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Original Article

CO_2 cryogenic milling of Inconel 718: cutting forces and tool wear

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ABSTRACT

Machining Inconel 718 alloy is a challenge due to its low machinability. This thermal resistant alloy combines high strength even at high temperatures with strain hardening tendency that causes high forces and extreme cutting temperatures during the machining. These issues force industries to achieve suitable machining processes to deal with this kind of alloys and the high worldwide competitiveness. Nevertheless, environmental considerations must to be taken into account due to growing environmental concerns. In the work here presented, cryogenic cooling with external MQL lubrication (CryoMQL) working along with CO2 as internal coolant is proposed for milling Inconel 718 with the aim of not only improving from a technical point of view but also environmental. This technique was compared with other lubricooling techniques. The results show that internal CryoMQL improves tool life by 57% in comparison with emulsion coolant, achieving 120% if it is compared with MQL in stand-alone mode.

1. Introduction

Heat resistant super-alloys (HRSA) in aeronautical turbomachinery industry are growing worldwide. HRSA are gratefully acknowledged by mechanical designers to satisfy the extreme requirements of combustion chambers and other hot parts in aircraft turbine. Nickel-based super alloy Inconel 718 is one of the most used in turbomachinery critical components due this HRSA presents good tensile strength, fatigue resistance, creep, along with high corrosion resistance at high temperatures [1,2]. However, these properties during machining processes become into high cutting forces, low material removal rates, alloy adhesion on cutting tool rake face, and cutting tool degradation processes such as abrasive and diffusion wear [3–7]. Therefore, improving these heat-resistant alloys machining becomes a challenge in order to look for a more efficient way to both lubricate and cool the cutting zone area, being oil emulsions used as cutting fluids as the key to deal with these issues. However, these oil emulsions can have injurious effect not only in the environmental foot print but also on workers which deal with them every day [8,9]. In particular, cutting fluids implies workers's diseases such as pneumonia, acne or even skin or lung cancer [10,11]. Besides, although once finished its useful life coolants are disposed and treated, 30% is lost in system leaks, evaporation, cleaning processes [12]. Therefore, looking for new lubri-cooling alternatives more effi-

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Nomenclature

ae	radial cutting depth
ap	axial cutting depth
CO2	liquid carbon dioxide
CryoMQL	cryogenic cooling combined with MQL
fz	feed per tooth (mm/z)
HRSA	heat resistant super-alloy
LN2	liquid nitrogen
MQL	minimum quantity lubrication
MRR	material removal rates
Vc	cutting speed (m/min)
VB	average flank wear

cient, cheaper, reliable and environmentally sustainable are welcome.

In this line, green lubricooling technologies at the moment are dry cutting, minimum quantity lubrication (MQL) and cryogenic machining. Dry cutting is not applicable in HSRA due to the high cutting temperatures achieving during its machining. MQL technology consists in spraying biodegradable oil microparticles with compressed air flow in the cutting zone [13]. It was demonstrated that applying MQL during machining, the cutting fluid reaches tool edges more efficiently than conventional cutting fluids due to the pressurized air high velocity [14,15]. Despite MQL technology provides higher lubrication in the cutting zone, its cooling capacity is reduced. Due to this, in difficult to cut materials – such as titanium and nickel alloys – where adhesion or diffusion phenomena are typical tool wear mechanisms, MQL cannot remove machining heat efficiently.

In this context, cryogenic cooling is presented as solution to avoid thermal causes related with tool wear. Cryogenic cooling consists in injecting liquefied gases in the cutting zone such as liquid nitrogen (LN2) or liquid dioxide carbon (CO2). However, the refrigeration mechanisms are considerably different in the two gases. In the particular case of LN2, it has to be stored in isolated reservoirs because at room pressure, it melts from solid into liquid phase at $-210\,^{\circ}$C and starts to boil at $-196\,^{\circ}$C. Then, LN2 as cutting fluid is very efficient to control high cutting temperatures but the low temperatures also require insulating supply lines.

Otherwise, CO2 can be stored in medium-pressure reservoirs at liquid stage with a pressure of 6 MPa at room temperature. In the case of CO2, when it is expanded a mixture of solid and gas particles at $-78.5\,^{\circ}$C are presented. This become in *dry ice* phenomenon which plugs the channels. In order to avoid *dry ice* formation, a pressure control device is mandatory. However, insulating supply lines is not required. Moreover, from an environmental point of view CO2 is obtained as a waste product from chemical and industrial processes, so environmental neutrality associated to conventional cryogenic machining is maintained, even improved as was analyzed in previous works by the authors in which a life cycle assessment was carried out where the main lubricooling techniques were compared [16].

In comparison with CO2, the time LN2 needs to decrease temperature of all supply pipes causes that the process is not stable [17].

LN2 was studied for various work materials [18–20]. However, to improve the machinability of different material by cryogenic machining it is important to establish the proper cooling strategies because different materials respond to temperature and machining processes differently [21]. Thus, it is necessary to study the different workpiece-tool material pairs individually in order to define the appropriate cryogenic cooling technique and this work will focused in machining of nickel-based alloys.

Cryogenic cooling effect presents particularly interest in machining HSRA such as nickel-based alloys [22]. In this line, Wang and Rajurkar 2000 [23] compared dry and cryogenic turning of different hard-to-cut materials and they concluded that cryogenic cooling reduces significantly cutting zone temperature improving tool life and workpiece surface. In the turning of Inconel 718 with H13A straight carbide tools, they show that tool wear is reduced applying LN2 and surface roughness is below Ra of 1.5 μm meanwhile 7.8 μm was typical when dry turning. Pusavec et al. [24] also reported that Inconel 718 cryogenic machining assists to reduce surface roughness in comparison with dry and MQL conditions. Besides, cryogenic machining caused much large compressive residual stresses and thicker compressive zone beneath machined surface.

LN2 cooling prevents tools from excessive adhesive and diffusive wear and maintains tool temperature under thermal softening temperature avoiding its plastic deformation [25]. The former authors using a tribometer found a significant reduction in friction coefficient under cryogenic conditions. Later, Pusavec et al. [26] presented the importance of cryogenic fluid phase in orthogonal cutting of Inconel 718 with TiAlN coated carbide tool. The better lubrication produced by LN2 cooling can be due to the formation of a fluid/gas cushion between tool/workpiece interfaces that provides a lubrication effect by absorbing heat and evaporating quickly [27].

On the other hand, cryogenic cooling with CO2 has not been extensively studied yet. In Busch et al., 2016 [17] various hybrid cooling strategies such as high-pressure cooling, CO2 cryogenic cooling and aerosol dry lubrication were investigated during Inconel 718 and Ti6Al4V turning, respectively. For example, in Inconel 718 turning, they stated that finishing operations with CO2 cooling needed additional lubrication to prevent adhesions on workpiece surface. In this sense, Rahim et al. [28] presented a CryoMQL device, which uses this physical phenomenon to get micro-oil droplets cooled. This device also was used by Stephenson et al. [29] and Superkar et al. [30]. In the former, Inconel 750 was turned and in the latter Ti6Al4V was milled. They reported improvements in the use of CryoMQL technology in comparison with wet machining, getting higher material removal rates (MRR) in both cases.

However, in these cases CO2 consumption was not taken into account, which is a crucial aspect to achieve a successful lubricooling technique. In fact, in Krammer et al. [31] and Klocke et al. [32] was reported that a higher pressure reduced the cutting temperature compared with a flow rate increment. Considering this approach, in Pereira et al. [33] was analyzed several CO2 outlet diameters with the aim of achieving a proper balance between CO2 consumption and injection efficiency. Results obtained are shown in Fig. 1. In this case, 1.5 mm was the optimal hydraulic diameter size to get a successful assistance of CO2 as coolant.

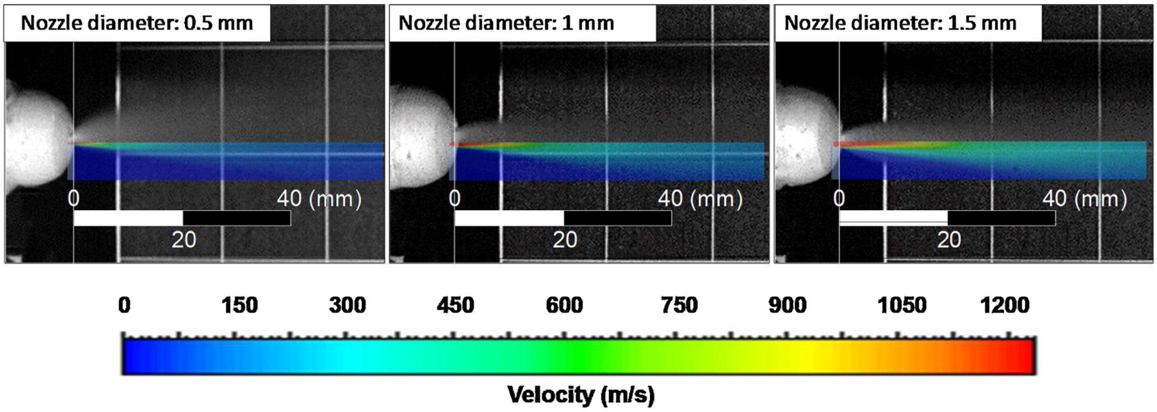


Fig. 1 – Results obtained with several CO2 outlet diameters [33].

Regarding Inconel 718 machining, most of the research focused on turning operations comparing dry and LN2 cryogenic techniques. In milling Inconel 718, Shokrani et al. [34] reports that cryogenic LN2 cooling reduced the tool life compared to dry cutting. Similar results were obtained by Musfirah et al. [35], concluding that the extreme liquid nitrogen low temperature can lead brittleness of tool material and to reduction of Inconel 718 thermal conductivity. These results are contradictory with those obtained by Aramcharoen and Kah-Cuhan [36] in which cryogenic cooling supposed tool wear reduction compared with dry milling. Nevertheless, the CO2 cryogenic cooling was tested in milling Inconel 718, thus Halim et al. [37] conducted experimental milling tests reporting significant tool life. Fernández et al. [38] compared internal CO2 cryogenic milling machining with emulsion in three different material, namely Inconel 718, Gamma TiAl and grade EA1N steel. They also found that tool life increment when cryogenic milling depends on the machined material, obtaining flank wear reduction above 60% when Gamma TiAl and Steel but similar tool wear when milling Inconel 718.

In this research work, different cooling techniques are studied for milling Inconel 718 regarding their influence in such aspects as cutting forces and tool wear. In particular, this manuscript is composed by an experimental setup description in which a new CO2 injection system is presented and a results section in which tool forces and tool edge are analyzed, respectively.

The novelty of this work stems from the idea of combining (a) CO2 as internal coolant and (b) MQL as external one applied to Inconel 718 end milling with the aim of using the CO2 through the tool and therefore, reducing CO2 consumption. The results show that the use of this combination implies an ecofriendly alternative to substitute oil emulsions in industrial environments at medium-term.

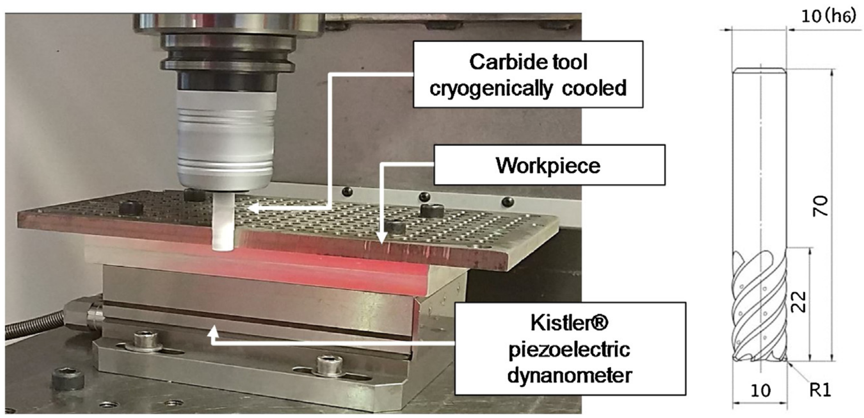
2. Machining eco-friendly lubricooling techniques

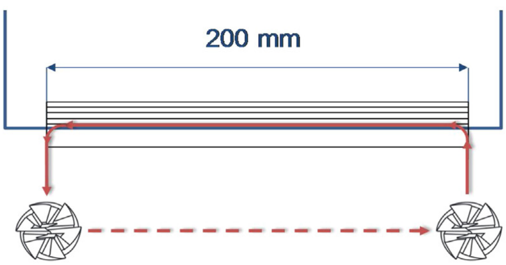
Experimental testing with different cooling technologies were performed in a Kondia three axis-machining center provided with a 17 kW spindle suitable to reach 12,000 rpm. The setup is shown in Fig. 2. Cutting strategy was planned as successive passes of contour down-milling of 200 mm length with tangential entrance and exit with a radius of 15 mm. Cutting forces and noise spectrum were recorded using a triaxial Kistler^{TM} 9255 piezoelectric dynamometer and an OROS$^{®}$ OR35 real-time multi-analyzer with a sample frequency of 16,384 samples/s. Tool wear VB was progressively measured by pausing the passes at different stages with a Nikon SMZ-2T microscope. In particular, tool wear was measured in the incidence face of the cutting edge. As wear criterion, tests were stooped at VB = 0.2 mm because higher values can affect part surface integrity due to high cutting temperatures reached [39,40].

Workpiece material was aged Inconel 718 (nickel-based super alloy) which is hardened by precipitation for secondary phases into the metal matrix (45HRc). The chemical composition of specific work material is shown in Table 1.

Cutting tools used were S10 carbide end mills with microgain with 10% of cobalt binder, $D = 10$ mm, 6 flutes, helix angle $\beta = 45^{\circ}$ and TiAlN coating. Cutting conditions were chosen according to previous experiences and performing adjustment tests in order to obtain a stable milling process. In particular, cutting speed selected was 40 m/min, feed per tooth 0.03 mm/tooth and radial and axial depth of cut 0.2 mm and 10 mm, respectively.

During experimental tests, different lubricooling techniques were tested, such as wet machining, Minimal Quantity of lubricant (MQL), CO2 cryogenic cooling and MQL and cryogenic combination (CryoMQL). To ensure repeatability, each milling experiment was repeated twice. The CryoMQL device is shown in Fig. 3(a). The developed system allows combining MQL and cryogenic technologies as CryoMQL or use them in “stand alone” mode. The MQL subsystem is performed as two channels microlubricator. Thus, the oil is pulverized in the nozzle by Venturi’s effect. In one of the channels flows air at 6 MPa. In the other one, there is biodegradable oil with 43 mm^2/s of cinematic viscosity and 920 kg/m^3 of density. The oil flow rate is controlled by the frequency generated by an electrovalve. On the other hand, the CO2 injection subsystem is provided with liquid CO2. In particular, this subsystem creates an intermediate pressure stage over the triple point which avoids dry ice formation. In Fig. 3(b), CO2 phase diagram with the stages followed by the CO2 injection subsystem is shown.





Cutting Conditions	
Cutting speed (V_c)	40 m/min
Feed per tooth (f_z)	0.03 mm/tooth
Helix angle	45 degrees
Radial depth (a_e)	0.2 mm
Axial depth (a_p)	10 mm

Fig. 2 – Experimental setup.

Table 1 – Inconel 718 percentage composition.

Ni	Cr	Co	Fe	Nb	Mo	Ti	Al	B	C	Mn	Si	Others
52.5%	19%	1%	17%	5%	3%	1%	0.6%	0.01%	0.08%	0.35%	0.35%	1.79%

During the tests, CO2 was injected in two ways. In the first one, CO2 was used as very cold jet to remove heat by means of convection mechanism, in a similar way as emulsion coolants. In the other one, CO2 was used as very cold fluid that removes heat inside the tool and just in the tool rake face outlets, acting more as heat exchanger than convection jet coolant. Regarding CryoMQL technique, based on the results obtained with the tests carried out with CO2 in stand-alone mode, CO2 was used as internal coolant. However, meanwhile CO2 is used internally, MQL could not be applied in this way because this system needs a double-channel nozzle to make Venturi's effect and pulverize the oil.

The five lubricooling technologies tested are summarized in Table 2. The oil flow rate used during MQL and CryoMQL machining was 100 ml/h. CO2 was injected at 14 bars and −78 °C during cryogenic and CryoMQL machining.

3. Results and discussion

3.1. *Cutting forces*

Measuring cutting forces along the process can be a good indicator to decide amongst the different alternatives. Fig. 4 and Table 3 show, respectively, the averaged total cutting forces and the form evolution at three wear stages with the three force component values when milling Inconel 718 under different cooling strategies. The average values for the three cartesian components were calculated after filtering the experimentally obtained brute cutting forces. These forces were smoothed in Matlab© (Signal Analyzer) to remove the noisiest part, but without altering the general shape of the original forces. The average value is then computed over a relevant time interval (ten periods) using mean command.

It can be seen that the cutting forces are very sensitive with the increase in the value of flank wear, and in all cooling strategies, there is a correlation between the cutting force variations components and the flank wear width. The relative sharp tools at the initial stages of machining produce low cutting forces. With the increase of cutting time, the tool edges became blunt, higher friction coefficient and more contact area at the tool/chip interface is generated. As a result, the high cutting forces are obtained at the end of machining.

In particular, in the first stage, where tool wear can be neglected, the lubricooling techniques properties takes major relevance in cutting stresses. At this point, among the eco-friendly alternatives to wet machining, MQL performance was the technique which presents the highest value (184 N). Taking this value as a reference, the other techniques are below it. In case of using CO2 as internal coolant, this value was reduced ≈17%. However, if it is used as external coolant the difference with MQL is 11%. Therefore, the use of CO2 as internal coolant represents an improvement in comparison with its external

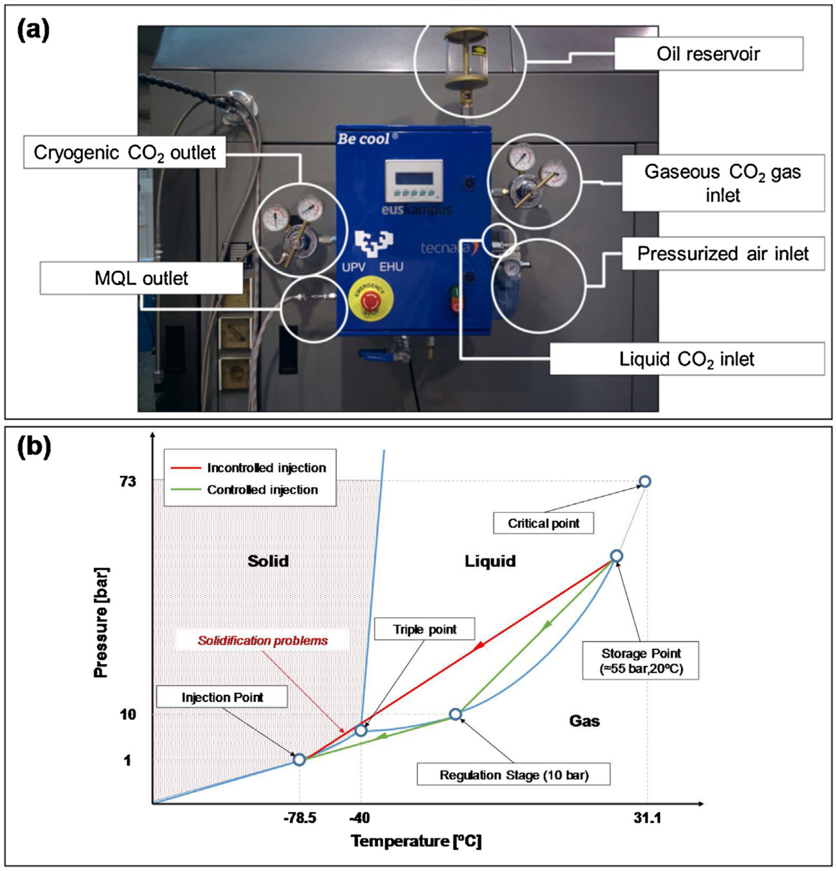


Fig. 3 – (a) Cryogenic CO2 system developed by UPV/EHU and Tecnalia (b) CO2 phases diagram.

Table 2 – Different lubri-coolant techniques compared in this work.

Lubricooling technique	Characteristics and description
Wet Machining	Oil emulsion (10% synthetic oil)
MQL	Canola oil 920 kg/m^3 and biodegradable additives. Flow rate = 100 ml/h; air pressure = 6 bars
External/Internal CO2	Carbon dioxide assisted machining (14 bar, −78 °C)
CryoMQL	MQL (6 bar + 100 ml/h) + Carbon dioxide assisted machining (14 bar, −78 °C)

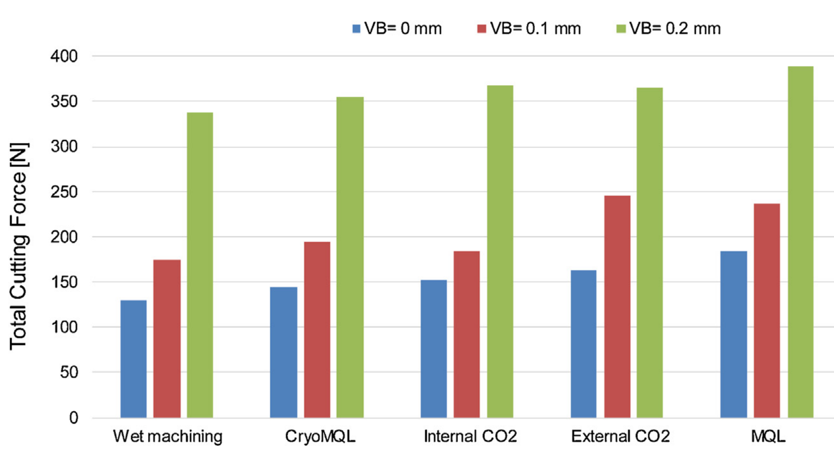
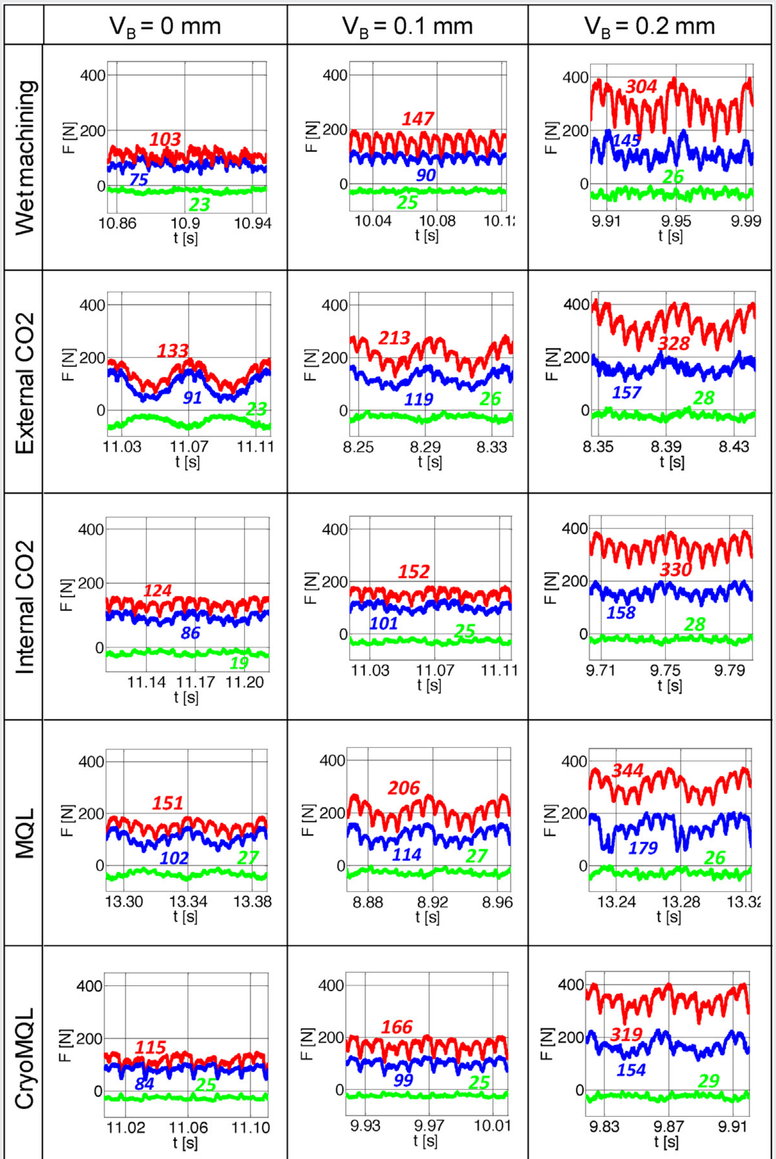


Fig. 4 – Total cutting force evolution for the different lubri-coolant techniques at different wear stages.

Table 3 – Forces (Fx: blue, Fy: red, Fz: green) evolution for the 5 techniques.



		VB=0	VB=0.1	VB=0.2
Wet machining	Fx [N]	75.64	90.38	144.30
	Fy [N]	102.60	146.70	304.20
	Fz [N]	22.69	25.40	27.53
CryoMQL	Fx [N]	84.24	98.13	153.52
	Fy [N]	114.93	166.50	319.23
	Fz [N]	24.51	25.11	29.01
Internal CO2	Fx [N]	85.99	100.86	157.94
	Fy [N]	123.99	152.08	330.02
	Fz [N]	19.10	25.10	28.10
External CO2	Fx [N]	90.54	118.75	156.77
	Fy [N]	133.30	213.11	328.11
	Fz [N]	23.08	26.24	28.00
MQL	Fx [N]	102.67	113.58	178.50
	Fy [N]	150.62	206.21	344.28
	Fz [N]	26.58	27.17	25.60

use. Based on this, in the CryoMQL tests CO2 was used as internal coolant. In this case, the difference with MQL was ≈21% and if is compared with wet machining a slight increase of 11% is achieved.

In the following stages, the wear effects take relevance in detriment of the lubricooling techniques implying an instability increase. This behavior can be appreciated in cutting forces patterns along the milling, shown in Table 3. In this table, the

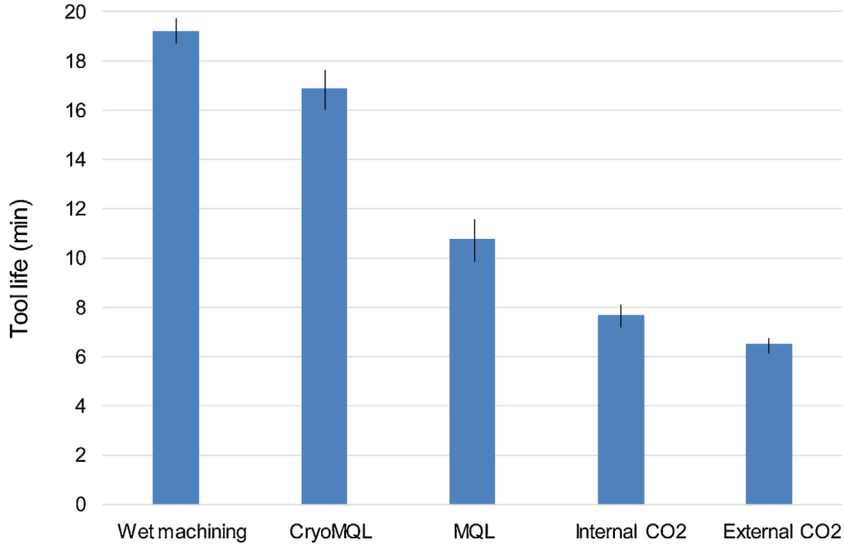


Fig. 5 – Tool life with the different lubricooling techniques.

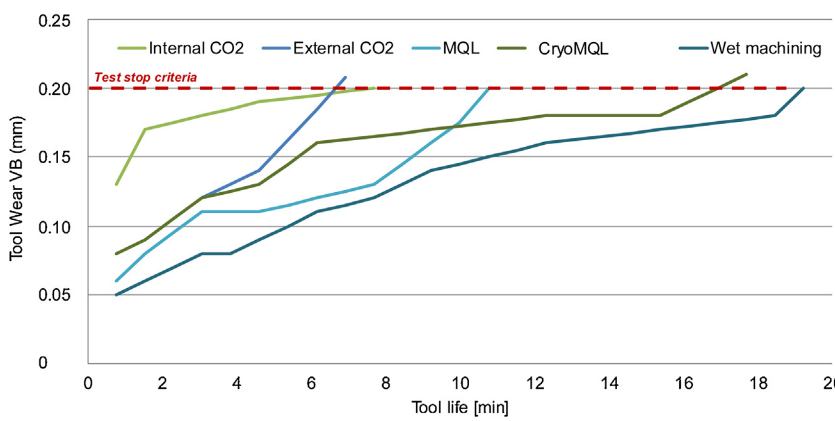


Fig. 6 – Tool wear evolution.

magnitude and shape evolution is presented for two revolutions of the cutting force components (2T). In sight from these patterns, all components present a sinusoidal pattern typical of milling processes. However, it should be noted that this pattern is affected by a noise increase at the same time that also tool wear increase, what, consequently, destabilize the process.

Finally, comparing the different cooling alternatives with wet machining, the use of oil emulsions as cutting fluids supposes the lowest cutting forces in all wear stages; however, it is not a sustainable strategy due to health and environmental negative effects associated with its use.

Therefore, internal CryoMQL appears as the most suitable cooling strategy due to achieve a balance between environmental and technical issues, obtaining only 5% higher cutting forces than wet machining with 0.2 mm tool wear. In this case, the oil of the MQL system reduces the friction in the cutting zone and a cooling effect is also obtained due to internal cryogenic CO2.

3.2. *Tool wear*

Regarding tool wear, it was progressively measured by pausing the passes at different stages. Flank wear at the clearance face is the most critical wear type when machining with carbide inserts. In HRSA such as Inconel 718, flank wear is caused mainly by the austenitic matrix which hardens after each tool pass leading to work deformation, even provoking a notch at depth-of-cut level. Fig. 5 shows the results of tool life with the different lubricooling techniques analyzed.

Analyzing tool life obtained with the different cooling strategies, using 0.2 mm tool wear criterion, the external and internal CO2 cryogenic cooling presents the worse results, reaching 7.69 and 6.5 min of machining. The worst results obtained with external cryogenic cooling can be explained by the intermittent milling process that can made difficult the CO2 flow penetrates the cutting zone. Although the cryogenic cooling can effectively extract heat from the cutting zone, it is not able to lubricate the tool-workpiece contact area. The experimental results revealed that MQL improves the tool life

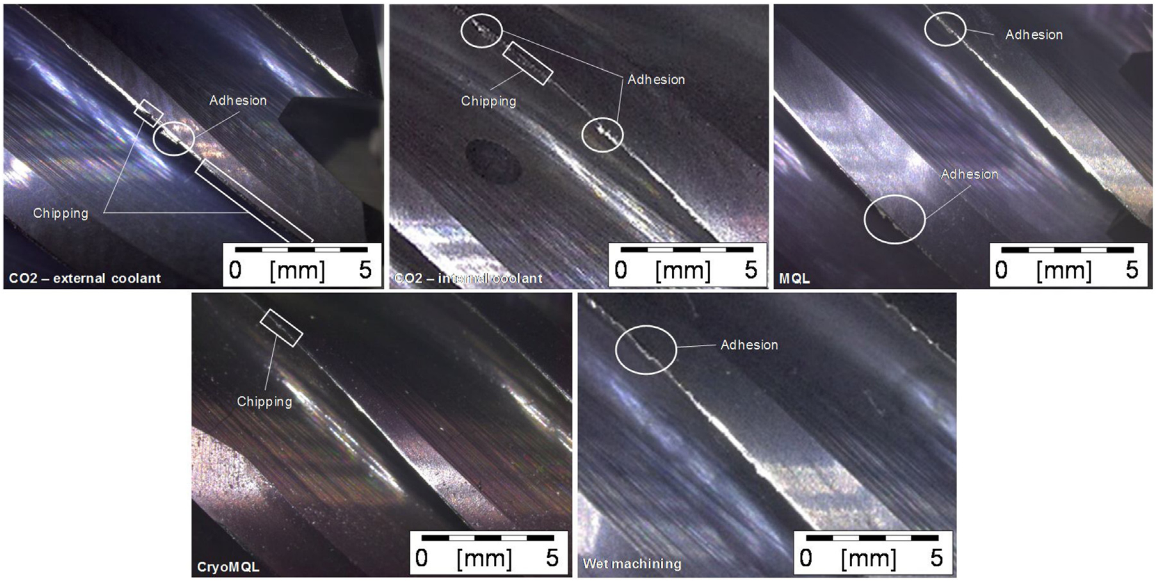


Fig. 7 – Cutting edges at final stages.

Table 4 – Cutting edge wear at final stage.

	Wet machin.	CryoMQL	MQL	Ext. CO2	Int. CO2
Edge 01	0.17	0.2	0.17	0.17	0.2
Edge 02	0.18	0.21	0.2	0.16	0.2
Edge 03	0.17	0.17	0.14	0.16	0.18
Edge 04	0.18	0.19	0.16	0.17	0.18
Edge 05	0.18	0.2	0.18	0.17	0.2
Edge 06	0.2	0.2	0.15	0.21	0.19
Standard deviation [σ]	**0.011**	**0.0137**	**0.0216**	**0.0186**	**0.0098**

compared with cryogenic cooling reducing friction and heat generation during milling Inconel 718.

Results show that combining internal CO2 cryogenic machining with external MQL (CryoMQL) tool life improves by 57% and 120% if it is compared with MQL and internal cryogenic machining, respectively. In this case, the cooling effect of cryogenic machining and the lubrication effect of MQL overlap reducing tool wear. On the other hand, in comparison with wet machining, the use of CryoMQL presents a slight reduction in tool life of 12%. These results are consistent with the analysis of cooling capabilities of emulsion, LN2 and CO2 performed by Pusavec et al., 2019 [41]. They obtained experimentally that depending on the flow rate used, emulsion can provide better cooling capacity than cryogenic cooling resulting in lower cutting temperatures.

In Fig. 6 is shown cutting edge wear evolution of the different lubricooling technologies. Evaluating the different performances, the importance of lubrication effect to control mechanical effects on tool wear during Inconel 718 milling is observed. In particular, when CO2 is injected in "stand alone" mode without any oil lubrication assistance, tool wear increases drastically, reaching the end of test criteria immediately. This is due to thermal effects on tool wear are reduced but mechanical ones not. In the opposite, with MQL lubrication the thermal effects are not mitigated but mechanical ones. In this case, tool wear increases in a controlled manner, being able to anticipate its final useful life. Then, comparing these two opposite techniques, it is highlighted which mechanical effects have more impact on tool wear than thermal ones. Finally, CryoMQL and the use of oil emulsions in wet machining combine cooling and lubrication phenomenon, presenting the most stable increase of tool wear evolution.

During milling tests, the tool wear mechanisms observed on the cutting tool were adhesion and microchipping. In all cooling strategies, flank wear was the dominant type of wear. Built up edge was detected in the last milling passes in both external and internal CO2 cryogenic cooling and when MQL cooling. The adhesion was remarkably reduced using CryoMQL, which proves the effectiveness of the combined cooling capacity of CO2 with the lubrication capacity of MQL. Fig. 7 shows the cutting edges at the last stage of each cooling strategy.

Finally, in Table 4 the values of the six edges of each mill and the deviation standard at the final stage were shown with the aim of analyzing the stability of the process. The results show that the use of CO2 as internal coolant implies a tool wear along the edges more stable than using it as external one. In fact, in the case of using CO2 as internal coolant several cutting edge wear reach the test stop criteria value at the same time. On the other hand, analyzing standard deviations, the best stability is achieved by internal CO2 followed by wet machining, presenting a difference between them of 12.24% if external CO2 is taken as reference. Regarding the other alternatives, CryoMQL presented a difference with the reference of 13.98%, MQL 20.41% and external CO2 89%, respectively. Then, these results shown that the use of CO2 internally to the tool implies to reach a more stable cutting edge wear in which all edges are wear homogenously. Nevertheless, the green technique which achieves a balance between a homogenous wear in its edges and tool life is CryoMQL, being the most suitable technique to substitute oil emulsions as cutting fluid.

4. Conclusions

In this paper, different eco-efficient lubri-cooling technologies were analyzed in Inconel 718. Among them, a new method to combine internal CO2 cryogenic cooling and MQL lubrication was proposed. In this way, based on experimental tests, some conclusions were derived:

- Although the longest tool life was reached with wet machining, the aim is to walk toward an eco-efficient machining process. Hence, this technique should be avoided from industrial environments in a medium term.
- Near-to-dry lubri-coolant techniques, CO2 cryogenic cooling as well as MQL lubrication working on their own, are not enough to be applied in HRSA due to machined length rates were insufficient to substitute wet machining technology. In particular, cutting forces presented by MQL in the first stage was 184 N, being the higher value. In case of using CO2, when is injected external to the tool this value was reduced ≈11% and when is used as internal coolant this value was reduced ≈17%. Regarding tool life, MQL presents better lubrication performance and therefore, tool life is increased ≈40% and ≈65% in comparison with external and internal CO2 cryogenic cooling, respectively.
- In case of using CO2 as cutting fluid, it is better using it as internal coolant than external. When CO2 flows throw the tool, cooling is closed to a heat changer effect that to expel gases, without hardening material what causes minor cutting stresses.
- CryoMQL, as combination of MQL and CO2 cryogenic technologies, is the best alternative to be applied. In comparison with other green alternatives, internal CryoMQL proved to be an effective way for extending tool life in milling Inconel 718. Taking MQL as reference, cutting forces are reduced ≈21% and tool life increased ≈57%. Besides, in comparison with wet machining, the tool life is reduced ≈12% and cutting forces are increased ≈11%. Then cutting forces pattern and too wear were similar. However, with CryoMQL a balance between technical and environmental matters is achieved.

Conflicts of interest

The authors declare no conflicts of interest.

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