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Machining assistance techniques: impact on tool wear and surface integrity on aeronautic alloys

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Abstract

This article discusses the effect of machining assistance on the machinability and surface integrity of titanium and nickel-based alloys for turning operations. The presented results are based on a literature review of the principal experimental work published by the French research laboratories within the framework of the Manufacturing 21 group. The work presented focuses on the assistances the most studied by the research group: cryogenic assistance and high-pressure assistance. This paper specifically addresses the experimental approaches used to determine the effect of the assistant on the cutting force, tool wear, chip formation, microstructural changes, and residual stresses generated on the workpiece machined surface. This literature review is completed by new results comparing machining tests on the Ti6Al4V titanium alloy using high pressure and cryogenic assistances. The results show that the assistances increase the tool life, as well as improve the surface integrity of the parts. However, these gains are not identical from one material to another. In particular, titanium alloys and nickel alloys show how a very different gains for a fixed assistance. The conclusions presented highlight current trends and research needs.

Keywords Machining · Cutting assistance · High pressure · Cryogenics · Machinability · Surface integrity

1 Introduction

Titanium and nickel-based alloys are very interesting materials for high-value-added components in many industrial fields. Their outstanding mechanical and chemical properties are suitable for components with very stringent functional requirements (such as maintaining good mechanical properties at high temperatures).

Indeed, the ability of these alloys to withstand very high temperatures results in high cutting forces [1]. In addition, the low thermal conductivity of these so-called refractory materials leads to a high concentration of heat in the tooltip and in the cutting zone, which increases the tool wear and consequently decreases tool life [2].

These alloys are therefore described as difficult-to-cut materials. Hence, to improve the productivity or the quality of the machined components (dimensional accuracy, surface integrity), the machining process for these materials should be improved. Indeed, many challenges must be addressed, such as improving tool life by reducing thermomechanical loads on the tool, improving chip separation and fragmentation, reducing cutting forces, and improving surface integrity (e.g., surface roughness and residual stress). To this end, different strategies can be adopted. It is then possible to (i) improve the performance of the cutting tools or the machine-tool components, (ii) optimize the tool paths [3], and (iii) optimize the workpiece microstructure (i.e., grain size, precipitates size, and morphology) [4]. Finally, assisted machining presents an excellent way to improve the machinability of difficult-to-cut materials.

The main machining assistances are (i) high-pressure assistance [5–7], (ii) cryogenic assistance [8–10], (iii)

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laser-assisted machining [11–13], and (iv) vibration assistance [14]. The basic principle of machining assistance is to evacuate or to provide energy from/to the cutting zone. Figure 1 shows the areas of the different cutting assistance according to their mechanical and thermal contributions.

This additional mechanical and/or thermal action leads to a change in the chip formation mechanisms. In the following chapter, this point is detailed for each assistance. In order to highlight the effect of mechanical and thermal actions on chip formation, a synoptic is proposed. The synoptic shows the effect of the assistance on the three chip formation areas (shear zones), and their repercussions on the cutting force, tool wear, and residual stresses. Indeed, the machining assistances can modify not only the temperatures in the three shear zones, but also the contact length and the tool/chip friction coefficient. Figure 2 shows the synoptic that will be used for each assistance. The interactions are visible by arrows that link the different effects. The interactions that increase the values (temperature, effort) are colored in red. The blue color indicates that the values decrease, and the white color that they are unchanged.

It will be shown in this article that depending on the machined material and the cutting conditions, the assistance effectiveness could vary. The assistances are not necessarily in competition with each other, but rather complementary depending on the material being machined and/or the type of gain one wishes to achieve. They are different from each other by their industrial maturity and by their effect on tool wear and surface integrity [15–17].

2 Description of assistances

It is well known that temperature is a key factor controlling tool wear evolution through the activation and/or the acceleration of some tool wear mechanisms (i.e., diffusion, adhesion, and oxidation). Its reduction leads to a tool life increase. Hence, different lubrication techniques are used to decrease temperature levels in the cutting zone. High-pressure and cryogenic lubrication are among the most efficient solutions.

2.1 High-pressure assistance (HPA)

HPA consists of projecting a high-pressure lubricant jet between the chip and tool rake face and/or the tool flank face and the machined surface. The lubricant is a classic fluid such as an emulsion coolant or sometimes even whole oil. The HPA ensures chip fragmentation and efficient heat dissipation. High tool life increase is generally reported when using this technique [18, 19]. Moreover, its relatively simple implementation within an industrial framework presents an important advantage. Figure 3 shows the CNC lathe equipped with a Hammelmann HDP 42 high-pressure pump (380 bar, 36 L.min⁻¹) used to carry out the experimental tests in the LAMPA laboratory.

It will be shown in Chapter 3 that for high-pressure assistance, the lubricant jet reduces the temperature of the cutting zone and applies a significant stress on the chip which leads to a smaller tool/chip contact area. In

Fig. 1 Mechanical and thermal contribution for each assistance

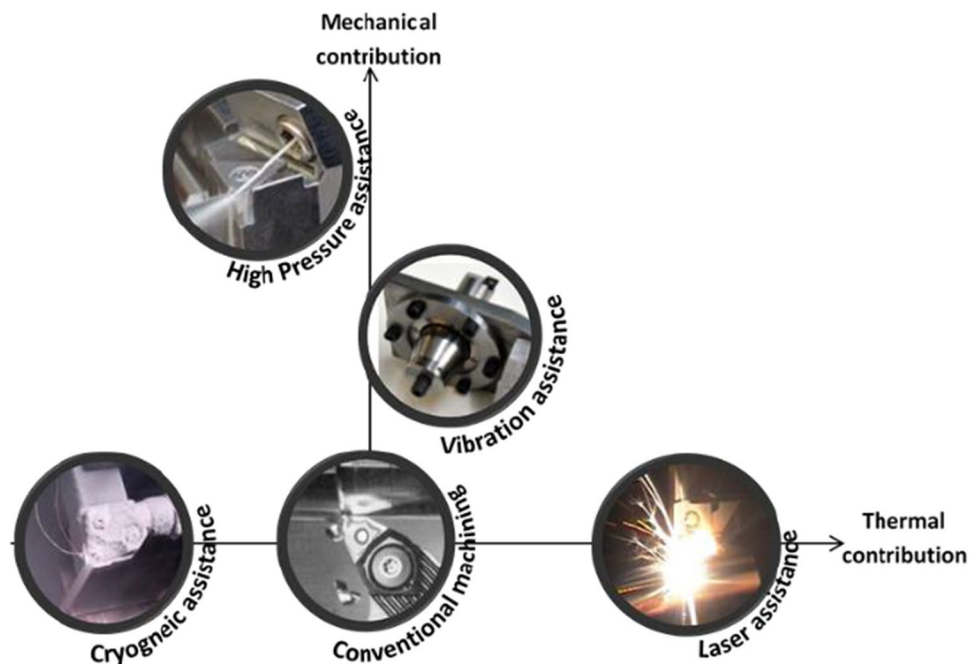
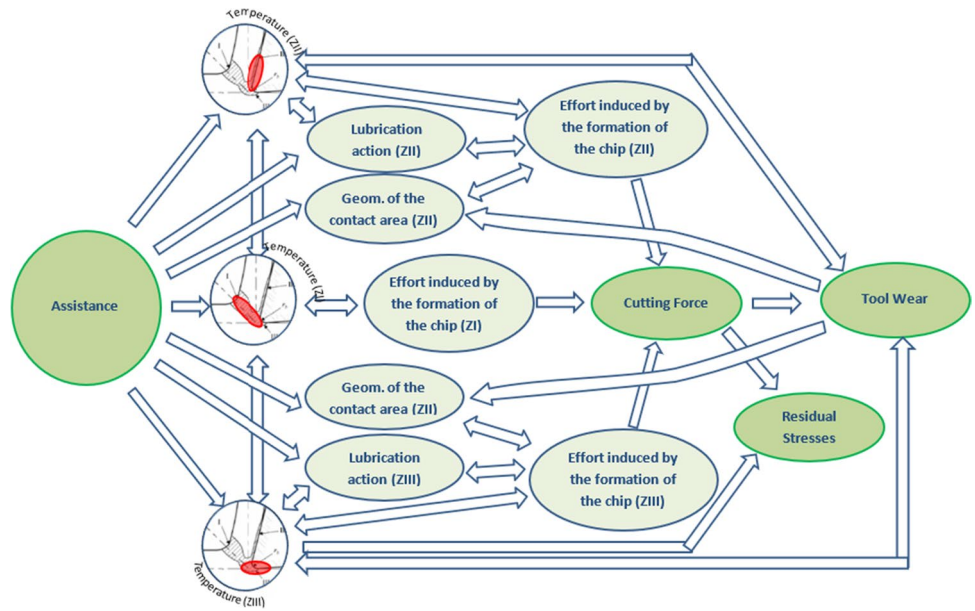


Fig. 2 Simplified synopsis of thermal and mechanical interactions in the cutting zone



addition, with the high pressure, the lubricant is inserted between the chip and the tool which reduces the friction coefficient. These interactions can be visualized by the following synoptic (Fig. 4).

2.2 Cryogenic assistance

Similarly to HPA, the principal of cryogenic assistance (CA) is to cool the cutting area by the means of a cryogenic fluid such as liquid nitrogen (LN2), liquid carbon dioxide (LCO2), or supercritical CO2 (ScCO2) [20]. The liquid nitrogen supply is ensured by a ranger at a regulated pressure (around 12 bars). The tool is fed through heat-insulated pipes and a phase separator to remove nitrogen gas from the feed line. Figure 5 shows the LN2 supply chain. Regarding the LCO2 and the ScCO2 fluids, the tool supply can be carried out directly without any phase separator or heat-insulated pipe.

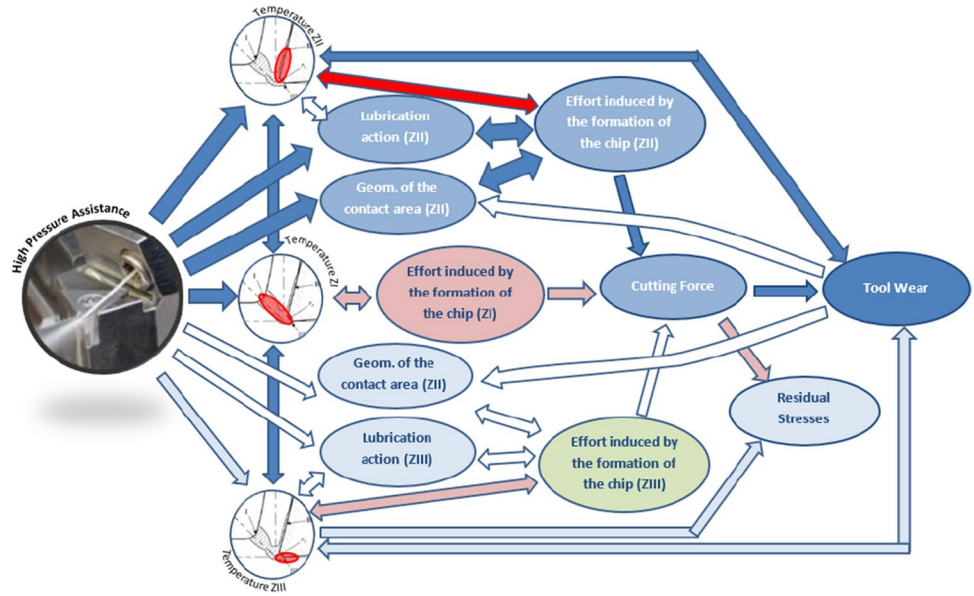
The interactions between the different actions induced by the cryogenic assistance show very strong cooling of the cutting zone. On the other hand, unlike HPA, the mechanical effect on the cutting zone is not significant, and the chip is not fragmented. The cutting force does not change significantly. Indeed, cooling tends to harden the material, but the cryogenic fluid decreases the tool-chip friction coefficient [21], so the cutting effort is not very affected. With the decrease of the thermal effect, the tool wear will decrease, as shown in Fig. 6.

Different works carried out in French research laboratories have focused on the drilling process with cryogenic cooling [22–24] for the drilling of the Ti6Al4V titanium alloy. It has been shown that there is a gain in machinability and an improvement in the surface integrity of the holes. A critical review article has been published on cryogenic assistance in drilling operation [25].

Fig. 3 High-pressure assistance experimental setup (LAMPA)



Fig. 4 Simplified synopsis of high-pressure assistance interactions



In addition to its ability to increase tool life and material removal rate, cryogenic machining is an environmentally friendly technique. In fact, it ensures the reduction of health risks and waste generation. Moreover, it contributes to saving machining costs and to ease the cleaning and the decontamination of both workpiece and chips. In order to improve the lubricating performance of these fluids and to reduce the friction coefficient, it is possible to mix them with MQL (minimum quantity of lubrication) [26]. However, the use of MQL makes the CO2 footprint of the process much worse. This is why cryogenic assist without MQL (without cutting oils) is a sustainable and environmentally friendly green process.

2.3 Laser assistance

Unlike cryogenic assistance, which cools the tool, laser assistance machining (LAM) consists of heating with a laser beam, the area of the part to be machined (Fig. 7a). This assistance uses the principle of hot machining, as used with an inductive heating for the machining of the titanium alloy Ti555-3. [27, 28].

In the machining enclosure (Fig. 7b), the laser beam is focused on the surface of the part a few millimeters upstream of the tool to heat the volume of material that will be machined by the tool. A pressurized air jet is blown at the outlet of the focusing head (cross-jet) to prevent

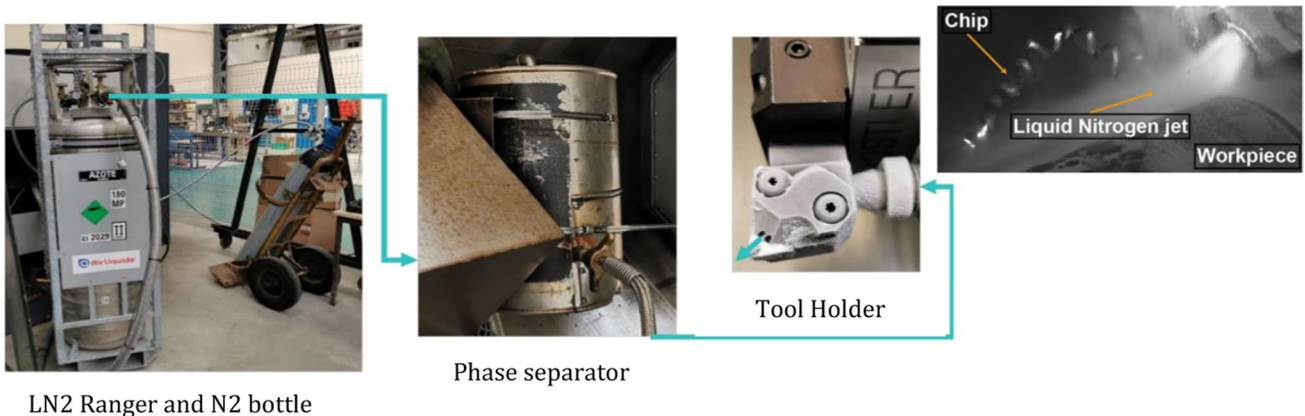
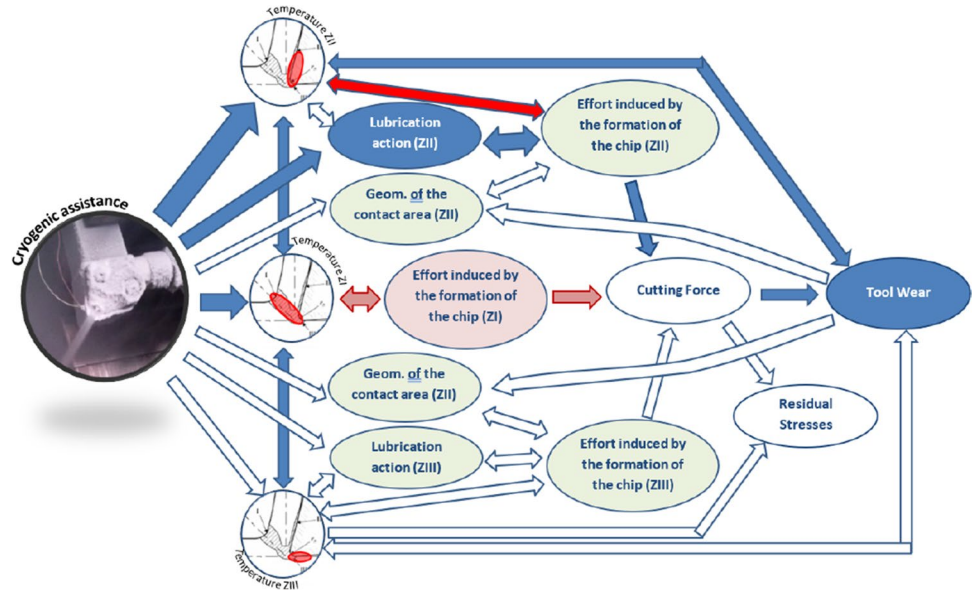


Fig. 5 Liquid nitrogen supply device (LAMP)

Fig. 6 Simplified synopsis of cryogenic assistance interactions



chips and fumes from coming back to the focusing lens. Increasing the temperature of the part allows for decreasing the flow stress of metallic materials (decrease of the cutting force) or to pass in the ductile domain for ceramic materials (improvement of the machinability), but with the disadvantage of increasing the temperature in the cutting zone, which decreases the tool life and favors residual tensile stresses that are harmful to the surface integrity of the workpiece (Fig. 8). In addition, intensive laser beam heating can easily cause phase changes on the surface of the workpiece (hardening) if the laser-tool position is not well respected.

LAM may be useful for machining specific materials such as ceramics or metal matrix composite [29, 30]; however, it presents limited interest in machining the metallic materials [31, 32]. It is, therefore, of little interest for the machining of aeronautical alloys such as titanium and

nickel bases, so it will not be developed in the following chapter.

2.4 Vibration assistance

Vibration-assisted machining (VAM) consists of applying a high frequency and a low amplitude vibration to the cutting tool. For the turning process, the tool is excited by a piezoelectric sonotrode (Fig. 9a) [33] which allows the tool to vibrate in the direction of the feed motion or elliptically (Fig. 9b) [34].

Yang et al. in their review article [33] state that vibration assistance improves workpiece surface quality, reduces cutting force and chip fragmentation under certain conditions, and increases tool life (especially for low cutting speeds). This assistance brings only a modest gain

Fig. 7 **a** Principle of laser assistance machining and **b** LAM device (LAMPA)

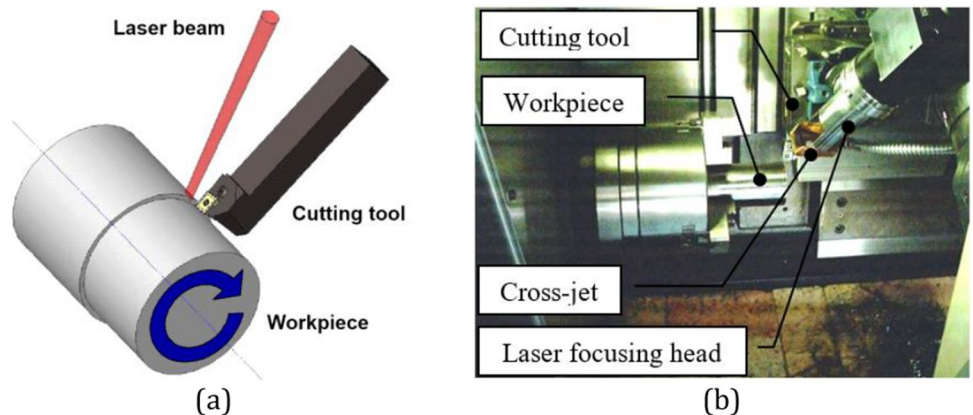
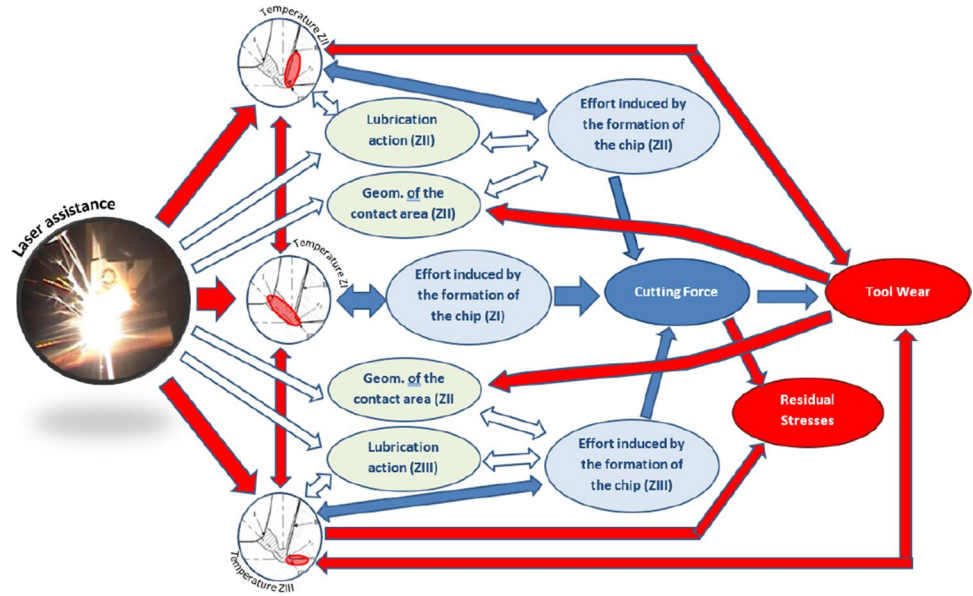


Fig. 8 Simplified synopsis of laser assistance interactions



to the turning process and has not been studied by the Manufacturing 21 group.

On the other hand, vibration assistance in drilling brings very significant gains. The vibration assisted drilling (VAD) was studied by the French research group [35–37] for drilling titanium alloys [37, 38], composite materials, and CFRP/Ti6Al4V stacks [39–42]. This article will not develop the drilling process but only the turning process, so this assistance will not be developed in the next chapter.

3 Impact of high-pressure assistance (HPA) and cryogenic assistance (CA) on machinability

The previous chapter presented the four most studied machining assistances. It has been shown that laser and vibratory assistants do not bring significant gains for a turning operation. For the turning process, only two assistances are interesting for the machining of aeronautical alloys: the high-pressure assistance and the cryogenic assistance. These two assistances will be detailed in this chapter. The machinability is defined according to three criteria related to chip formation (i.e., cutting forces and chip morphology), tool wear, and surface integrity (i.e., residual stress, surface roughness and topology, and affected/white layer). This chapter will detail the work done in France on these aspects

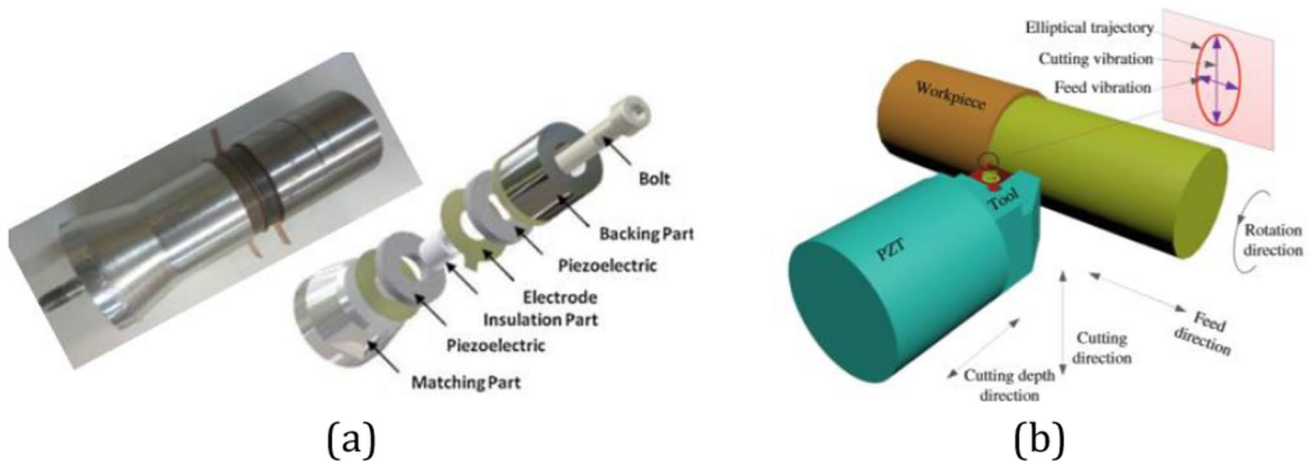


Fig. 9 a Sonotrode device with piezoelectric exciter [33] and b vibration of the cutting tool [34]



Fig. 10 a Experimental and b numerical chip fragmentation [38]

with a section on chip formation and tool wear and another section on surface integrity.

3.1 Impact of HPA and CA on tool wear and chip formation

The HPA has been the object of several research studies with the double objective of studying the physical mechanisms of cutting and optimizing the process for titanium alloys [43–45] and nickel alloys [46, 47]. The high-pressure lubricant jet breaks up the chip very effectively. As such, the study carried out by Ayed et al. [48] showed that chip fragmentation (Fig. 10), an important effect of the HPA, is not only due to the mechanical action of the lubricant jet but also to its thermal action. Indeed, the chip

is fragmented if its temperature decreases (becomes less ductile) and if the mechanical effort is sufficiently high.

In addition, due to the significant decrease in temperature in the cutting zone, the tool life is greatly improved. The assured improvement can exceed 500%. Figure 11 shows the results of two studies concerning the machining of Ti17 and Ti5553 titanium alloys using HPA [43, 49]. It clearly highlights the existence of an optimal lubrication pressure of around 100 bar, whatever the cutting condition. The increased pressure allows the lubricant to be inserted between the chip and the tool, thus protecting the tool. However, if the pressure is too high, the material clusters on the cutting face of the tool are torn off, which greatly accelerates adhesive wear. The tool life decreases when the pressure is too high.

The high-pressure assistance allows very good fragmentation of the chip and a very significant increase in the tool

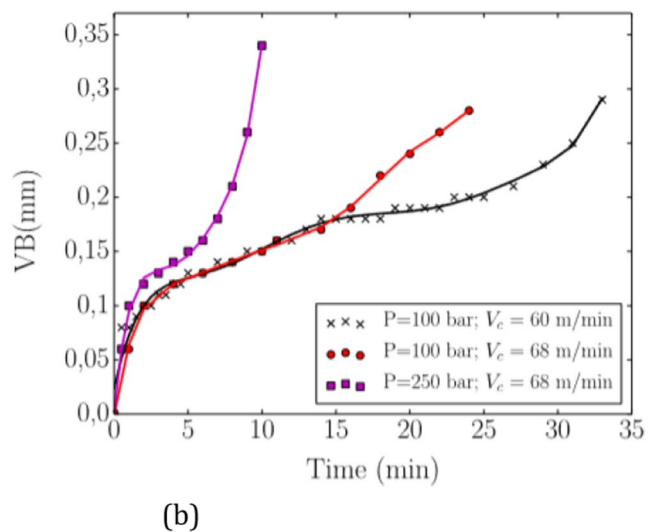
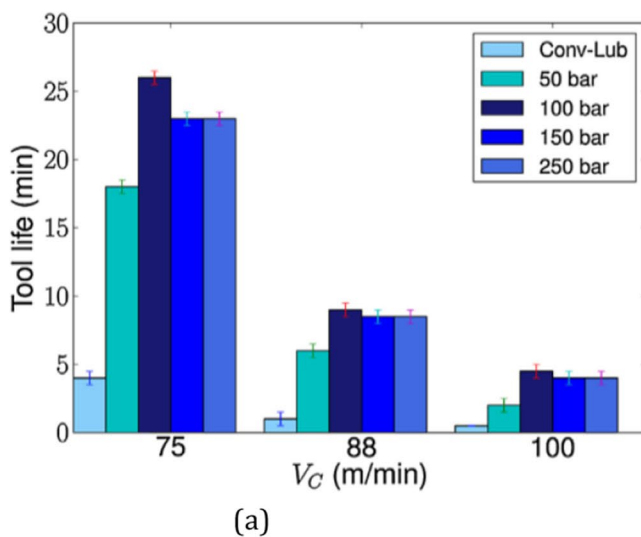


Fig. 11 Cutting speed and lubrication pressure effect on tool wear: a Ti17 titanium alloy ($ap=1$ mm, $f=0.1$ mm/tr) [49] and b Ti5553 titanium alloy ($ap=1.5$ mm, $f=0.1$ mm/rev) [43]

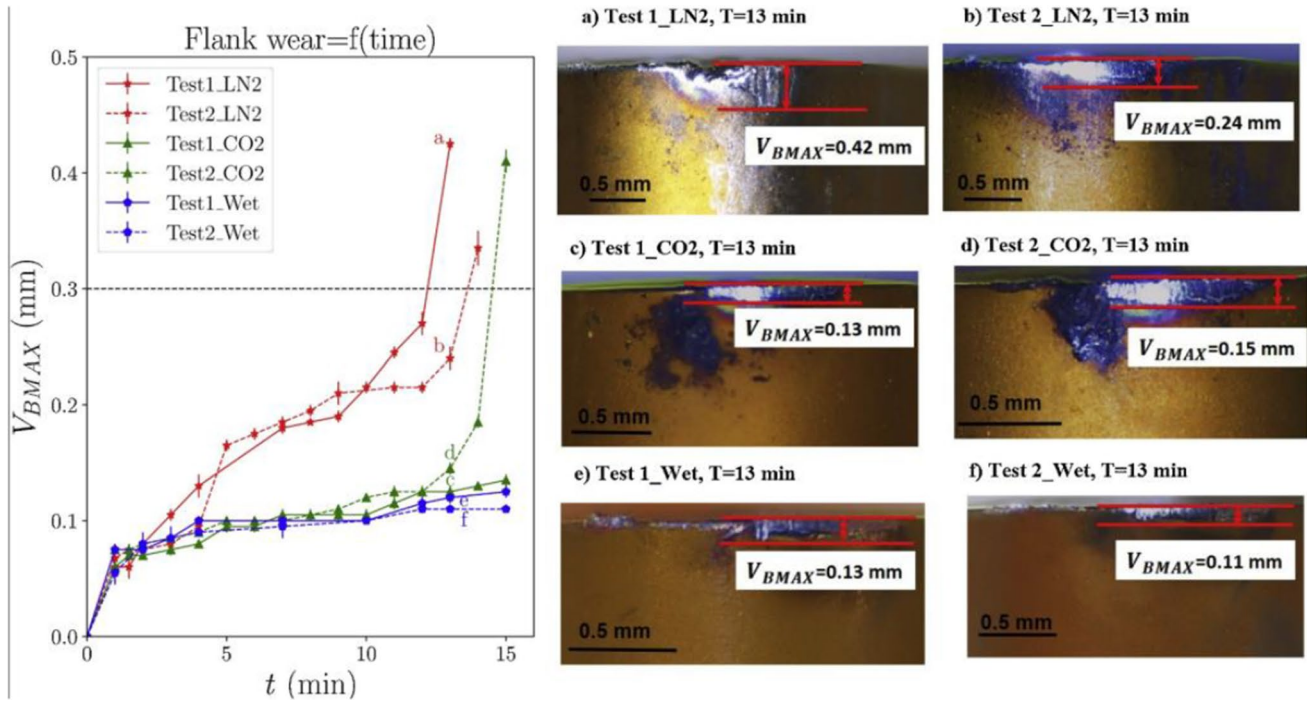


Fig. 12 Evolution of flank wear for machining Inconel 718 with and without cryogenic cooling [53]

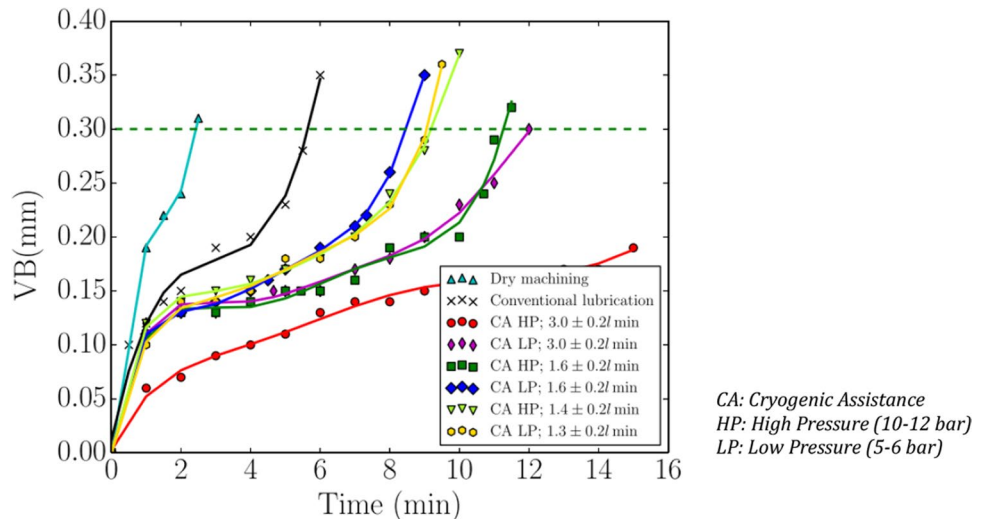
life. This assistance is therefore very advantageous for the machining of aeronautical parts.

While HPLA assistance ensures chip fragmentation and increased tool life under almost all tested conditions, the effect of cryogenic assistance on machinability is variable. Regarding chip fragmentation, it was reported only in drilling. As for tool wear, recent studies have shown that it is very dependent on the machined material and the cryogenic cutting fluid parameters. Indeed, on the one hand, a significant tool life increase could be achieved when machining titanium alloys and steels [50, 51]. On the other hand,

contradictory findings were reported when machining Inconel 718 [52]. As illustrated by Fig. 12, Chaabani et al. [53] reported a tool life decrease under LN2. Better tendency was obtained using LCO2. Nevertheless, there is no improvement compared to conventional machining.

The cryogenic fluid parameters such as the flow rate and the pressure, so far rarely studied, were described by Ayed et al. [50] as key factors impacting tool life. Figure 13 summarizes the main findings. The best results were obtained at the highest pressure and the highest flow rate. Nevertheless, an optimum combining reasonable LN2

Fig. 13 Evolution of flank wear for machining Ti6Al4V with and without cryogenic cooling and with different flow rates and pressures [50]



consumption and efficiency should be achieved. In this context, it can be noted, for example, that a tool life of about 12 min could be obtained either with the condition “LP; 3 L/min” or with the condition “HP; 1.6 L/min.”

3.2 Impact of HPA and CA on surface integrity

As previously mentioned, surface integrity was investigated by analyzing the machined surface topology, its roughness, and residual stresses levels.

3.2.1 Geometric criterion

Usually, surface roughness only depends on cutting parameters and on tool geometry. Therefore, there is not a specific trend (improvement/degradation) associated with the use of machining assistance. However, under some conditions, new phenomena may appear. Chip fragment welding/recycling was observed when machining Ti17 titanium alloy under high-pressure lubrication (above 150 bar) [49, 54] and when using cryogenic assistance for the machining of Inconel 718 [52, 53]. Figure 14 shows these defects. For the first case, very small chip fragments could be obtained under the action of very high lubrication pressure levels. They are projected at high speed onto the machined surface and may also be recycled by passing under the cutting edge. For the second case, it is not simple to give a valuable physical explanation. Hence, further investigations should be carried out.

3.2.2 Microstructural criterion

In contrast to surface roughness, machining assistances have a considerable impact on the areas affected by the thermomechanical loads generated during machining. The vicinity of the machined surface is then subjected to severe plastic deformation (SDP). The local change of the grain crystallographic orientations and the high temperature may lead to

microstructural changes. Figure 15 illustrates the effect of machining assistances on the highly deformed layer.

3.2.3 Thermomechanical criterion (residual stress)

Residual stresses are induced by the thermomechanical loads acting on the machined surface during the cutting operation. Thus, they are particularly sensitive to changes in the cutting temperature. In this case, cryogenic assistance makes it possible to reduce considerably the thermal loads and consequently to favor compressive residual stresses. Several studies highlighted the impressive increase in residual stress levels under cryogenic assistance [55–57].

The effect of cutting conditions, high-pressure lubrication assistance, and/or cryogenic assistance on residual stresses was investigated when machining the Ti-6Al-4 V titanium alloy and the Inconel 718 nickel-based alloy.

A similar trend, illustrated by Fig. 16, was also obtained when machining Inconel 718 under cryogenic lubrication conditions (LN2 and LCO2) [53]. Despite the lower resulting tool life (LN2/LCO2), in-depth induced residual stress levels are more compressive.

4 Study of HPA and CA assistance for Ti6Al4V machining

This review of the work carried out by the Manufacturing 21 research group is completed by additional tests for the machining of the Ti6Al4V titanium alloy.

The experimental means used are those presented in Fig. 3 for high-pressure assistance and Fig. 5 for cryogenic machining with liquid nitrogen. To do this, different means of testing and analysis were used. The tests were carried out by a straight-turning operation, with a depth of cut, a_p of 1 mm, a feed rate of 0.2 mm/rev, and a cutting speed of 80 m/min. The cutting force evolution was tracked by the means

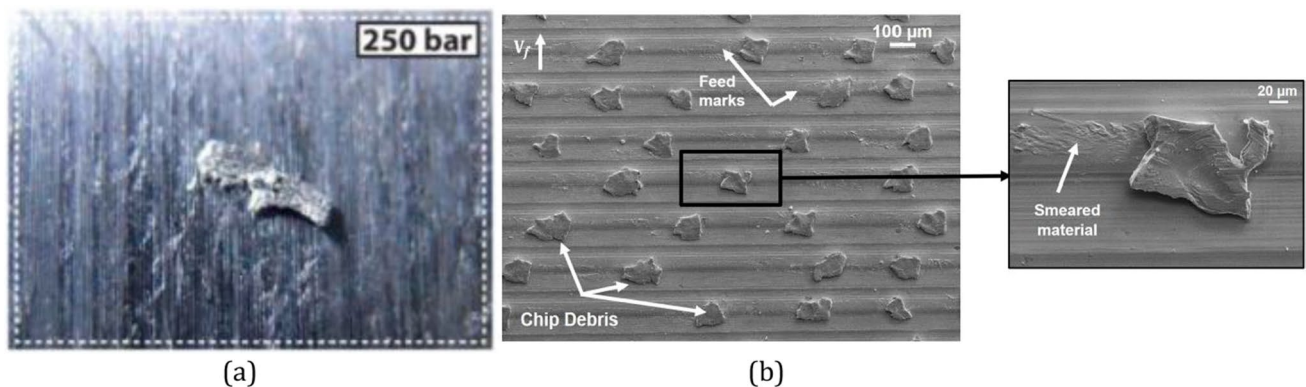


Fig. 14 Chip welding/recycling: **a** high-pressure lubrication assisted machining of Ti17 titanium alloy [49] and **b** cryogenic assisted machining of Inconel 718 (liquid nitrogen) [53]

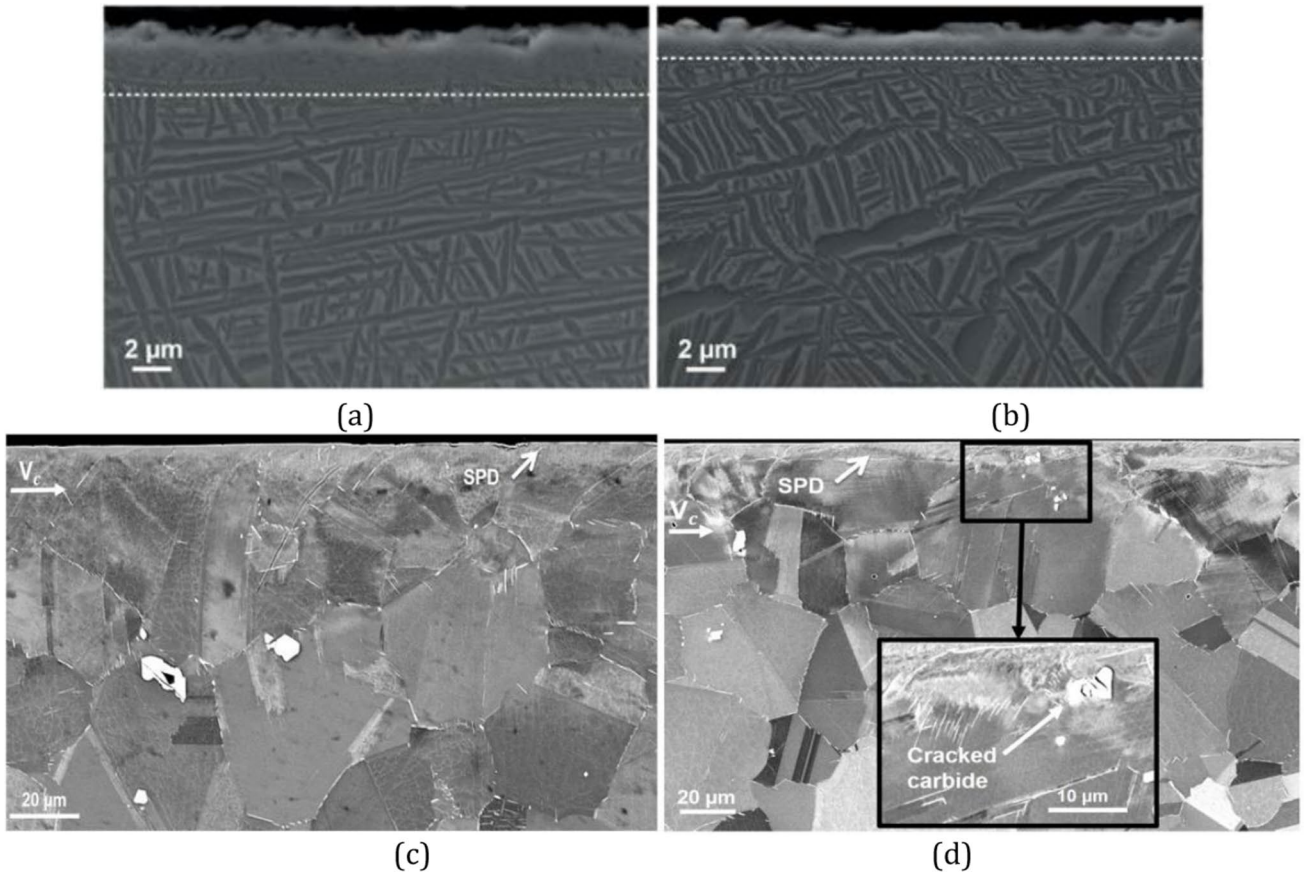


Fig. 15 Impact of machining conditions on surface deformation: **a** dry machining of the Ti17 titanium alloy, **b** high pressure-assisted machining of the Ti17 titanium alloy [54], **c** machining of Inconel 718 with conventional lubrication, and **(d)** LCO₂-assisted machining of Inconel 718 [53]

of a piezoelectric force sensor. The tool wear was controlled with a binocular microscope. As for the wear mechanisms, they were analyzed by means of the SEM and an EDS detector. Finally, the residual stresses were analyzed by X-ray diffraction.

4.1 Machinability of TiAl4V in HPA

The HPA tests were performed with a pressure of 100 bar with a tool holder (Seco tool Jetstream) and a CNMG 120408 MS MP9015 insert from Mitsubishi®. This tool has

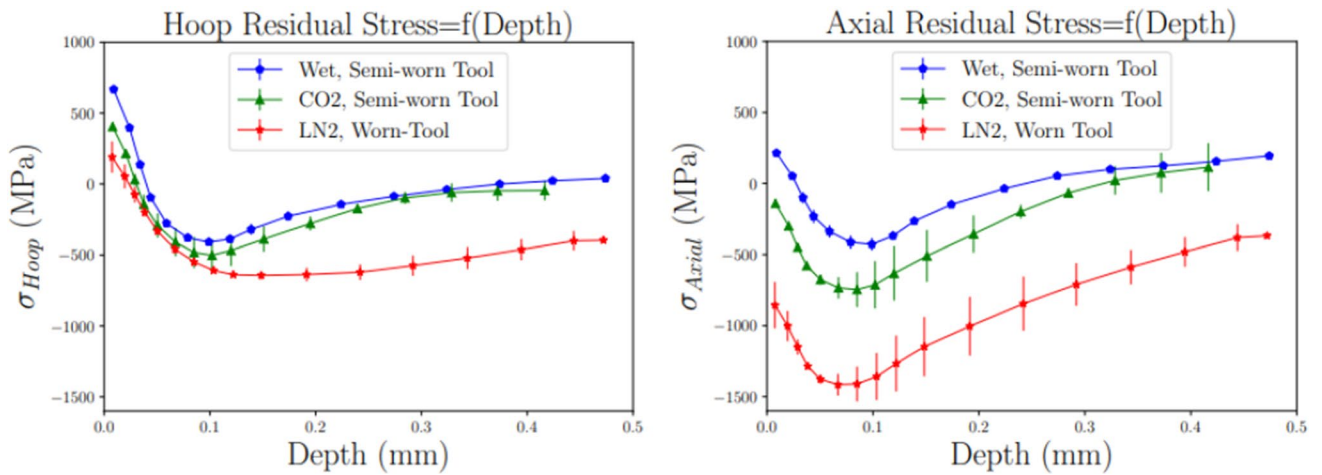


Fig. 16 Evolution of residual stresses for different cooling configurations and different cutting parameters [53]

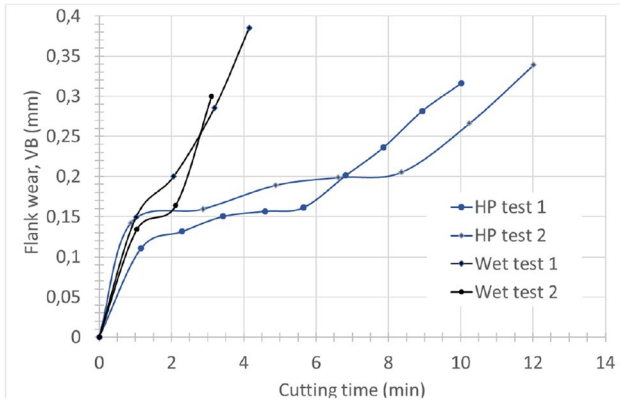


Fig. 17 Evolution of flank wear as a function of time for tests with and without HPA

two 1.2-mm-diameter nozzles that focus the lubricant jet on the cutting edge (Fig. 3).

As shown in Fig. 17 and in line with the other studies, the machinability of the Ti-6Al-4 V titanium alloy has been remarkably improved under high-pressure lubrication-assisted machining. For a tool wear criterion $VB = 0.3$ mm, tool life was tripled, from about 3 min in machining with conventional lubrication (emulsion) to nearly 10 min with HPA. This is mainly due to the reduction of the cutting temperature, which results in the deceleration of high temperature activated wear mechanism.

Regarding the chips, in conventional machining, they are long with a spiral shape. However, under the action of the lubricant jet, they are fragmented and C-shaped as shown in Fig. 18. The chips obtained in HPA have been fragmented with a length of a few millimeters which facilitates their evacuation.

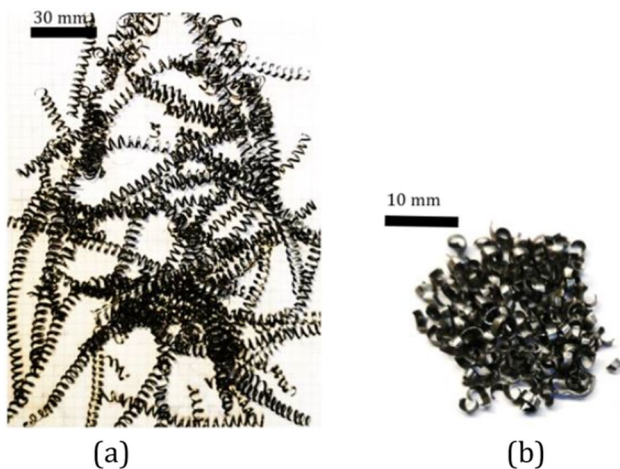


Fig. 18 Chips obtained a with conventional lubrication and b with high-pressure assistance (100 bar)

4.2 Machinability of TiAl4V in CA LN2

The trials in CA were carried out with the same commercial tool holder (Seco tool Jetstream) but with different cutting inserts. Two grades of CNMG 120,408 cutting inserts, MP2015 from Mitsubishi and H13A from Sandvik, were used. The liquid nitrogen is delivered through the two nozzles of the tool onto the cutting area, and the supply pressure is 10 bar.

Figure 19 shows the main findings. Regardless of the obtained results for the MP9015 inserts, cryogenic assistance does not appear to improve tool life in these cutting conditions. It is noticed that the gain in terms of tool life due to cryogenic cooling with the MP9015 grade insert is only 3 to 4.5 min. In fact, to be effective, specific or optimized conditions should be obtained. As the main role of the cryogenic jet is to cool the cutting zone, its temperature should be higher enough to see a difference compared to conventional machining. However, at very high cutting temperatures, the assistance efficacy may drop. Thus, the operating window of the cryogenic assistance is restricted to a certain range of cutting conditions. As the cutting speed increases, tool life decreases, regardless of the cooling fluid used. In addition, more differences could be observed in tool wear evolution. For the gain to be significant, the cutting insert must be in a certain range, which does not seem to be the case for the MP9015 insert.

In contrast, a very significant difference is visible between the two inserts whether in machining with conventional lubrication or in cryogenic machining. The H13A grade insert has approximately 5 times longer tool life for the same cutting parameters. Indeed, the lifetime increases from 3 min in conventional machining to nearly 20 min in cryogenic machining. On the other hand, the good tool life of the H13A insert led to stopping the tests before reaching the lifetime

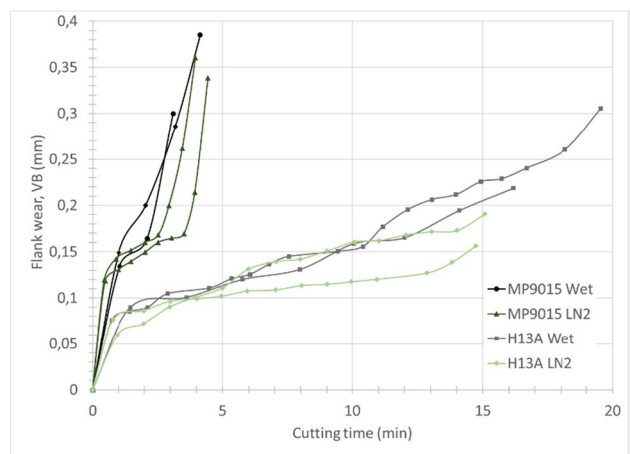


Fig. 19 Effect of cryogenic machining on tool wear evolution for both inserts grades

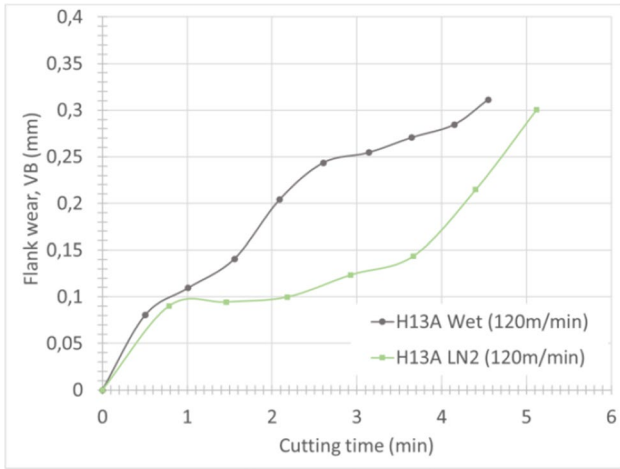


Fig. 20 Evolution of flank wear for machining Ti6Al4V with and without CA (grade H13A and $V_c = 120$ m/min)

criterion, but after 15 min of machining. Wear remains much lower with cryogenic assistance.

Two additional tests, one in conventional lubrication and the other with cryogenic cooling, were carried out with grade H13A by increasing the cutting speed to 120 m/min. Figure 20 shows the wear evolution for these two tests. It appears that the tool life decreases strongly at this cutting speed, with a lifetime of about 4 min for the two conditions. For machining in conventional lubrication (wet), the evolution of wear is important and regular. On the other hand,

with cryogenic cooling, the wear curve shows a plateau at a $VB = 0.1$ mm which shows that this assistance limits the evolution of wear. But after about 3 min, the cooling of the cutting zone does not seem to be efficient enough, which strongly accelerates the wear of the tool. It can be seen that this evolution of wear, with a cutting speed of 120 m/min, is close to that obtained with the grade MP9015 at a cutting speed of 80 m/min, which indicates greater productivity with the grade H13A.

For the machining of titanium alloys, the results show that tool life is systematically increased with cryogenic assistance, but the gain strongly depends on the cutting condition.

4.3 Residual stresses after machining of Ti 6Al4V in HPA and CA

In view of the first results, the following cutting parameters were used: CNMG 120408 H13A grade insert, $V_c = [80, 120]$ m/min, $f = [0.1, 0.2]$ mm/rev, and $a_p = [0.5, 1]$ mm. For each cutting condition, machining tests were carried out with conventional lubrication (emulsion), high-pressure lubrication (100 bar), and LN2 cryogenic cooling. The tool holder (Jetstream) is the same for all tests.

Figure 21 presents the obtained results. A significantly positive effect of the machining assistances on surface residual stresses (axial and hoop directions) can be highlighted. In almost all cases, the residual stresses in the axial and circumferential directions are lower in cryogenic assistance, except for the configuration ($V_c = 120$; $f = 0.1$; $a_p = 1$) where

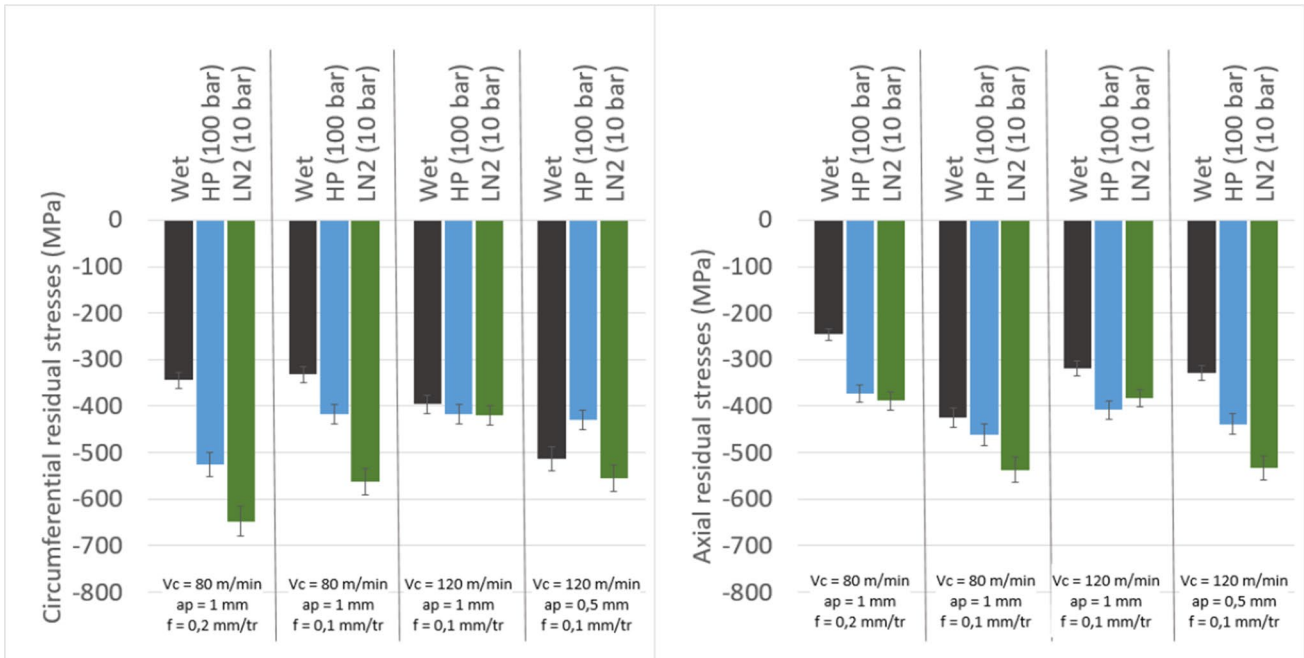


Fig. 21 Residual surface stresses for different cooling configurations and different cutting parameters

they are equal to those for high-pressure assistance. The residual stresses for high-pressure assistance also give better results in most cases compared to conventional lubrication.

It is not easy to draw conclusions about the influence of each parameter on the residual stresses in the circumferential direction, but for the residual stresses in the axial direction, for each lubrication condition, an increase in feed rate or cutting speed leads to an increase in axial residual stresses. The influence of the depth of cut is less pronounced for standard lubrication or lubrication or high-pressure assistance, but with cryogenic assistance, the reduction of the depth of cut leads to a significant reduction of the residual stresses.

These two assistances decrease the cutting temperature (thermal load), even more strongly for the cryogenic assistance, without strongly modifying the cutting force (mechanical load). The residual stresses are functions of the thermo-mechanical loads on the surface of the part. By reducing the thermal load, for a similar mechanical load, the residual stresses will be more in compression, which explains the results obtained. It was shown in Chapter 4.1 (Fig. 20) that for a high cutting speed (120 m/min), the cryogenic assistance was less effective. This is even more true if the depth of cut and the feed rate is large, which explains why the gain is low for the operating point ($V_c = 120, f = 0.1, ap = 1$).

5 Conclusion

It is known that refractory aeronautical alloys such as titanium alloys and nickel alloys have poor machinability. Numerous research projects have made it possible to improve their machinability, in particular, by optimizing the tools used and the cutting parameters and/or mechanical and thermal loads in the chip formation area by machining assistance, which makes it possible to significantly improve the productivity of the machined components. But the different assistances are not equivalent and depend on the type of operation. Indeed, the work done by the French research group, Manufacturing 21, has shown that laser assistance is not interesting for these materials, and that vibratory assistance gives good results only for drilling operation. For turning operations on titanium alloys, high pressure and cryogenic assistance give the best results.

For Nickel alloys, high-pressure assistance improves tool life (up to two times) and improves the surface finish. On the other hand, cryogenic assistance is rather negative for this alloy, because the tool life decreases, and the surface finish can be degraded as well, but the residual stresses on the surface of the workpiece are more in compression.

For titanium alloys, the results of the studies carried out, and the tests presented in this article have shown that the high pressure and cryogenic assistances (i) do not have a significant

effect on cutting force and surface roughness, (ii) can significantly increase tool life (up to five times) (This increase is similar for the two studied assistances (with fixed cutting conditions)), and (iii) improve residual stresses with higher compression values, especially with cryogenic cooling.

In addition, the high-pressure assistance allows efficient chip breaking, unlike the cryogenic assistance. But cryogenic assistance avoids the use of cutting oil, resulting in unpolluted surfaces, giving it the benefits of dry machining without the drawbacks such as the use of an oil filter or oil mist extractors and washing the chip.

The different machining assistances are therefore complementary to each other, as they do not have the same benefits depending on the material being machined and depending on the type of operation used. It is, therefore, important to properly understand these machining assistances to make the best choice from an industrial point of view.

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Declarations

Competing interest The authors declare no competing interests.

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