculate the mass flow rate. Figure 2 shows the measuring system. First of all, preliminary tests have been carried out in order to determine the correspondence of the flow rate with the nozzle diameter, for a given pressure. The tests have been carried out as follows:

- Select the nozzle diameter.
- Open the nitrogen valve and measure the weight loss of the ranger.
- Calculate the mass flow rate.

Table 1 summarizes the results of these tests.

Table 1 Calibration of the flow rate and the pressure

Liquid nitrogen pressure 8–10 bar		Liquid nitrogen pressure 4–5 bar	
Nozzle diameter (mm)	Flow rate (l/min)	Nozzle diameter (mm)	Flow rate (l/min)
1.6	1.6 ± 0.2	2.2	1.6 ± 0.2
2.5	3.2 ± 0.2	3.0	3.0 ± 0.2

3 Tool wear

The first series of tests consists in varying the flow rate of the liquid nitrogen while maintaining the pressure constant. Figure 3 shows the results of these trials. First of all, it could be remarked that the cryogenic assistance allows a significant increase of tool life compared to dry machining or to conventional lubrication (emulsion). It allows, in the worst case, to increase the tool life of about four times compared to the dry machining. This is mainly due to the drop of the cutting temperature, which results in a slowdown of certain wear mechanisms evolution. Moreover, these tests demonstrate that the LN2 flow rate has a great impact on tool life. Indeed, the obtained results with a flow rate of 3.0 l/min are better than those obtained with a flow rate of 1.6 l/min whatever the pressure of the liquid nitrogen. Figure 3a shows that after 15 min of machining, the flank wear does not exceed 0.2 mm with a flow rate of 3.0 l/min.

The second series of tests consists in varying the pressure of the liquid nitrogen while maintaining the flow rate constant (low pressure LP and high pressure HP). Figure 4 spotlights the impact of LN2 pressure on tool wear. On the one hand, in the low flow rate condition (LFR), tool life has been multiplied by 3.5 and 4.5 for LP and HP, respectively.

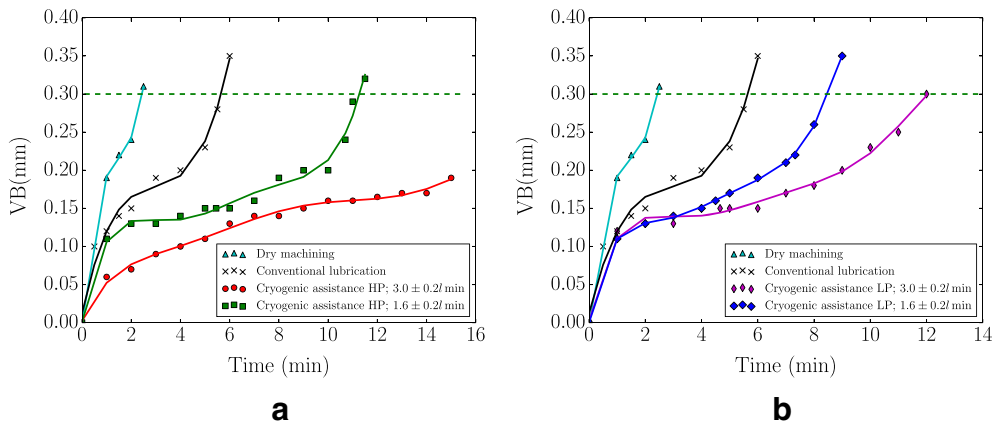

Fig. 3 Evolution of tool wear ($V_c = 80$ m/min, $a_p = 1$ mm f, $f = 0.2$ mm/rev). **a** High pressure (HP). **b** Low pressure (LP)

The high pressure condition results in the best tool performance. On the other hand, in the high flow rate condition (HFR), the impact of the LN2 pressure is more pronounced. Tool life has been multiplied by 4.8 at low pressure condition. Hence, it could be noted that the results obtained from LFR+HP and HFR+LP are very close; this is very interesting especially in order to optimize the LN2 consumption. Overall, the best results have been obtained at high pressure and at high flow rate.

In order to investigate tool wear mechanisms, the cutting edges have been observed firstly using a scanning electron microscope. Figure 5a shows the formation of a built-up-edge (BUE), a built-up layer (BUL), and the early formation of a crater. All these observations are the symptoms of different tool wear mechanism, particularly diffusion and adhesion. In order to have more extensive investigation, EDS analysis has been carried out and has permitted to draw a distribution map of the existing elements on the tool rake face. Figure 5b shows the material adhesion zones on the tool rake face. Indeed, the entire area of tool/chip contact is coated with titanium deposits (red). This is mainly due to the strong chemical affinity of the titanium alloy, the high cutting temperature and the high contact pressures. In fact, in some cases, the formation of these adherent layers may protect the tool. However, when their formation reaches a stagnation level, adhesive wear occurs. This involves the pulling-out of deposits and consequently the tearing-off of the stacked carbide grains.

In the case of the cryogenic machining, the phenomenon of adhesion is slightly less important as demonstrated by Fig. 6a, b. Hence, it can be concluded that adhesive wear remains the main tool wear mechanism in both cases. Indeed, even if cryogenic assistance can significantly reduce the temperature in the cutting zone (which slows some tool wear mechanisms) and thus increases tool life, the liquid nitrogen can not access the contact area tool/chip. Temperature levels at tool tip still important and wear continue to involve even if it has been slowed down by the action of the liquid nitrogen [12–14].

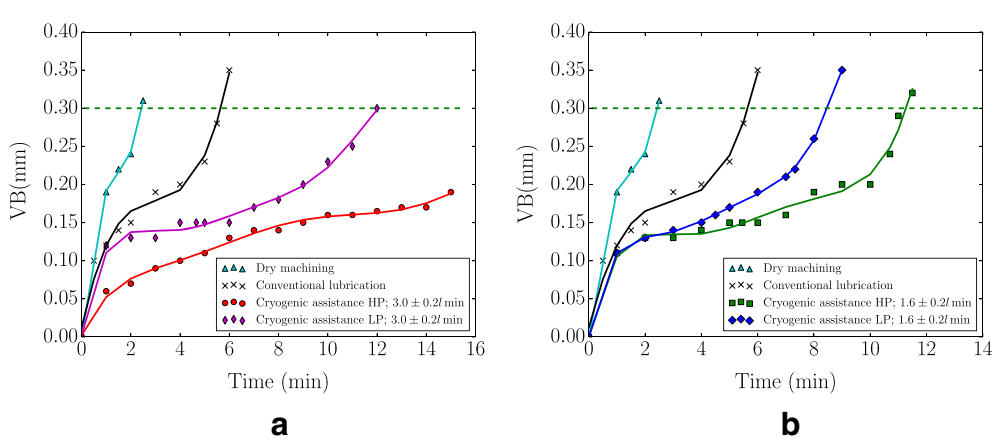

Fig. 4 Evolution of tool wear ($V_c = 80$ m/min, $a_p = 1$ mm f, $f = 0.2$ mm/rev). **a** High flow rate. **b** Low flow rate

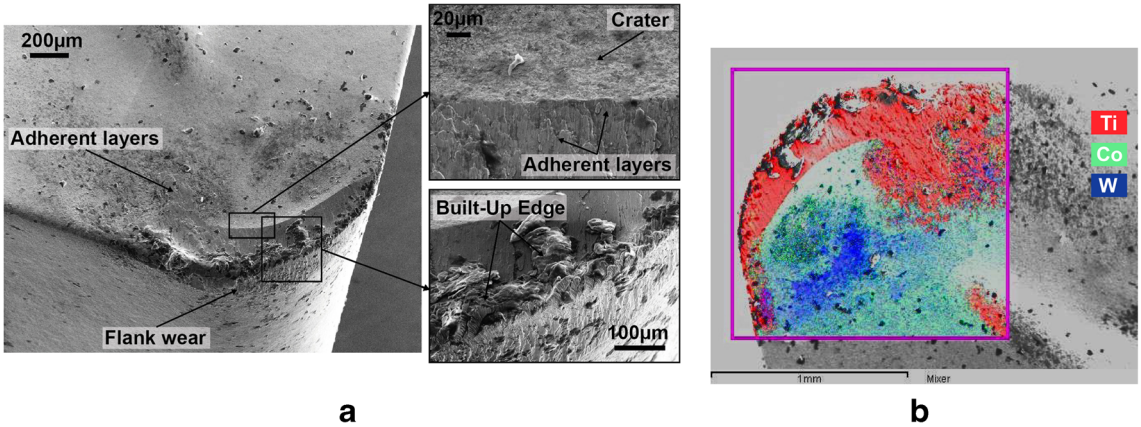

Fig. 5 Tool wear analysis (dry machining; T = 2.5 min; VB = 0.31 mm). **a** SEM analysis. **b** EDS analysis

4 Surface integrity

The surface integrity of a workpiece is a crucial and a critical parameter that requires special monitoring. Indeed, it integrates surface roughness, residual stresses, and microstructure. Regarding the residual stresses, they are mainly due to the combination of mechanical and thermal loads. The question that arises now concerns the influence of the cryogenic assistance on surface integrity. To respond to this question, different types of measurements have been performed. First of all, the cutting forces (F_f: feed force, F_c: cutting force, F_p: passive force) have been measured for all tests (with $F=\sqrt{{F_f}^2+{F_c}^2+{F_p}^2}$). Figure 7a shows an increase of efforts levels with the increase of the flow rate (15% maximum). This might be due to the fact that the liquid nitrogen jet cools not only the cutting area but also a part of the workpiece. Hence, the hardness and the mechanical characteristics of the material increase which subsequently induces an increase of the cutting forces. Cryogenic assistance does not seem to influence the surface roughness as demonstrate by Fig. 7b. The evolution of R_a does not appear significant. These measurements have been carried out using MarSurf PS1 with a cutoff of 0.8 mm. All tests have been repeated three times at least.

After that, the residual stress measurements have been carried out using PROTO iXRD. Analysis results showed a significant improvement of the residual stress using the cryogenic assistance. Compared to the dry machining condit ion, the compressive residual stress level has been doubled (from −200 to −430 MPa). It can also be pointed out a significant influence of the liquid nitrogen flow rate and pressure as shown by Fig. 8. At the same pressure (HP), the increase of the flow rate from 1.6 l to 3.0 l/min has permitted to increase the compressive residual stress of about 120 MPa (40%). However, at the same flow rate (3.0 l/min), the pressure decrease (from 10 to 5 bar) has caused a degradation of the residual stress of about 27% as illustrated by Fig. 8b.

As the mechanical loads induce compressive stresses while the thermal loads induce tensile stresses, the observed differences could be due to the attenuation of the thermal

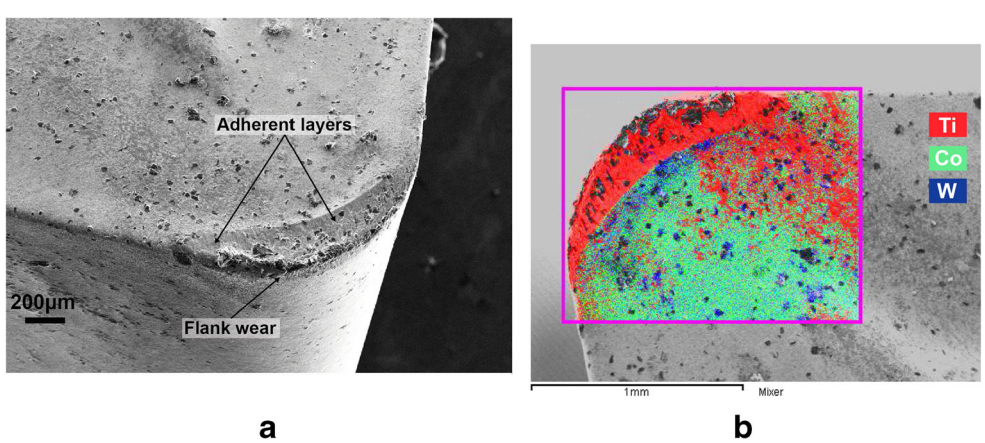

Fig. 6 Tool wear analysis (HP; 3.0 l/min; T = 15 min; VB = 0.19 mm). **a** SEM analysis. **b** EDS analysis

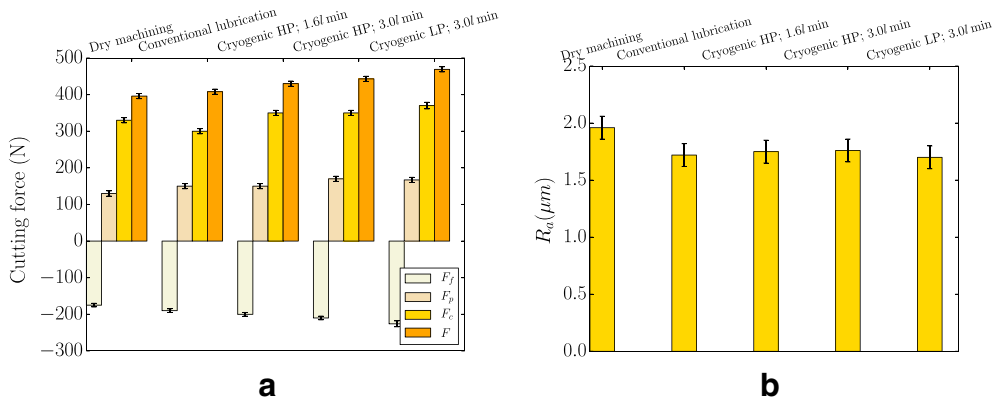

Fig. 7 **a** Cutting forces. **b** Surface roughness

effects and the cutting forces increase. In fact, an effective cryogenic cooling of the cutting area permits to reduce temperature as reported by many authors [13, 16, 17, 24, 25, 29]; this will reduce the contribution of tensile stresses and the overall residual stress become more compressive. In addition, the increase in cutting forces will lead to an increase in residual stresses of mechanical origin. Thus, the combination of these effects could explain the great improvement of the compressive residual stresses.

5 Discussion

In order to confirm the obtained results, a complementary series of tests has been carried out with a flow rate around 1.4 l/min (Fig. 9). These tests showed that at very low flow rate the LN2 pressure does not have a remarkable impact on tool wear. It should be noted that under these conditions, the jet of nitrogen is no longer liquid but rather a mixture of gas and liquid which considerably reduces its cooling capacity [36]. The cryogenic lubrication permits to slow down the evolution of certain wear mechanisms that are activated at high temperatures and thus slowing down the tool wear evolution. The SEM and EDS analysis showed that the main tool wear mechanism is adhesion. Despite the cryogenic cooling, wear continues to evolve; this evolution is very sensitive to the liquid nitrogen flow rate and pressure. The liquid nitrogen jet that cools the better the tool/chip contact zone ensures the longest tool life by reducing and slowing down the evolution of these mechanisms. Moreover, under these conditions, cutting forces increase has been recorded. It could be due to the workpiece hardness increase at cryogenic temperatures.

Residual stresses are also highly impacted by lubrication conditions. The best results are obtained with the best cooling conditions; the fact of reducing cutting temperature, reduces the contribution of thermal loads responsible of traction residual stresses. Moreover, the contribution of the mechanical loads becomes more important due to the cutting forces increase. The reduction of the thermal loads and the increase of the mechanical loads may explain the recorded improvements of the compressive residual stresses.

It is thus crucial to optimize lubrication condition and in particular (pressure, flow rate) couple. In a first approach, it seems that the LN2 pressure has more impact on tool wear than the flow rate. It would be interesting in this case, and in order to reduce LN2 consumption and subsequently costs, to have to highest possible pressure and then to optimize flow rate.

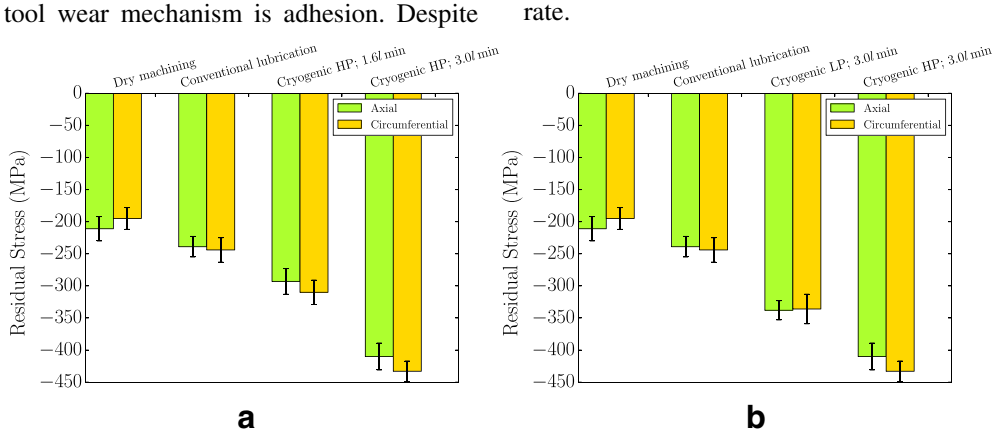

Fig. 8 Surface residual stress. **a** Flow rate influence. **b** Pressure influence

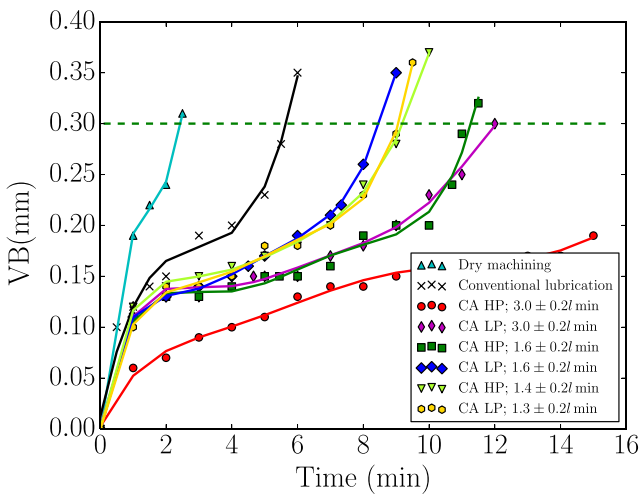

Fig. 9 Complementary wear tests (V_c = 80 m/min, a_p = 1 mm f, f = 0.2 mm/rev)

In the light of this study, it would be interesting to focus the research not only on the processes but also on the lubrication parameters: liquid nitrogen delivery system, the number and the diameter of nozzles, reducing the loss of load inside the tool holder, etc. It is thus necessary to re-concept the existing tool holders for a better cutting performance.

6 Conclusion

This study has allowed to investigate the impact of the pressure and the flow rate of the liquid nitrogen on tool life and surface integrity. Based on the different tests and analysis, it has been demonstrated that cryogenic cooling can significantly increase tool life, at least four times. Tool wear evolution strongly depends on lubrication parameters notably the flow rate. The best tool performance has been obtained at high flow rate and high pressure. Under these conditions, the flank wear has not exceed 0.2 mm after 15 min of machining. According to the EDS analyses, adhesive wear remains the most influential wear mechanism. The cutting effort is slightly increased with cryogenic assistance.

Concerning the residual stresses, a great improvement has been noticed especially at high flow rates, which would mainly due to the attenuation of thermal loads. However, the surface roughness does not significantly vary using the cryogenic assistance.

Hence, it seems that the cryogenic assistance presents an interesting alternative to conventional machining from an ecological and technical point of view. Finally, it is necessary to point out that this study has permitted to respond to some scientific inquiries but it has raised other challenges which open up many perspectives to optimize this process.

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