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Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304

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ABSTRACT

In recent years, the need for more efficient machining processes has notably increased, both in terms of productivity and eco-efficiency. In this paper, the use of combined techniques based on cryogenic cooling and minimum quantity of lubrication is proposed and compared with other near-to-dry coolant alternatives. To evaluate the success of the proposed technique, technical feasibility on the one hand and ecological footprint on the other should be analyzed. Results show that this combined solution implies a tool life improvement (more than 50%) and the possibility of increasing the cutting speed (more than 30%) comparing with dry machining. Moreover, cutting forces and surface integrity are maintained or even improved in comparison with conventional techniques. From an ecological point of view, a life cycle assessment was performed providing a comparison of the different alternatives proposed. Results show that the combination of cryogenic and minimum quantity of lubrication techniques is the key to success, reaching a balance between technical and environmental issues. Stand-alone systems (no combined ones) do not provide a complete solution. Cooling without lubrication or vice versa is not enough when machining these materials.

1. Introduction

Nowadays, and taking into account the existing competitiveness, industrialized countries need to perform a continuous improvement in their manufacturing processes. Concretely, machining processes should be more efficient to deal with emerging countries which do not have strict rules in terms of working conditions and environmental laws. Improvement of machining performance on difficult-to-cut materials for high added value parts is a hot topic today. Achieve new alternatives and solutions in this line is extremely worthy for machinists to find an opportunity to deal with competitors. Stainless steels and other difficult-to-cut materials such as nickel-based alloys or titanium were studied by authors in the last years (Fernández-Valdivielso et al., in press; Fernández-Abia et al., 2011). Results from these papers provide data to improve productivity taken into account a technical point of view, but eco-efficiency should be highlighted to perform a full process optimization.

Cutting fluids are commonly used during machining difficult-to-cut materials (Srikant and Ramana, 2015). The use of wet machining can produce health problems and increase manufacturing costs. Some authors claim that they represent between 7% and 17% of the total manufacturing cost in the automotive industry (Klocke and Eisenblätter, 1997), reaching values of 20% for difficult-to-cut materials (Shokrani et al., 2012). Chemical components can be harmful to workers health, causing skin and breathing problems. According to NIOSH (National Institute of Occupational, Safety and Health), there are 1.2 million of workers in the United States of America exposed to these injurious effects (Sharma and Sidhu, 2014; Park et al., 2010). Moreover, it is well-know that their application is not efficient enough. Over the ≈320,000 tonnes/year consumed in Europe (Debnath et al., 2014; Lawal et al., 2012), 30% is lost in system leaks or evaporation (Byrne et al., 2003) and their treatment and disposal costs between one and two times its purchase price.

In the last years, some advanced lubri-coolant techniques were developed inside the "green manufacturing" philosophical framework. The driver of these techniques is to minimize or eliminate the use of conventional cutting fluids and oils. Some of these alternatives are based on the cryogenic assisted machining concept. This

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cooling technique consists on applying cryogenic gases just on the cutting zone to reduce cutting temperature. Cryogenic cooling can be considered as a clean, safe and environmental friendly technology directly applicable to machining processes. Liquid nitrogen (LN_2) and carbon dioxide (CO_2) are the most used cryogenic fluids. Scientific bibliography shows a great number of success stories, normally comparing cryogenic cooling with dry or wet machining. First important references on cryogenic machining appear more than 15 years ago. For example, in (Hong and Ding, 2001) LN_2 cryogenic cooling was applied to Ti-6Al-4V turning. Results in this material show that the cutting temperature was reduced below 500 °C and the cutting speed was increased notably in comparison with wet machining. Note that the main problem during machining titanium stems from thermal effects. Other papers presented by these authors analyzed the lubricant properties of LN_2 (Hong et al., 2002). In (Hong, 2007), author claims that LN_2 lubricant properties have a close relation with the injection hydrostatic pressure. Thus, to obtain the highest effect, the cryogenic gas should be injected as near as possible of the cutting zone. Similar ideas were reported in (Kramer et al., 2013) and (Klocke et al., 2012), concluding that a pressure increase reduces the tool temperature better than a flow rate increase. Regarding tool life and tool wear behavior, some authors reported improvements around 40% when turning Ti-6Al-4V using LN_2 (Strano et al., 2013) and also grooving other titanium alloys (Machai et al., 2013).

When dealing with other difficult-to-cut materials, such as nickel based alloys, hardened steels or austenitic stainless steels, succeeds stories are not so representatives. In this case, the main tool wear mechanism is produced by the combination of lubrication problems and the high cutting temperatures reached in the cutting zone (Kopac, 2009). Thus, authors tend to combine techniques or develop novel advanced lubri-coolant systems. In this line, in (Supekar et al., 2012) supercritical CO_2 ($scCO_2$) is tested combined with two different oil microparticles flow rates. The $scCO_2$ machining technology is based on using the special properties of CO_2 in supercritical state, which is capable of dissolving oil. Liquid CO_2 is introduced in a pressurized tank with soybean oil. When reaching triple point pressure, CO_2 dissolve the oil and the mix is prepared to be injected over the cutting zone. This process is technically viable but investment is considerable.

Other authors found alternatives to minimize both the thermal effect and the mechanical stress in the tool during the machining. LN_2 and MQL oil microparticles where used for first time turning Inconel 718 by (Pusavec et al., 2010). In this preliminary work, authors reported better surface roughness and surface quality using the combined techniques rather than the stand-alone ones. Three years later, in (Pusavec et al., 2014) the same combination of CryoMQL with LN_2 and in stand-alone mode was studied in-depth. Workpiece pre-cooling and its combination with minimum quantity of lubrication was presented by (Shokoohi et al., 2015) as an eco-friendly alternative. Other authors tested combined solutions using LN_2 (Tazehkandi et al., 2015) and also CO_2 (Stephenson et al., 2014). With this technique, material removal rate (MRR) was increased between 25% and 45% in comparison with wet machining. The flow rates consumed by the CryoMQL were 450 g/min (27 kg/h) of CO_2 and 15 ml/h of oil. In other aspects, in (Truesdale and Shin, 2009) it was demonstrated a cost saving based in a MRR increase despite tool life decrease. In this research Udimet 720 was milled with LN_2 and high pressure mineral coolant. When high pressure mineral coolant is injected, it is shown that the cutting speed is limited by the material structural deformation in 10 m/min. On the other hand, when LN_2 is used, this structural deformation is over 120 m/min. Although with this phenomenon tool costs increase an 84%, the MRR increase leads to a profit of 90%. This fact demonstrates the great difficulty existent when trying to optimize this kind of technologies. Thus, it is important to perform a full study taking into account all the possible lubri-coolant strategies in order to obtain the best choice. The novelty of the work here presented stems from the idea of compare all the possible near-to-dry coolant alternatives in order to detect the best alternative for this material and conditions, taking into account environmental aspects as well.

2. Experimental setup and tests performance

Experimental tests were performed using AISI 304 stainless steel. Concretely, type 304L, which is an extra low-carbon variation of type 304 with a 0.03% maximum carbon content that eliminates carbide precipitation due to welding. Austenitic stainless steels, such as the one here analyzed, represents more than 70% of the worldwide stainless steel production. These materials, which are considered as difficult-to-cut materials, are commonly used in automotive, aerospace and medical industry. Their mechanical properties are highly suitable for high added value components. These materials present a high tensile strength, ductility, fracture toughness and fatigue resistance on the one hand, and a low thermal conductivity and high heat capacity with low corrosion rates on the other. Its low thermal conductivity causes high cutting temperatures and high wear rates due to thermal effects. Built-up-edge is a common problem during cutting these materials, so it is important to use a correct lubri-coolant technique to avoid this phenomenon and reduce tool wear (Lawal et al., 2012; Shokrani et al., 2012; Rivero et al., 2008; Korkut et al., 2004).

Tests were performed in a CMZ TC25-BTY turning center with 45 kVA of power installed and 35 kW of main spindle power. Material used was supplied in bar form (Ø 60 mm, 200 mm length). The insert used was a TiN coated carbide DNMG 150608-MM (GC2025) with chip-break. The tool holder was a PDJNR 2525M-15-JHP with internal cooling for wet high pressure machining. This standard tool holder allows the injection of coolant both on the rake face and on the clearance face. Tests were performed in common conditions but using different lubri-coolant alternatives. Tools, material and cutting conditions were established by accounting for previous literature (Fernández-Abia et al., 2011; Gandarias et al., 2008) and performing adjustment tests in order to obtain a stable turning process. Cutting speed (V_c) selected was 225 m/min, feed rate (f) of 0.25 mm/rev and 1.5 mm of depth of cut (a_p). Tool life is measured till flank wear exceeds 0.3 mm (V_{Bmax}) as ISO 3685 establishes, or till a catastrophic failure happens. During the process some signals were recorded in real time, such as: the three components of cutting forces using a triaxial Kistler 9255 piezoelectric dynamometer; the power consumption of the whole process using three Vydas UPC-E power cells. Besides, during tests, some stops were carried out to measure the tendency described by the tool wear (flank wear V_{Bmax} using a Nikon SMZ-2T microscope) and the surface finishing (R_a parameter using a roughness tester Taylor Hobson Surtronic Duo 112-3115). Having finished tests, surface integrity was analyzed. Surface and sub-surface hardness was measured with a micro-hardness tester Future Tech FM-80; 3D surface topography was obtained using a Leica confocal microscope and the affected layer was measured with a Nikon Optiphot-100. The experimental setup is shown in Fig. 1.

Apart from validating the proposed CryoMQL technique, this paper aims to compare conventional and other advanced lubri-coolant techniques with the proposed one. In this line, tests were performed maintaining the same cutting parameters but using different coolant alternatives, as shown in Table 1. The ones tested in this work are the so-called dry or near–to-dry machining: dry machining (DRY); machining using minimum quantity of lubrication (MQL); cryogenic machining using liquid nitrogen (LN_2);

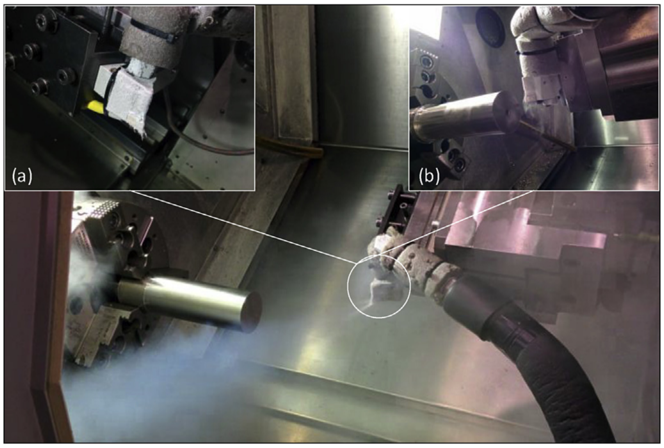

Fig. 1. Experimental setup. (a) CryoMQL setup. (b) Cryogenic setup.

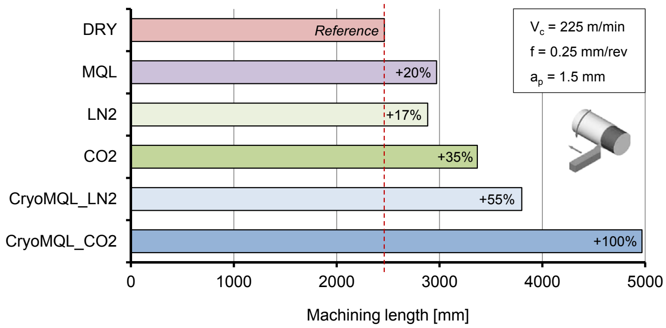

Fig. 2. Tool life using different near-to-dry machining techniques on AISI 304.

cryogenic machining using carbon dioxide (CO_2); machining using liquid nitrogen and minimum quantity of lubrication (CryoMQL_LN_2); and machining using carbon dioxide and minimum quantity of lubrication (CryoMQL_CO_2).

3. Results and discussion of experimental tests

The aim of this work is to validate the CryoMQL technology as an advanced lubri-coolant technique for turning AISI 304 stainless steel. For this purpose, an ecological and technical feasibility exam has to be passed, mainly comparing the proposed alternative with other near-to-dry machining techniques. In the technical way, the proposed technique should be checked in different terms. Thus, tool wear behavior, cutting forces and surface integrity have to be analyzed.

3.1. Tool wear behavior

Results of tool life are shown in Fig. 2. Using DRY conditions, the tool is capable to machine around 2500 mm using the common nominal cutting conditions and applying the ISO 3685 for standardized measurements of tool wear. Taking into account this value as a reference, the other alternatives checked in this paper improve the tool wear behavior. For example, using MQL the tool is capable of machining ≈2900 mm before the end of the tool life. This value represents an increase on tool life around 20%, as shown in Fig. 2. Using LN_2 and CO_2, the increase is ≈ 17% and ≈35% respectively. Finally, using CryoMQL techniques, results are notably better: ≈55% improvement in tool life using LN_2+MQL and more than 100% using CO_2+MQL (approximately double tool life). High temperatures during DRY machining imply lower tool life due to thermal effects on tool wear. Using MQL, the lubrication effect of the oil injected implies an increase on tool life. However, the thermal effect of the MQL is not enough to achieve a feasible process. In the case of cryogenic assisted machining, both using LN_2 and CO_2, results show an increase in tool life due to their contribution in minimize thermal effects. These stand-alone techniques, such as MQL, LN_2 or CO_2 are not enough to deal with this material in these conditions. Lubrication effects and thermal effects should be combined to achieve a feasible solution. Results show that combining MQL and CO_2, tool life can be doubled. Differences between the two CryoMQL solutions proposed (using LN_2 or using CO_2) is out of the scope of this paper and should be analyzed precisely in a separate way.

Results obtained for a cutting speed of $V_c = 225$ m/min show that it is possible to increase the cutting speed when CryoMQL machining is used. Some tests were performed using a cutting speed of $V_c = 300$ m/min. This fact implies an increase of process velocity and ≈33% reduction in process time. Compared with DRY machining, CryoMQL_CO_2 machining when turning with a cutting speed of $V_c = 300$ m/min, provide same results regarding tool life, as shown in Fig. 3.

3.2. Cutting forces

Results from the cutting forces measurement are shown in Fig. 4. These values were obtained in each stage along tool wear. Forces are divided in three axial components, the cutting force (F_c), the feed force (F_f) and the back force (F_r). Besides, also the modulus of total cutting force is shown (F). The effect of tool wear can be neglected when the tool is new, and therefore cutting fluid effects are what make the difference in cutting forces. In this stage, radial forces are small and very similar due to the tool is not worn. Besides, both cutting forces and feed forces only present slight differences, being around 800N and 325N, respectively. Taking dry machining cutting forces as reference, the other values obtained with the other lubri-coolant techniques are below between 0.05 and 6% for cutting force components and vary between −4% and +6.5% for feed force ones. These little variations indicate the feasibility of the lubri-coolant alternatives proposed.

On the other hand, also cutting forces values are related with the tool wear and grow with it. However, despite CryoMQL_LN_2 presents during the whole process smaller cutting force modulus than

Table 1
Different lubri-coolant techniques compared in this work.

Lubri-coolant technique	Characteristics and description
DRY	Dry machining, no lubri-coolant
MQL	Canola oil 0.92 g/cm^3 and biodegradable additives. Flow rate = 100 ml/h; air pressure = 6 bars
LN_2	Liquid nitrogen assisted machining (15 bar, −196 °C)
CO_2	Carbon dioxide assisted machining (15 bar, −78 °C)
CryoMQL_LN_2	MQL (100 ml/h) + LN_2 (15 bar, −196 °C)
CryoMQL_CO_2	MQL (100 ml/h) + CO_2 (15 bar, −78 °C)

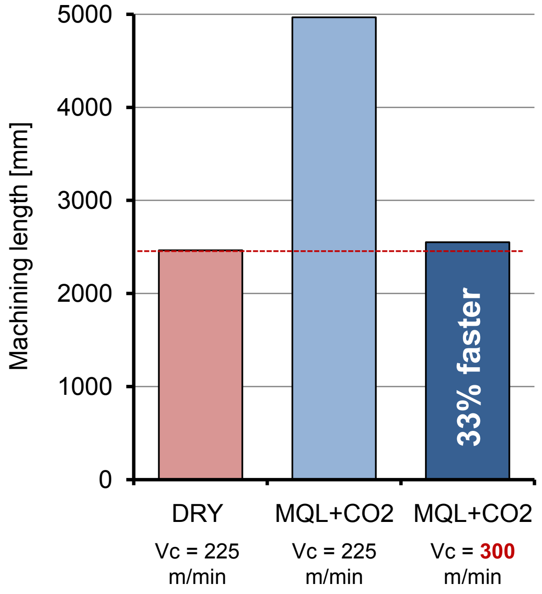

Fig. 3. Comparison between machining technologies using different cutting speeds.

CryoMQL_CO_2, its cutting force component is larger. This behavior is enhanced when flank wear is near 0.3 mm. Thus, in order to validate the results obtained in these cases, T-student tests were made with the aim to stablish a confidence interval for the three axial components in whole CryoMQL processes. The confidence level was stablished in 90%; 6 and 9 degrees of freedom for CryoMQL_CO_2 and CryoMQL_LN_2, respectively; average cutting forces during the whole process were used for calculate the values. In Table 2 the results obtained are summarized.

Regarding the results obtained in the statistical test based on T-Student, the cutting force values are inside the confidence interval in each tool wear stage when CryoMQL_CO_2 is used as lubri-coolant technique with a confidence level of 90%. However, in the case of CryoMQL_LN_2, cutting forces values are outside of the confidence interval when flank wear reaches 0.3 mm. This phenomena makes unstable the cutting process at this stage, causing a possible uncontrolled tool failure, what justify the flank wear value specified in ISO 3685. Therefore, the cutting forces obtained with the CryoMQL presented techniques do not affect negatively to the cutting process.

3.3. *Surface integrity*

Surface integrity of machined components is of great importance in order to validate a cutting technology. One of the common indicators used to analyze the surface integrity are the roughness parameters, topological aspects, microstructure analysis and subsurface hardness measurement. To accept the implementation of a new machining process, not only surface roughness should be maintained or improved. Also, material deformation and influence of the cutting process in material hardness must be taken into account.

Results of surface roughness when turning with different lubri-coolant techniques are presented in Fig. 5. This figure represents the values obtained at different tool wear stages. When the insert is new, the tool wear influence can be discounted. Taking into account the roughness theoretical values, only with MQL and dry machining the average roughness values (R_a) are below theoretical one. However, the mean values of five consecutive maximum heights between peak-valley (R_z) are over its theoretical value. These values decrease along machining time and thus with tool wear. This phenomena is classic in this type of inserts where the machining stable zone is obtained in wear values around 0.2 mm and thus surface roughness parameters reach the minimum values (Fernández-Valdivielso et al., in press). At this stage (Vb = 0.2 mm), both R_a and R_z values are below their theoretical values. Only LN_2 R_z values are over their theoretical values. Best results were obtained

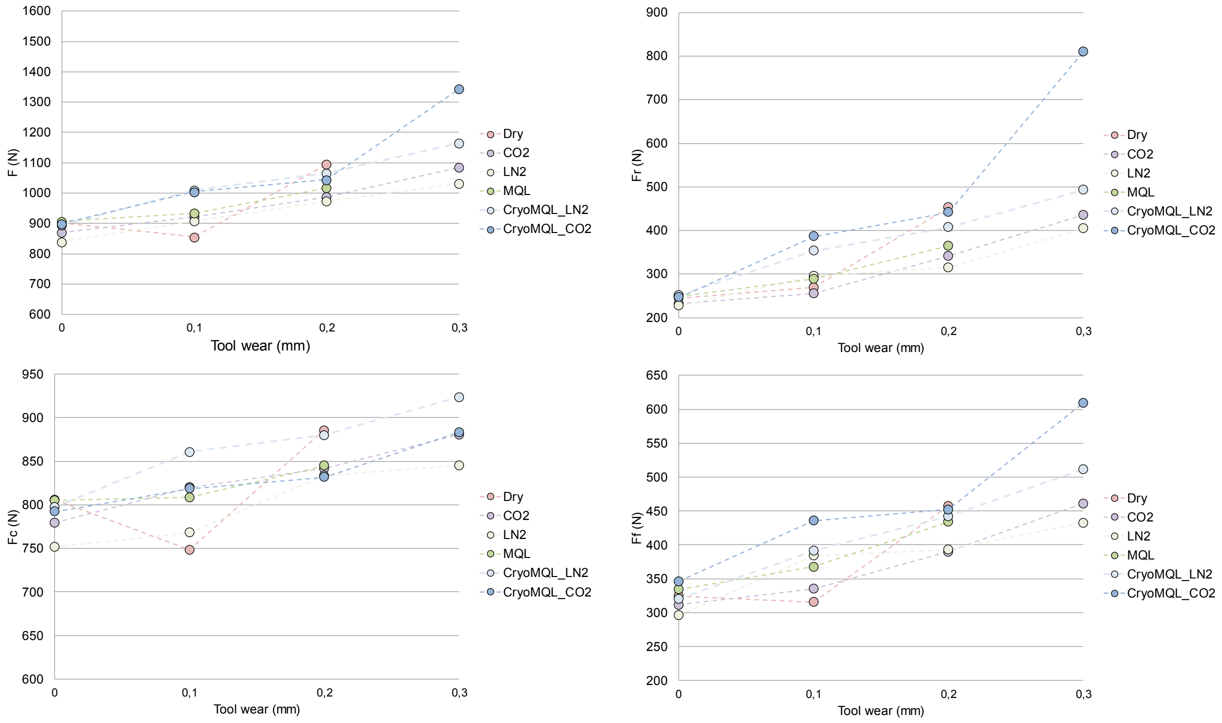

Fig. 4. Cutting forces for the different tested cooling alternatives.

Table 2
Calculation of confidence interval (T-Student).

	Radial force (F_r)		Cutting force (F_c)		Feed force (F_f)	
	CryoMQL_LN$_2$	CryoMQL_CO$_2$	CryoMQL_LN$_2$	CryoMQL_CO$_2$	CryoMQL_LN$_2$	CryoMQL_CO$_2$
Total average (X)	353.27	471.88	861	828.35	402.09	455.50
Quasi standard deviation (S_c)	258.05	76.18	43.62	35.17	120.78	61.03
$V_b = 0.1$ mm	352.43	385.69	860.80	818.31	391.07	435.90
$V_b = 0.2$ mm	407.35	441.28	880.23	831.60	442.64	452.34
$V_b = 0.3$ mm	492.99	809.30	923.61	883.40	511.58	609.13
Confidence level = 90%						
Grades of Freedom (CryoMQL_LN2) $= 9 \rightarrow \textit{T student table value}\left(t_{n\text{-}1,\frac{\alpha}{2}}\right) = 1.592$						
Grades of Freedom (CryoMQL_CO2) $= 6 \rightarrow \textit{T student table value}\left(t_{n\text{-}1,\frac{\alpha}{2}}\right) = 3.707$						
Confidence interval $= \left[X - t_{n-1,\frac{\alpha}{2}} \cdot \frac{S_c}{\sqrt{n}} \le \mu \le X + t_{n-1,\frac{\alpha}{2}} \cdot \frac{S_c}{\sqrt{n}}\right]$ ***; where*** μ ***is force value***						
$X\text{-}t_{n\text{-}1,\frac{\alpha}{2}} \cdot \frac{S_c}{\sqrt{n}}$	307.26	110.33	839.76	767.23	365.23	286.28
$X + t_{n\text{-}1,\frac{\alpha}{2}} \cdot \frac{S_c}{\sqrt{n}}$	399.28	833.44	882.25	889.47	438.96	624.73

using MQL and CryoMQL_CO$_2$ with an improvement of 40.6%; both lubri-coolant technologies provide 1.45 μm for R_a in the stable zone. Regarding R_z, the values obtained in this stage are quite similar with these lubri-coolant technologies, meaning and improvement of ≈18%. Theoretical roughness values were obtained using the following equations (Kant and Sangwan, 2014; Shaw, 1984):

$$R_z = f^2/(8 \cdot r_{insert}) \tag{1}$$

$$R_a = R_z/4 \tag{2}$$

Where R_a is the average roughness and R_z is the mean value of five consecutive maximum heights between peak-valley. Both values are measured in micrometers. On the other hand, f is the feed per revolution (mm/rev) and r_{insert} is the insert radius measured in millimeters.

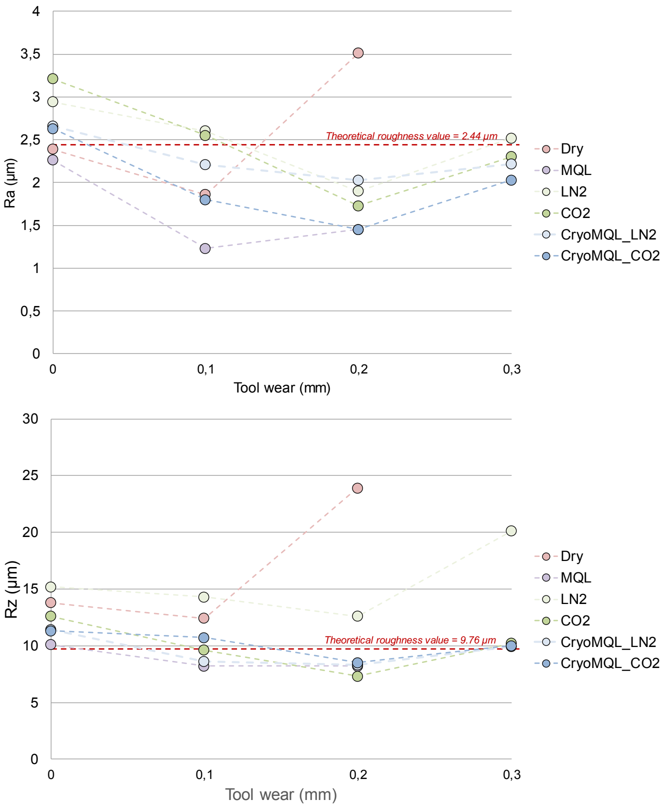

Fig. 5. Surface roughness parameters based on tool wear.

Apart from the roughness parameters, it is also important to analyze the surface topography. 3D topographies of DRY and CryoMQL_CO$_2$ surfaces are shown in Fig. 6, selected as the most representative ones when tool wear is 0.2 mm. Results obtained show that using CryoMQL, the typical surface turning pattern was perfectly generated. This implies a stable and controllable cutting process. For DRY machining, results show a deformation process of the peaks and valleys of the roughness profile. This fact implies some negative aspects such as: bigger deformed affected layer, non-uniform surface roughness and probably a lack of tool life.

Microstructural analysis is essential to determine the affected zone during machining, if exists. In Fig. 7, the microstructure of two specimens using DRY machining and CryoMQL_CO$_2$ machining are presented. Specimens were obtained from the test part when the tool has approximately in the middle of their whole life (V_b ≈ 0.15–0.2 mm). Results show that using DRY machining, the thickness of the deformed layer is notably bigger than using combined techniques (≈30 μm of affected zone for DRY machining and less than 10 μm using cryogenic alternatives). This fact is extremely important when dealing with high added value components and high responsible ones, such as engine components or similar.

Deformed layer can affect notably to the surface and sub-surface hardness, just as shown in Fig. 8. Values were taken each 40 μm till 200 μm depth. A lateral displacement of 30 μm was used between measures to avoid any distortion coming from previous measurements. Hardness of the material used in tests round 200-210 HBN in raw conditions. After machining using different cooling techniques, results of hardness vary. Austenitic steels suffer strain hardening after machining and this phenomena is increased when used wear tools or a non-appropriate cooling technology. Results show that the higher hardness values appear on the surface for DRY conditions. This is coherent with previous results of affected layer obtained in microstructure analysis. Besides, raw material hardness is reached at 200 μm only when MQL or LN$_2$ are applied. However, despite subsurface microhardness obtained with both CryoMQL techniques are over the raw material hardness, it is improved 11% in comparison with DRY machining, which is taken as reference.

Results obtained in experimental tests (tool wear behavior, cutting forces and surface integrity) demonstrate that the alternatives presented in this paper are feasible for turning AISI 304 stainless steel. Concretely, near-to-dry techniques, such as CryoMQL_CO$_2$ machining is an interesting and technically viable alternative to achieve and eco-efficient process. Once analyzed technical aspect, the next step is to consider ecological aspects and sustainability. For this purpose, a Life Cycle Assessment (LCA) comparing the near-to-dry proposed alternatives and the

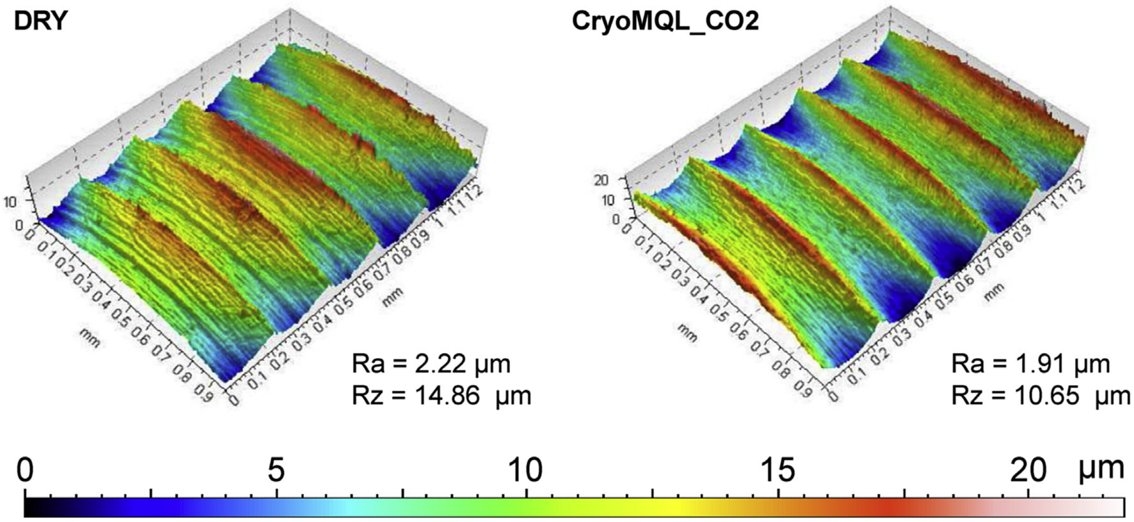

Fig. 6. Surface topology for the different tested cooling alternatives.

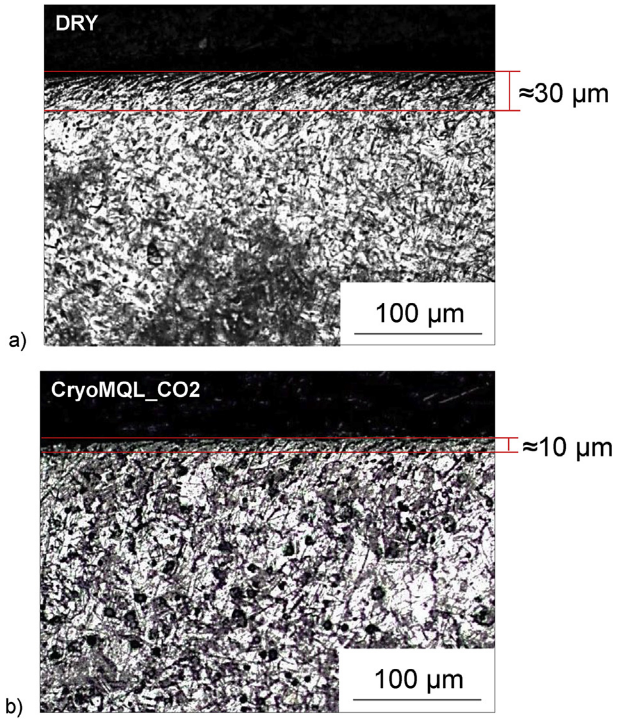

Fig. 7. Microstructure after turning using DRY conditions (a) and CryoMQL_CO_2 conditions (b). Deformed layer thickness.

conventional ones (cutting fluids and oil) are developed in this work. LCA takes into account the environmental impact caused by each cooling technique when turning AISI 304. Thus, an objective eco-comparison can be performed under the same conditions.

4. Life cycle assessment of advanced lubri-coolant technologies

The turning process of a bar of AISI 304 was considered as function system for the LCA. Function unit was established as the chip volume obtained when a part is turned from Ø59 mm to Ø32 mm using a cutting length of 150 mm. This value was 290,094.67 mm^3. System boundaries are shown in Fig. 9. Unit processes are defined based on their importance in the turning process. Differences between the use of a conventional cooling techniques and a near-to-dry machining are also show. Inside the system boundaries; cutting fluid production and electrical power consumption during the turning process were included; and if necessary, chip cleaning process and cutting fluid elimination treatment. Other unit processes were established outside the system boundaries because they do not modify the global results significantly. These processes values are similar for each cooling technology because they are independent of them. In particular, the omitted processes were the production of AISI 304 blanks, the machined parts reused process, the guides oil and the tools treatment once their useful life is finished. Although the heat generated in the cutting zone changes with each cooling technique, it was omitted because from an environmental point of view it is insignificant.

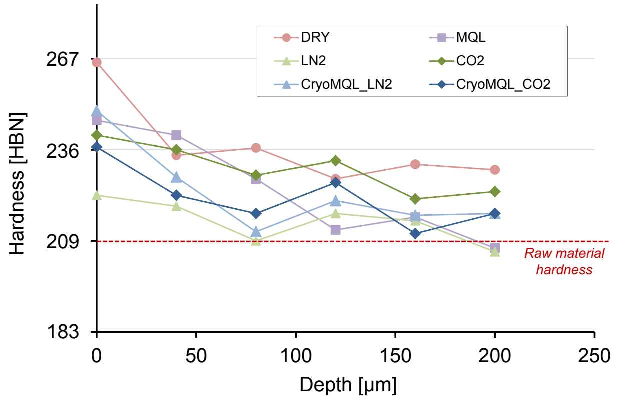

Fig. 8. Surface hardness and subsurface microhardness.

Allocation processes for each unity process, both inside and outside the system, were classified based on its origin. In the one hand, they are material unity processes, such as the blank, tools, parts and chips. On the other hand, the energetic unity process was the power consumed by the lathe. Finally, the most important environmental unity processes were defined as: generation, use and treatment of cutting fluids; chip cleaning processes and; if necessary, fog extraction out of the machine.

Although the impact categories related with the turning process

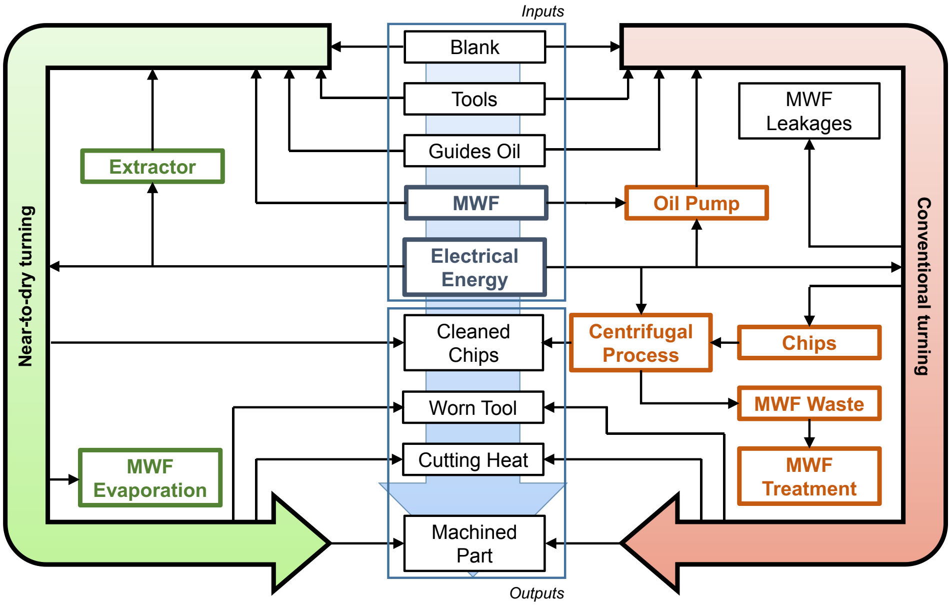

Fig. 9. System boundaries defined for the LCA.

were selected from the ISO14047:2003 standard, the TRACI methodology was used to analyze these categories (Wang and Yuan, 2014; Saer et al., 2013). Therefore, results indicators and characterization factors were selected from this methodology. This choice is made because using this method, apart from reflecting the environmental impact; a greater emphasis is put in human toxicity with regard to other methodologies.

This LCA is mainly based on 6 assumptions:

- Tools used during machining. The wear is supposed the same, as proposed in (Pusavec et al., 2010). Furthermore, despite the insert coating produces a high environmental impact; it is outside the system boundaries. If this impact is distributed along the tool life, it is insignificant with respect to the other unity processes, as claim in (Fratila, 2010).
- Cutting fluid leakages. Only leakages produced by the mineral oil emulsions were taken into account. This is because cryogenic coolants evaporate without any waste generation when they are injected. Oil used with MQL systems is also negligible and it is biodegradable. In the case of mineral oil emulsions, leakages produced by cleaning processes, losses, dirt, etc. have been omitted. In other words, there was taken into account only leakages produced by the emulsion adhesion to the chips. This is because other leakages are negligible, even returnable, in comparison with the emulsion dragged by the chips.
- Cutting fluid treatments once its useful life is finished. Only data about 1 kg of mineral oil emulsion treatment was collected. It should be noted that the subsequent treatment is different depending on the geographic region (IHOBE, 2015; PRTR, 2015). Usually, the process to remove the organic material out of the exhausted mineral oil emulsion consists on an ultra-filtering, put through inverse osmosis, dilution and biological degradation. Finally, depending where it is processed, it is inerted and eliminated in a dumping site or it is recycled. In this last case, it is turned into SN-80 base oil, hydrocarbons and heavy naftas. Due to this diversity, Chalmers University's generic data were chosen as basis (Strandberg and Wik, 1999).
- CO_2 as cutting fluid. There are no greenhouse gases emissions produced by this cryogenic gas. As aforementioned, the CO_2 is obtained from a primary process and it is not generated specifically for the machining process. In this way, it is conserved the "green machining" philosophy associated to cryogenic cooling techniques.
- Power consumption was analyzed according to the Spanish state energetic mix. It is important to take into account this fact to differentiate between the so-called "energy green technologies" and the conventional energies, which produce more impact. In Spain, data about the mix used to produce the electricity are provided by the REE annual report (REE = Spanish Electricity Network). In this case, the last report published in 2013 was used in the LCA.
- Data here presented do not exceed 15 years old and comes from OCDE countries. This assumption was established with the aim of doing the life cycle assessment as realistic as possible.

Based in these assumptions, the impact categories used, and data found in literature (Bart et al., 2013; REE, 2013; McManus, 2011; Strandberg and Wik, 1999), the environmental impact was calculated to: i) generate 1 kg of each cutting fluid; ii) to treat 1 kg of exhausted mineral oil emulsion; iii) to generate 1 kW of electricity according to the energetic mix. Results are shown in Table 3.

In order to quantify the power consumption, the 3 lathe servomotors consumption was measured (spindle, feed axis and radial axis, respectively) with each cooling technology. Consumption during machining and consumption during empty movements were measured. Moreover, power consumption by the peripherals devices during turning was also measured. Consumption made by the pumps or cyclones was also measured. Furthermore, under wet machining conditions a centrifuge was used with a power of 4 kW and capacity to dry between 300 and 650 kg/h of steel chips. The final humidity of the dry chips was between 1 and 4%. Although in most of the cases the chips drying process is made in a recycling plant, this step was also considered. It is because some companies are now installing centrifuges with the aim of obtaining more profit by selling the chips completely clean. On the other hand, when machining with MQL or cryogenic gases, the centrifuge is unnecessary. However, it is necessary a cyclone to evacuate the gases and to filter the generated fog, respectively. The cyclone has 0.5 kW of power and it filters 800 m^3/h. Table 4 shows the environmental impact caused by each cooling technique based on the machining

Table 3
Environmental impact caused by the production/generation of each unit process.

Impact category	Impact units	1 kg of canola oil	1 kg of mineral oil	1 kg of LN_2	1 kg of CO_2	1 kg of exhausted mineral oil emulsion treatment	1 kW of electricity generation
Global Warming	kg CO_2-eq	−0.36	3.56	0.431	0.816	4.52	0.632
Acidification	H+ moles-eq	2.7	0.46	0.101	0.106	0.602	0.137
Carcinogenics	kg benzene-eq	0.006	0.003	$2.26 \cdot 10^{-4}$	$2.21 \cdot 10^{-4}$	0.0011	$9.84 \cdot 10^{-4}$
Non carcinogenics	kg toluene-eq	33.4	14.3	4.86	6.07	11.5	12.4
Respiratory effects	kg PM 2.5eq	0.005	0.002	$6.23 \cdot 10^{-4}$	$6.53 \cdot 10^{-4}$	0.00185	$1.96 \cdot 10^{-4}$
Eutrophication	kg N eq	0.076	0.002	$7.15 \cdot 10^{-5}$	$2.7 \cdot 10^{-4}$	0.031148	$1.4 \cdot 10^{-4}$
Ozone depletion	kg CFC-11-eq	$2.8 \cdot 10^{-7}$	$6.5 \cdot 10^{-7}$	$2.13 \cdot 10^{-8}$	$5.45 \cdot 10^{-8}$	$2.37 \cdot 10^{-7}$	$3.77 \cdot 10^{-8}$
Ecotoxicity	kg 2,4-Diclorobenzen eq	1.78	1.22	1.01	0.828	40.23	0.507
Smog	kg NO_x eq	0.023	0.003	$7.25 \cdot 10^{-4}$	$8.5 \cdot 10^{-4}$	0.005	0.001

times and power collected during the tests.

Once calculated the environmental impact caused by the power consumption, the fluid cutting consumption was calculated for each cooling technique. On the one hand, the injected flow rate was measured when using MQL and cryogenic machining. The consumption of oil per machined part was 4.82 grams/part in MQL. However, when using cryogenic technology the flow rate was 1122 grams/part in the case of CO_2 and 1309 grams/part in the case of LN_2. On the other hand, the leakages dragged by the chips were calculated when using mineral oil emulsions. The percentage of lost as a function of the chips weight was 7.6%, that is, 174.147 grams/part. Besides, the mineral oil emulsion useful life was taken into account. It was estimated in 2016 h, that is, 2 shifts of 8 h during 126 working days.

With the generated data, the total environmental impact caused by each cooling technology was calculated from its production, through its use, to its elimination based on the function reference. Fig. 10 shows a kiviat diagram with the results calculated in the LCA. In this diagram, a general perspective of the environmental impact caused for each cooling technology during the AISI 304 turning can be observed.

From an environmental point of view, the alternatives to wet machining can be classified into 3 groups with similar environmental impact. The most efficient group was dry machining and the use of the MQL system as coolant. The second most efficient group was cryogenic machining with LN_2 or CO_2. And finally, CryoMQL with LN_2 and CO_2.

In the first group there were little differences. The first one is that with dry machining, there is a higher power consumption which causes an increment of 8.3% in the kilograms of generated toluene equivalent (kg toluene-eq). However, in the case of machining with MQL, there were 8 times more generation of kilograms of nitrogen equivalent (kg N-eq) than with dry machining due to biodegradable oils production. Also, it should be noted that canola based oil was used in the MQL system. This fact causes that the kilograms of CO_2 equivalent (kg CO_2-eq) in its production were negative. This is the reason why this impact category is lower for MQL than for dry machining.

Regarding cryogenic machining in stand-alone mode, the reason of the great difference between the use of LN_2 or CO_2 is in their production processes more than in their use during the machining. In fact, the power consumed during the turning when using the two gases was similar. The greatest differences were got in some impact categories, such as global warming, respiratory effects and ozone depletion. In particular, a 17% less kilograms of benzene equivalent (kg benzene-eq) was obtained with CO_2 than with LN_2. Also with CO_2, the kilograms of particles minor than 2.5 μm (kg PM 2.5-eq) were an 11% below that the generated with LN_2. On the other hand, mainly due to the LN_2 liquefaction process, it was spilled out a 43% less of kg CO_2-eq with LN_2 than with CO_2. Also, LN_2 was a 55% more efficient in the generation of kilograms of CFC-11 equivalent (kg CFC-11-eq).

Due to two factors, the use of CryoMQL technologies with LN_2 or CO_2 as coolants presents analog environmental similarities to the use of these gases in stand-alone mode. The first one is that the environmental impact generated by the cutting fluids production is calculated with the addition of the biodegradable oil production and the respective cryogenic gas used. The second one is that the power consumption during the machining between both is similar.

Finally, the use of mineral oil emulsions shows the highest environmental impact in comparison with other cooling techniques. Although mineral oil emulsions have a lower environmental impact with regard to respiratory effects and non-carcinogenics impact categories, in other categories such as generated ecotoxicity and eutrophication were obtained values over 630% and 760%, respectively. If these figures are combined with the other impact categories, it can be observed that mineral oil emulsions are the most inefficient from an environmental point of view.

Table 4
Environmental impact caused by power consumption.

Impact Category	Impact units	Dry machining	Wet machining	MQL	CO_2	LN_2	CryoMQL_CO_2	CryoMQL_LN_2
Global warming	kg CO_2-eq	0.202	0.193	0.178	0.164	0.189	0.181	0.183
Acidification	H+ moles-eq	$4.38 \cdot 10^{-2}$	$4.18 \cdot 10^{-2}$	$3.87 \cdot 10^{-2}$	$3.5 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$3.92 \cdot 10^{-2}$	$4 \cdot 10^{-2}$
Carcinogenics	kg benzene-eq	$3.2 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$2.6 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$	$2.8 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
Non carcinogenics	kg toluene-eq	3.97	3.78	3.5	3.22	3.71	3.55	3.6
Respiratory effects	kg PM 2.5eq	$6.27 \cdot 10^{-5}$	$5.98 \cdot 10^{-5}$	$5.53 \cdot 10^{-5}$	$5.09 \cdot 10^{-5}$	$5.89 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$5.69 \cdot 10^{-5}$
Eutrophication	kg N eq	$4.48 \cdot 10^{-5}$	$4.27 \cdot 10^{-5}$	$3.95 \cdot 10^{-5}$	$3.63 \cdot 10^{-5}$	$4.18 \cdot 10^{-5}$	$4 \cdot 10^{-5}$	$4.06 \cdot 10^{-5}$
Ozone depletion	kg CFC-11-eq	$1.21 \cdot 10^{-8}$	$1.15 \cdot 10^{-8}$	$1.06 \cdot 10^{-8}$	$9.79 \cdot 10^{-8}$	$1.13 \cdot 10^{-8}$	$1.08 \cdot 10^{-8}$	$1.09 \cdot 10^{-8}$
Ecotoxicity	kg 2,4-Diclorobenzen eq	0.162	0.155	0.143	0.132	0.152	0.145	0.147
Smog	kg NO_x eq	$3.49 \cdot 10^{-4}$	$3.33 \cdot 10^{-4}$	$3.08 \cdot 10^{-4}$	$2.83 \cdot 10^{-4}$	$3.26 \cdot 10^{-4}$	$3.12 \cdot 10^{-4}$	$3.16 \cdot 10^{-4}$

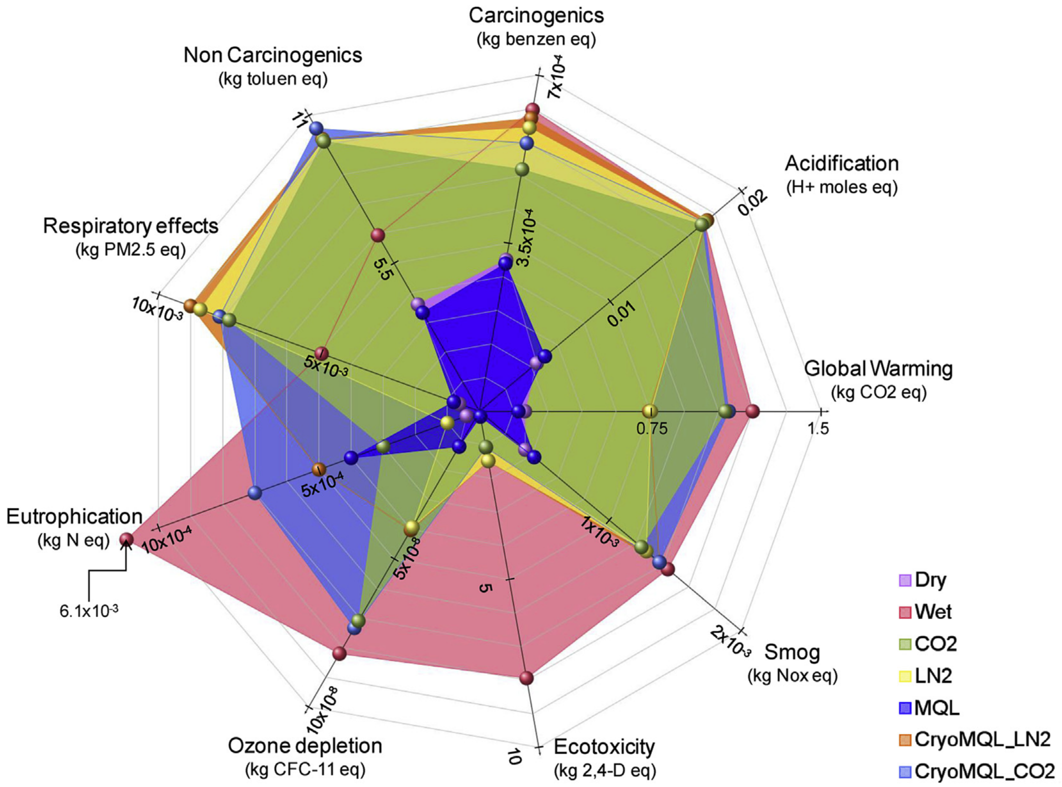

Fig. 10. Cutting fluids environmental impact.

5. Conclusions

In this paper, technical and ecological viability of a wide range of lubri-coolant technologies is analyzed when turning AISI 304 stainless steel. Authors propose CryoMQL solution as a combined technique based on applying cryogenic gases and minimum quantity of lubrication at the same time during machining. The main conclusions obtained from theoretical studies and experimental tests are listed below:

- Advanced lubri-coolant technologies are necessary to eliminate or minimize conventional coolant and cutting oils during stainless steel machining. Dry machining is not a feasible solution because tool wear rates in dry machining are not acceptable for this kind of difficult-to-cut materials.
- Regarding technical issues among the analyzed lubri-coolant technologies, similar results were obtained during the experimental tests. However, despite average surface roughness values are below the theoretical value with all lubri-coolant technologies, MQL and CryoMQL_CO_2 machining obtain the best results when tool wear reaches 0.2 mm. In this stage the improvement with both lubri-coolant technologies is 40% in comparison with the theoretical value.
- From an ecological point of view, LCA demonstrates that cryogenic techniques and minimum quantity of lubrication techniques are more eco-friendly than conventional wet machining. Best results are achieved by MQL, LN_2, CO_2 and CryoMQL, respectively in this order.
- Stand-alone techniques, such as CO_2, LN_2 or MQL, are not enough for a complete solution. Both, lubrication and refrigeration are necessary when machining these difficult-to-cut materials. Tool wear rates in these cases are not good enough to substitute conventional wet machining.
- Then, CryoMQL using CO_2 as cryogenic gas is the feasible alternative to minimize the use of conventional coolant. Although MQL is the most ecofriendly lubri-coolant technique, with CryoMQL_CO_2 the tool life is exceeded in a 30% and doubled in comparison with dry machining. Besides, with this near-to-dry technique, machinists may be favored by the numerous advantages that this technique provides, such as elimination of conventional coolants, dry chip generation, coolant costs minimization and other important ecological advantages. Therefore, taking into account technical, industrial and ecological factors, results show that CryoMQL technique is the most suitable alternative in a medium-short term to substitute conventional wet machining. Using CryoMQL, equilibrium between technical and ecological factors is achieved.

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