



A Cleaner Milling Process Replacing Emulsion Coolant by Cryogenics CO₂

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Abstract

In manufacturing sector, looking for a balance between environmental and technical efficiency taking into account productivity is mandatory. Some sectors, such as the biomedical manufacturing sector, also needs to consider the cleanness inherent to prosthesis manufacturing processes for avoiding pathogens transfer to the human body, that is, neither chemicals, bacteria, nor uncontrolled metals can be introduced during the surgical intervention. This work here presented stems from the idea of analyzing the cleanness of cryogenic cooling to be applied to medical pieces. For this, several samples were machined using CO₂ cryogenic technology and oil emulsions, respectively. In particular, a modified milling tool was used to apply not only efficiently as cutting fluid but also as cleaner fluid. Afterwards, they were analyzed by Scanning Electron Microscope (SEM) with the aim of looking for biological remains. Finally, with the aim of validating the modified tool in which CO₂ is introduced axially as internal coolant, its tool life was tested in comparison with a conventional one. The results shown that the use of CO₂ as internal coolant significantly improves the cleanness of current machining processes in comparison with the use of oil emulsions and the way in which is injected does not affect to machining performance.

Keywords Cryogenic machining · Ti6Al4V Grade 23 machining · Cryogenic cleanliness · CO₂ coolant

1 Introduction

In manufacturing sector, looking for a balance between environmental and technical efficiency considering productivity is mandatory with the aim of not losing market share [1]. However, biomedical manufacturing sector also must take into account another factor which is the key to obtain successful processes. This factor is the total cleanness inherent to prosthesis manufacturing processes for avoiding pathogens transfer to the human body, that is, neither chemicals,

bacteria, nor uncontrolled metals can be introduced during the surgical intervention.

For dealing with these issues, despite currently prosthesis are manufactured by machining processes, additive manufacturing is presented as the solution for a clean, environmental, and customized prosthesis of the future [2]. However, these statements have not considered economic issues or defects in the material integrity such as internal porosity in big prosthesis [3]. Besides, machining finishing operations are needed to finish them. Then, the improvements which this technology presents are not enough at the moment for replacing/suppressing machining processes in knee or hip prosthesis where the size is relatively large.

Nevertheless, current machining processes implies the use of cutting fluids which are mainly oil emulsions which are the main focus of dirty. Then, finished prosthesis have to be deeply cleaned. These clean processes consist of wrapping the prosthesis with several plastic protective layers and sterilized the boxed prosthesis by special radiation techniques [4]. However, despite this clean and sterilization processes, it should be noted that 170,000 knee prosthesis are implemented annually and 25% of patients will suffer

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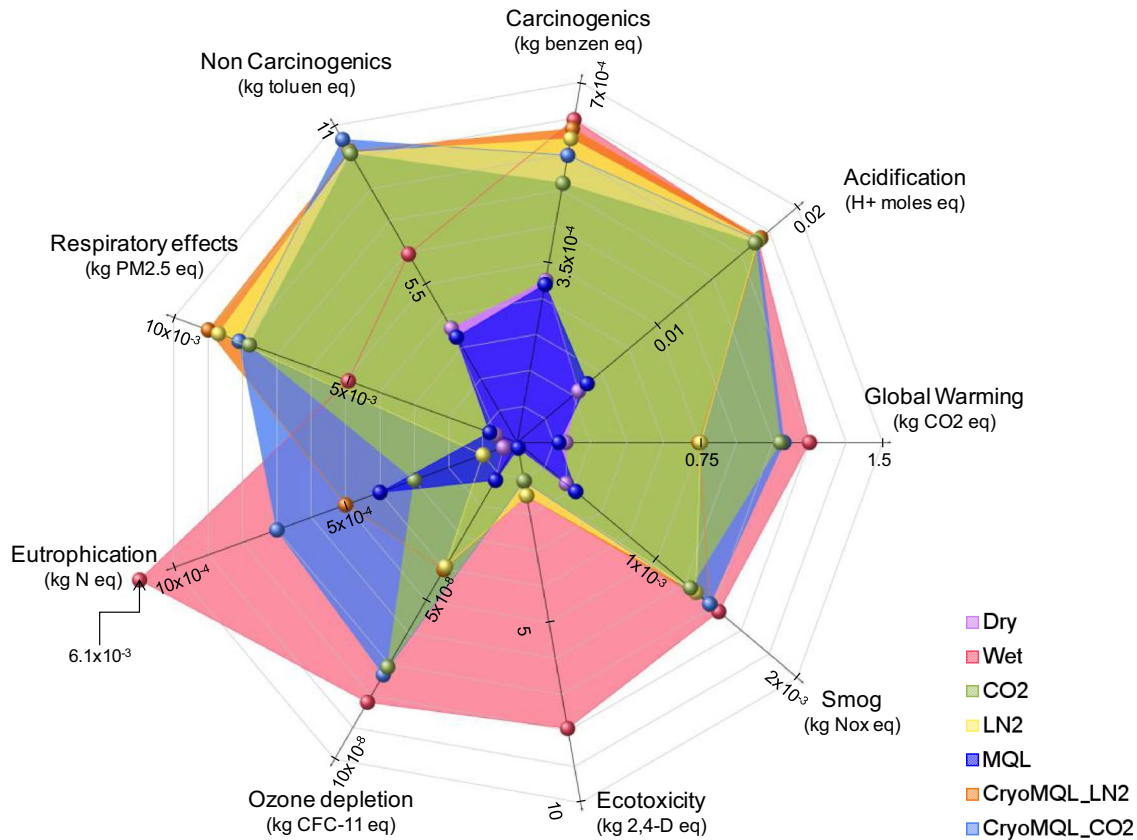


Fig. 1 Life Cycle Assessment (LCA) obtained in previous research [13]

revision surgeries within 20 years only in Germany, being the main reasons infections or wear [5]. In the short term, in France is calculated that 18% of the patients which present infection after the surgery, antibiotic treatments do not take effect and then, part of them need a second intervention to carry out a joint lavage [6] or in the case of Spain where the infection cases are two times higher than the National Healthcare Safety Network [7]. Then, suppressing cutting fluids of machining processes in order to help improving the efficiency of the current clean and sterilization processes—and therefore reducing the possible infections—is a goal to achieve by manufacturers.

On the other hand, human prosthesis needs to be manufactured with biocompatible alloys with the aim of not generated rejections after surgeries. These alloys are mainly stainless steels, cobalt-chromium alloys or titanium alloys [8, 9], that is, alloys considered difficult to cut materials [10]. Among these alloys, grade 23 titanium alloy, known as Ti-6Al-V grade ELI, presents low ion formation levels in aqueous environments and high capability of osseointegration which satisfies the high mechanical requisites in critical prosthesis such as knee ones [11]. However, this alloy presents more difficulties to be machined due to its low thermal

conductivity combined with its high reactivity [12]. Then, in these extreme cases cutting fluids are necessary to maintain both prosthesis surface integrity and tool life.

Therefore, in order to reach a balance between suppressing cutting oils and maintaining productivity, CO₂ cryogenic machining is presented as a suitable alternative. This technology is based on injecting recycled liquid CO₂ in the chip-tool interface instead of conventional cutting fluids based on oils. This technology was studied widely from an environmental point of view by the authors quantifying the environmental improvement achieved by this technology in comparison with other technologies. [13]. The results, summed in Fig. 1, showed that CO₂ cryogenic technology was the cooling technique without oils that the fewest environmental impact presents.

Regarding technological point of view, the suitability of CO₂ cryogenic cooling on titanium alloys is based on the accurate temperature control achieved which reduces the thermal effect on the tool wear, reducing the adhesion and diffusion process of the material on the tool [14]. It should be noted that, this effect is the predominant cause of tool life reduction [15]. In this line, in [16] the temperature effects on tool wear were studied, concluding that a lower temperature

does not imply a longer tool life. In this work, different LN₂ temperatures were used, obtaining the best results with LN₂ temperatures between $-75\text{ }^{\circ}\text{C}$ and $-100\text{ }^{\circ}\text{C}$. This rank of temperatures is in accordance with the temperature achieved by CO₂ during its expansion on the cutting zone ($-78\text{ }^{\circ}\text{C}$) whose heat removal potential in supercritical state achieves 60 W/m^2 [17, 18]. In fact, using CO₂ cryogenic cooling on turning processes, flank wear is reduced 2 times in comparison with conventional oil emulsions [19] and in milling processes compared to milling processes can reduce tool wear a 67.2% [20]. Besides, the use of CO₂ implies an increase of chip breakability with enhances tool life when Ti6Al4V is machined [21, 22]. On the other hand, the use of cryogenics reduces not only surface roughness but also microstructural alterations [23]. In addition, the use of the cryogenic cooling in Ti6Al4V implies higher values for micro-hardness in comparison with oil emulsions what implies better adhesion for surface coatings in case of being needed [24, 25] and also due to its higher cooling capacity, the reaction tendency between Ti6Al4V and the tool substrate is limited and reducing therefore, chip adhesion on the tool cutting edge [26]. In the particular case of Ti6Al4V milling, which is the main operation carried out in big prosthesis such as knee or hip prosthesis, the use of CO₂ cryogenic cooling during the machining can imply an increase of conventional cutting speed until achieving 90 m/min without affecting carbide tools microstructure [27]. In case of using PCD tools, this value can be even increased until 360 m/min [28].

Concerning the use of modified channels on milling tools to enhance the flow of cutting fluid, significant progress was carried out in recent years thanks to additive manufacturing. In Lakner et al. [29], for example, analyzed several channel designs with the aim of improving the cutting fluid injection. In particular, a new tool holder for indexable inserts was manufactured by LPBF technology in which the internal channels were reduced to 1.5 mm in diameter and added other L-shaped channels to properly lubricate the insert's release face. This new toolholder was compared with a conventional one that was equipped with 2.5 mm diameter channels. The results showed that using a tool holder made by LPBF with improved channels directly affects tool life, increasing it by 67% [29]. Other work related with it was presented in 2021 in which was analyzed the influence of the shape of internal channels in an indexable milling tool. Specifically, straight channels were simulated, as if they were obtained through conventional drilling, and curved and helical channels, as if they were obtained through LPBF technology. The results showed that using sharp-edged channels with a radius, the volumetric flow rate of the cutting fluid increased by approximately 23% [30]. Nevertheless, despite these improvements are interesting, they were focused on improving oil emulsions injection and not cryogenic fluids where flow rate savings is mandatory. Besides, the tools are

indexable tool holders and not entire carbide tools for finishing operations. Taken these issues into account, the authors carried out a previous research in which a carbide tool was transformed into a heat exchanger thanks to a modified channels carried out by EDM. Those channels were designed so that the primary function of CO₂ is to absorb the heat generated during the cutting process instead of simply being injected in the cutting zone [31]. However, although the improvement developed for using CO₂ as cutting fluid, its effectiveness from a cleanliness standpoint was not taken into account.

Therefore, despite the fact is considered a totally clean technology in the literature, there is a lack of rigorous research to quantify and demonstrate its real improvement. Therefore, this work focuses on analyzing the cleanliness of cryogenic cooling for medical components with the aim of demonstrate its suitability. For this, samples were machined using CO₂ cryogenic technology and oil emulsions. A modified milling tool was used as an efficient cutting and cleaning fluid. Scanning Electron Microscope (SEM) analysis was conducted to detect biological residues. Additionally, the modified tool, with axial CO₂ introduction as internal coolant, was tested for tool life compared to a conventional tool. Results showed that using CO₂ as internal coolant significantly improved cleanliness in machining processes compared to oil emulsions, with no impact on machining performance.

2 Experimental Setup

Tests were carried out in a Kondia HS1000 5-axis machining center and Kondia A6 machining center, respectively. In particular, two kinds of tests were done: one for analyzing the cleanness of the cryogenic technology and other with the aim of validating the use of the modified milling tool from a technical point of view.

In particular, the modification of the milling tools consisted in using carbide tools that were provided with an internal channel coaxial to the rotary axis was carried out by electro discharge machining (EDM) to introduce the CO₂ throw it axially. This design is based on two previous works carried out by the authors [31, 32]. However, this new internal channel design has two aims: The conventional one that is achieving a CO₂ expansion before it is injected outside the channel and therefore, becoming the tool in a heat exchanger maintaining constant the tool temperature during the cutting process. The new one, using the CO₂ pressurized flow as cleaning agent due to is injected to the workpiece surface from the tool tip. In Fig. 2 is shown a digital tomography with the modification carried out by EDM to the conventional milling tool.

Fig. 2 Digital tomography of the tool modified with an internal channel

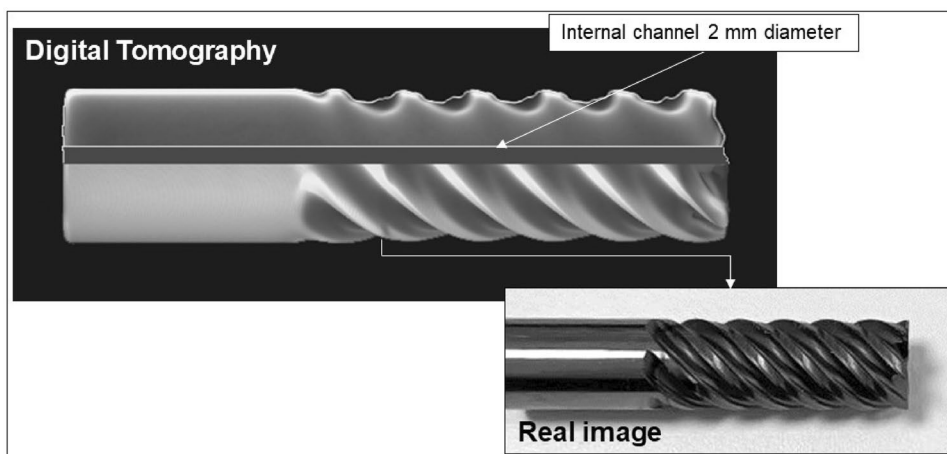


Table 1 Ti6Al4V Grade 23 mechanical properties and chemical composition

Chemical composition							
Ti	V	Al	O	Fe	C	N	H
Bal	4.2%	6.1%	0.1%	0.12%	0.03%	0.01%	0.008%
Mechanical properties							
Yield strength		Ultimate tensile strength		Elasticity modulus		Hardness	
930 MPa		970 MPa		116 GPa		32 HRc	

Regarding the material used during the tests, Ti6Al4V Grade 23 was selected. This alloy is characterized in comparison with Ti6Al4V Grade 5 used in aeronautics in which presents higher tensile and yield strengths and chemically presents lower content of oxygen. Its chemical composition and mechanical properties are shown in Table 1.

In the case of the tests for analyzing the cryogenic cleanliness, two samples were milled with CO₂ cryogenic technology and other two with oil emulsions in the Kondia HS1000 5-axis machining center. It should be noted that the samples before being used for the milling tests, they were encapsulated to facilitate their analysis under the SEM. The milling test carried out over them consisted in carrying out 3 passes with each technology. After each test, the sample milled were taken with latex gloves and introduced in a sterilized box without touching the surface machined. The size of each sample was of 13 × 13 mm. The tool used for carrying out of this test was a carbide mill of 10 mm of diameter coated with AlTiN. Cutting conditions used were 150 m/min of cutting speed, 0.07 mm/z of feed per tooth and an axial depth of 0.5 mm. In the case of using CO₂ as cutting fluid, it was injected with a pressure of 15 bars. However, in the case of using oil emulsions, it was injected with 10 bars. This difference is due to the industrial conditions used commonly. Once the samples were obtained, they were analyzed by a SEM Hitachi S-4800 with several magnification values with

the aim of looking for biological remains and verifying the cleanliness difference between using CO₂ as cutting fluid and oil emulsions. In Fig. 3 is shown the experimental setup carried out to obtain the samples.

On the other hand, the tests in which the modified milling tool was verified from a technical point of view were carried out in the Kondia A6 machining center. In this case, the modified milling tool, which injects CO₂ through its internal channel, was compared with a conventional one with external CO₂ during milling tests in which tool wear, cutting forces and cutting temperature were registered. In particular, the tests consisted of straight milling paths of 150 mm of length with carbide mills of 10 mm of diameter coated with AlTiN with initial cutting conditions of 150 m/min of cutting speed, 0.07 mm/z of feed per teeth, 7 mm of axial depth and 0.5 mm of radial one. The cutting conditions chosen are based on conventional industrial conditions. Also cutting forces were recorded using a triaxial Kistler 9255 piezoelectric dynamometer and an OROS® OR35 real-time multi-analyzer with a sample frequency of 16,384 samples/s. Each test was carried out two times obtaining the average value for the cutting forces values. Tool wear was progressively measured by pausing the passes at different stages with a Nikon SMZ-2 T microscope. Finally, a thermographic camera OPRIS® PI device working in the 7.5–13 μm range was used in the first pass of each tool with

Fig. 3 Experimental setup to obtain the samples for analyzing cryogenic cleanliness

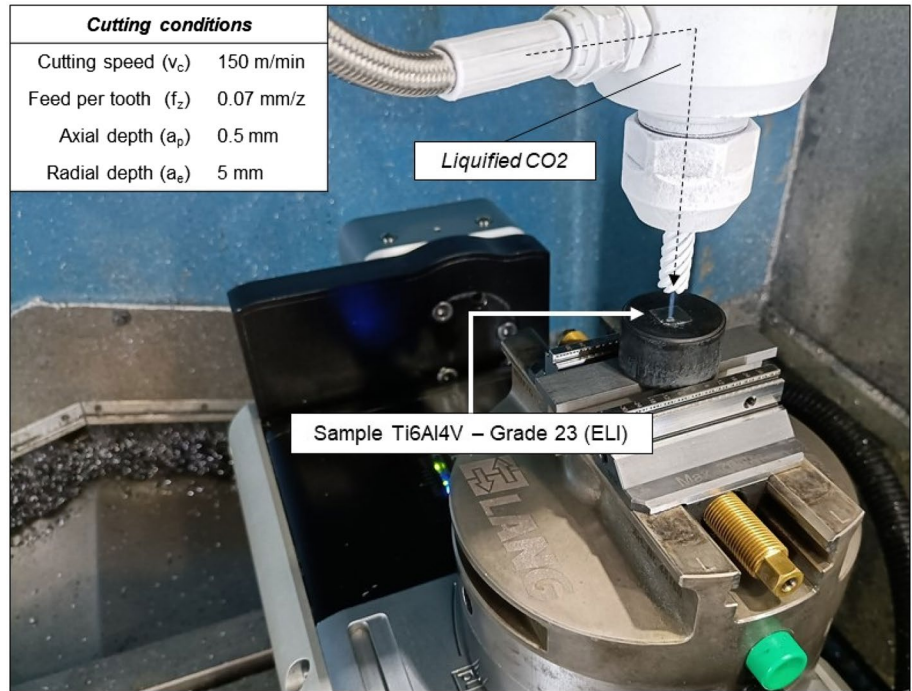
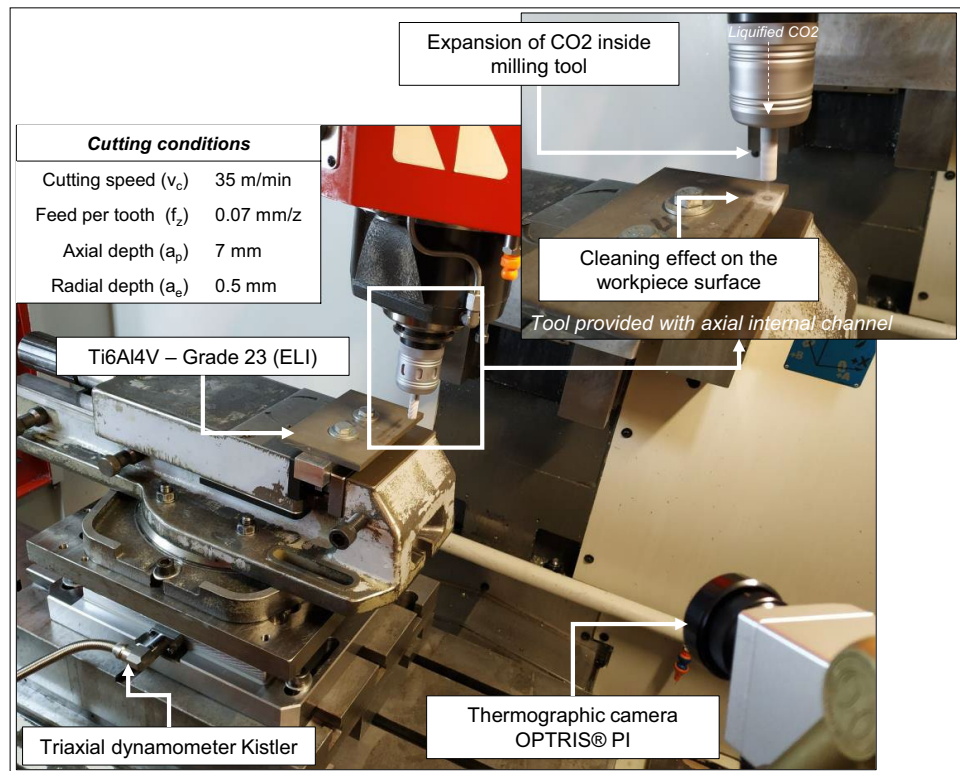


Fig. 4 Experimental setup for carrying out milling tests



the aim analyzing the influence of CO2 in the tool temperature in case of using it internally and externally. The stop test criterion was based on the ISO3685 or the achievement of 10.000 mm of machined length, whichever occurs first. In Fig. 4 is shown the experimental setup carried out:

3 Results and Discussion

The results obtained of the samples analyzed by SEM are shown in Fig. 5. In the left side, a representative zoom

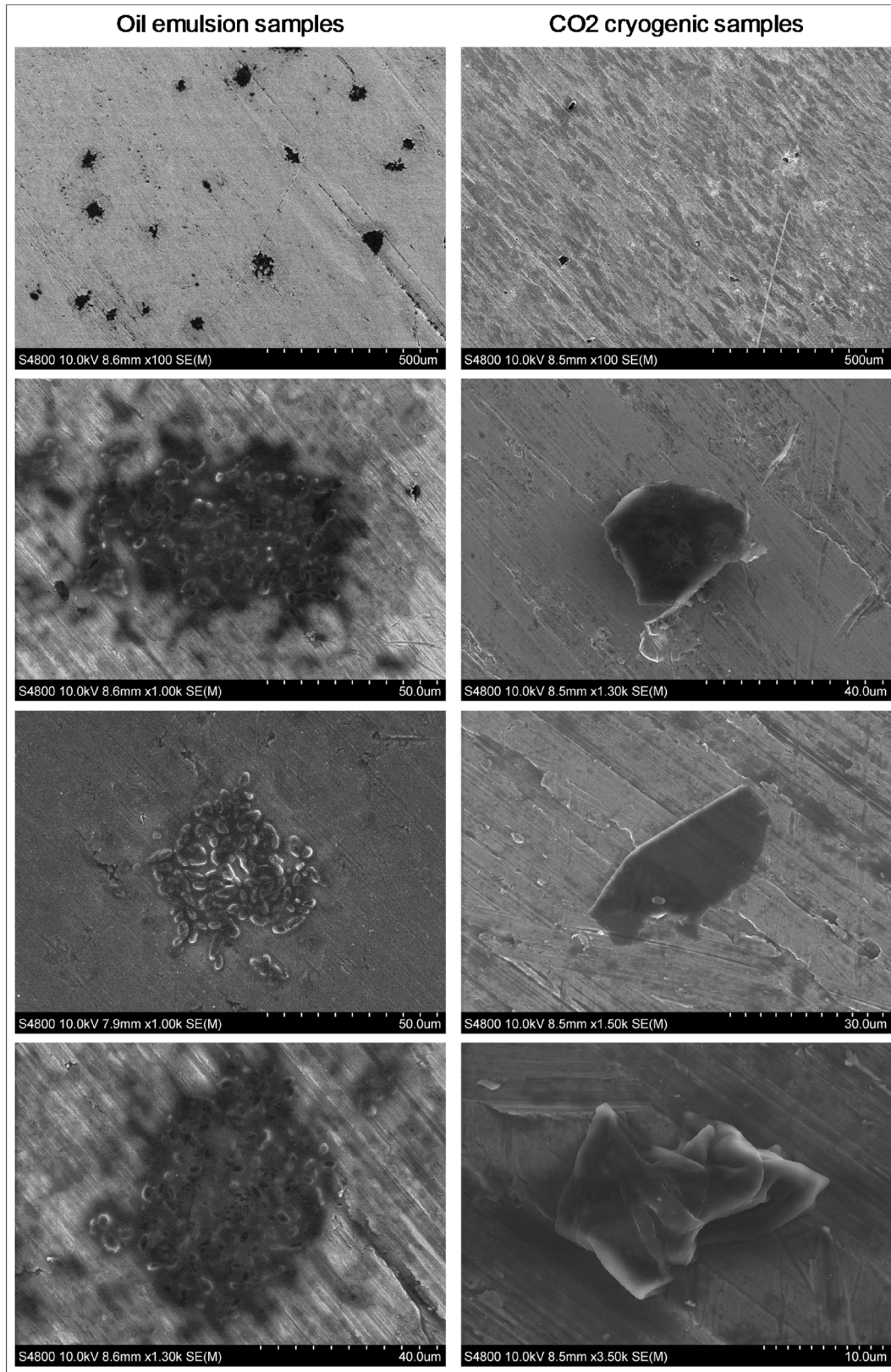


Fig. 5 SEM results obtained from machining using CO2 and oil emulsions

sequence obtained by milling with oil emulsions is presented and in the right one a zoom representative sequence obtained by using CO₂. In these zoom sequences, the first difference between both technologies is the quantity and size of dirty spots. In the case of oil emulsions, in 1.13 mm² the amount over 50 μm (μm) presented is 17 spots in comparison with CO₂ in which spots over this value is not achieved. In fact, only 7 spots presented values over 20 μm, that is, there is a decrease of number of dirty spots of 60% and with a reduction of size of 58.82%. Subsequently, in the case of oil emulsions when the zoom is increased from 10 times until 13 times, within all spots appear biological remains. This phenomenon occurs because when liquefied CO₂ is injected through the axial channel, it expands upon exiting, forming gaseous and solid particles that strike the workpiece. During this impact process, the solid particles dislodge dirt from the workpiece, while the gaseous particles blow most of the dirt away from the workpiece. Then, despite the use of cryogenic techniques does not implies a total clean process, this supposes a real improvement due to not only dirty spots are reduced in number and size but also any biological remain is suppressed from within the spots. Therefore, the application of this technology during machining processes results in cleaner prosthesis than once they are processed by cleaning treatments will end up to less surgery rejection rates.

Regarding, tool wear results obtained from the milling tests are shown in Fig. 6. The evolution of tool wear using external CO₂ as cutting fluid or internal to the tool through the axial channel obtained was similar. In particular, the difference between both technologies is below 5%, not appreciating coating degradation in both cases. In fact, this similar behavior of both techniques can be observed in the SEM images where in the edges not only appears similar tool wear due to mechanical effects but also the characteristic adhesion of machining Ti6Al4V present is analog.

Similar behavior was obtained in the results related with cutting forces, which are shown in Fig. 7. In this case, average and maximum forces were obtained. The evolution of them was constant, presenting differences of ≈2% in the case of maximum cutting forces and 2.4% in the average ones, what is negligible.

Finally, cutting temperature was captured which is shown in Fig. 8. In this case is shown the effect of using CO₂ as external coolant or internal one. With the first technique CO₂ not only cools the tool surface but also the workpiece one. Using the internal performance, the tool is become a heat exchanger in which the tool and the workpiece is maintained at the same temperature. In both cases, the cutting temperature is similar but with the advantage which the new tool performance avoids thermal fatigue from the tool and

allows an efficient application of the CO₂ with independence of the machining direction.

Then, from a technical point of view, the new way of injecting CO₂ through internal tool axial channel proposed is analog to CO₂ conventional use what implies that the milling process is not compromised but the cutting fluid injection performance is improved, achieving a way of injecting it with independence of cutting direction and at the same time the CO₂ can be used simultaneously as cleaning agent when the tool tip mills over workpiece surface.

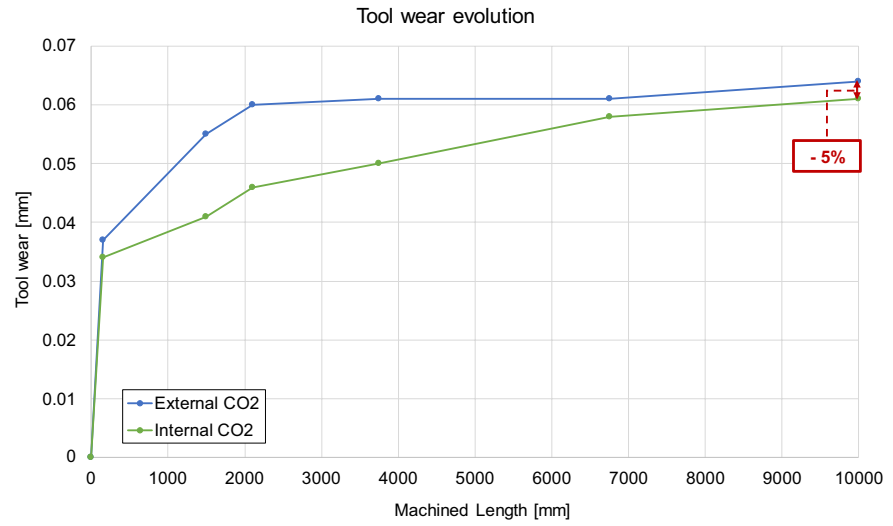
4 Conclusions

In this paper, an analysis of the cryogenic CO₂ cleanliness efficiency used as cutting fluid during milling process was carried out. Also, a new way of injecting CO₂ in which the liquified gas is introduced axially as internal coolant in a modified carbide milling tool with the aim of improving the milling performance was tested. In particular, Ti6Al4V samples machined with oil emulsion and liquified CO₂ were analyzed by SEM with the aim of quantifying the cleaner effect of cryogenics technique and on the other hand, regarding using CO₂ as internal coolant through the tool was carried out milling tests with the aim of verifying that this way of injection does not affect to milling performance in comparison with conventional CO₂ injection. The main conclusion obtained are listed below:

- The use of CO₂ as cutting fluid implies an improvement of machining process cleanliness in comparison with oil emulsions use. In particular, in the case of cryogenics cooling, there are fewer dirt particles with a smaller particle size, reducing 60% the spot number and 58.82% its size.
- Regarding the nature of the dirt, in case of oil emulsions biological remains appear on the sample surface. On the other hand, when CO₂ is applied as cutting fluid, the remain material has an inert origin what implies an improvement in cleanliness issues.
- From a technical point of view, injecting CO₂ as internal coolant through an axial channel does not affect significantly to milling performance. Similar results were obtained in comparison with CO₂ external injection, obtaining a slight improvement when CO₂ as inject as internal coolant.

Therefore, despite the use of cryogenic CO₂ cooling does not achieve a complete clean process, in comparison with oil emulsions the process is improved significantly what subsequently improves the sterilization process of

Fig. 6 Tool wear obtained in the experimental tests



Tool wear at final stages: Microscope & SEM images

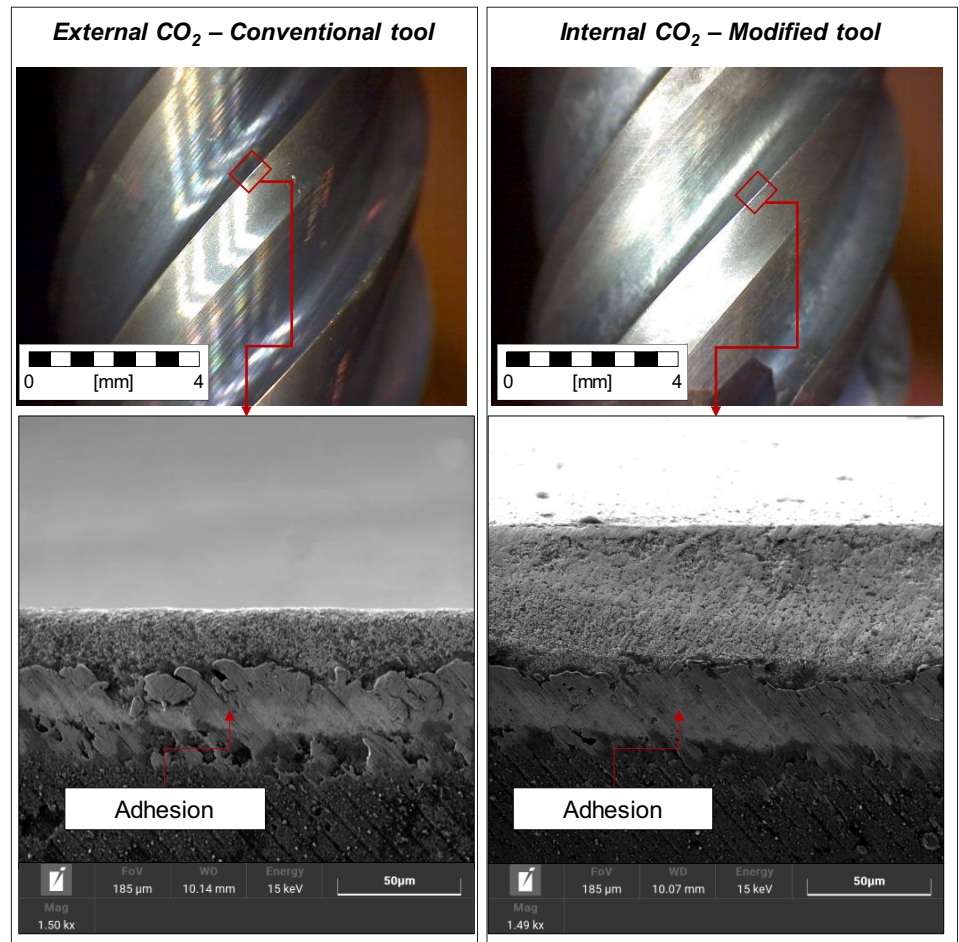
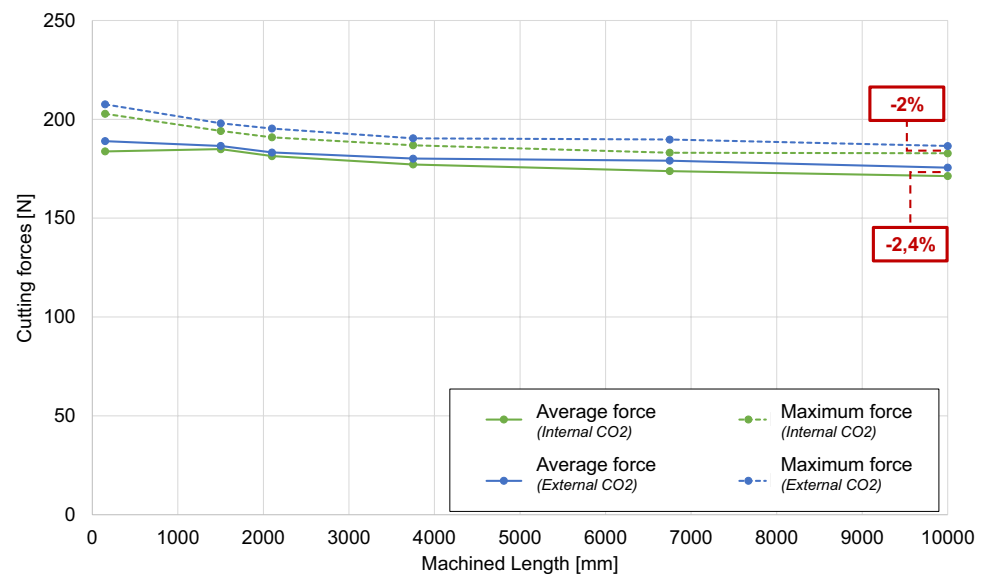
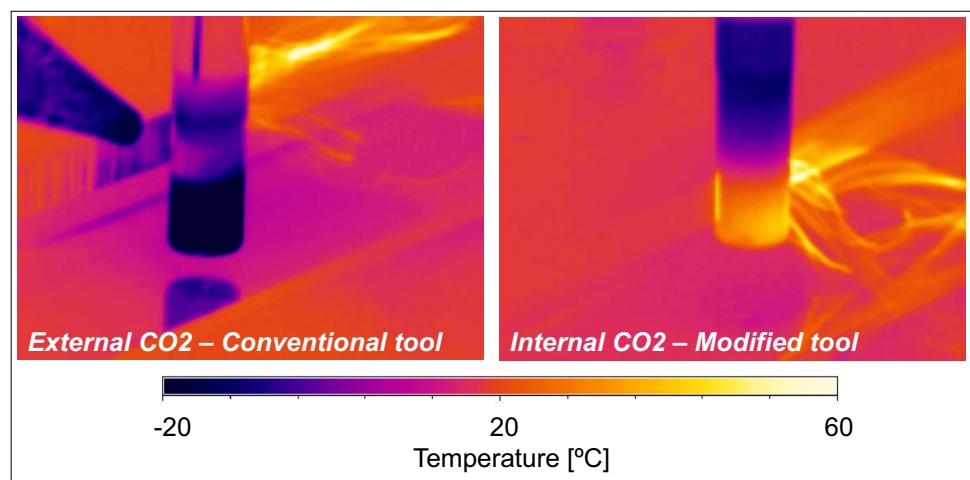


Fig. 7 Cutting forces obtained**Fig. 8** Cutting temperatures obtained with each cooling performance

medical prosthesis. Besides, the new way of injecting it through an axial tool internal channel does not affect to Ti6Al4V milling performance in comparison with conventional external CO₂ injection. Then, considering bio-medical manufacturing sector demands, the use of CO₂ as internal coolant is a feasible alternative which not only provides a more environmentally friendly process but also cleaner.

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Data availability Data availability in this case is restricted by the requirements of the projects being worked on.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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