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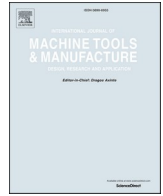
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# A novel cryogenic machining concept based on a lubricated liquid carbon dioxide

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## ABSTRACT

A novel single-channel supply of pre-mixed (a) liquid carbon dioxide (LCO<sub>2</sub>) and (b) oil – delivered via minimum quantity lubrication (MQL) – represents a significant advancement in cryogenic-machining technology. In this proof-of-concept study, an attempt is made to advance the understanding of the oil solubility in LCO<sub>2</sub> and to analyze the oil-droplets and their impact on machining performance. The results indicate that the physical and chemical properties of oil distinctively affect its solubility in LCO<sub>2</sub>. The achieved solubility further influences the achievable oil-droplet size and distribution and tool life.

## 1. Introduction

A recent approach to improve cooling and lubrication in cryogenic machining is the use of liquid carbon dioxide (LCO<sub>2</sub>) in combination with oil, delivered via minimum quantity lubrication (MQL) [1]. The currently available and state-of-the-art cryogenic-machining systems feature a separate, two-channel supply of the media. This method provides improved machinability in comparison to dry and/or MQL machining [2,3]. However, the two-channel supply systems are subject to potential difficulties associated with interactions between the two media (CO<sub>2</sub> and MQL) due to (i) LCO<sub>2</sub> expansion, and (ii) the difference in the pressure and the velocity in media, which can lead to insufficient cooling and lubrication as revealed by a shorter tool life compared to flood lubrication [4]. In addition, the implementation of the two-channel method requires tailored cutting-tool design, where multiple inner channels (nozzles) need to be carefully oriented to enable separate media delivery [5]. This is especially challenging in the case of tools with smaller diameters. On the other hand, the existing single-channel supply systems are characterized by high energy consumption and/or high CO<sub>2</sub> consumption (up to 650 g/min) due to: (i) external CO<sub>2</sub> pre-heating and pressurizing to achieve supercritical CO<sub>2</sub> [6,7], (ii) the application of gas and liquid CO<sub>2</sub> phases simultaneously (under pressure) to control the media delivery [8], and (iii) external oil pressurizing to ensure oil flow into the CO<sub>2</sub> [9]. This necessitates the need of developing a less complex, single-channel method for integrated delivery of pre-mixed LCO<sub>2</sub> and oil under typical LCO<sub>2</sub> conditions

( $p = 57 \text{ bar} = 5.7 \text{ MPa}$ ,  $T = 20 \text{ }^\circ\text{C} = 293.15 \text{ K}$ ). The requirement specifications for this technique are ease of implementation, moderate CO<sub>2</sub> consumption (up to 250 g/min) and no need for CO<sub>2</sub> pre-heating.

The objective of this paper is to report the technical details of the single-channel delivery of lubricated LCO<sub>2</sub> with respect to achieving the required solubility of oil and droplet size/distribution. The research background concerning oil solubility in CO<sub>2</sub> [10–12] and oil droplets [13–15] is rather limited in manufacturing science – and non-existent for the specific application of cryogenic machining. Therefore, the following proof-of-concept experiments are provided for validation and further development of the technology, namely: (i) solubility of different oils in LCO<sub>2</sub> using a high-pressure mixing chamber; (ii) solubility of different oils in LCO<sub>2</sub> flow; and (iii) investigation of oil-droplet size and distribution; followed by (iv) preliminary tool-life testing in a machining trial.

## 2. Concept

The novel cryogenic machining concept based on a single-channel, lubricated, LCO<sub>2</sub> is illustrated schematically in Fig. 1. The system enables a continuous supply of lubrication media into the LCO<sub>2</sub> flow, wherein the LCO<sub>2</sub> is supplied directly from the LCO<sub>2</sub> cylinder. In this system, a mixture of LCO<sub>2</sub> and lubrication media is obtained, wherein the flow of LCO<sub>2</sub> and lubrication media can be precisely controlled separately by two flow meters and needle valves [16]. Moreover, the concept is operable with any lubrication media in any state, such as oil

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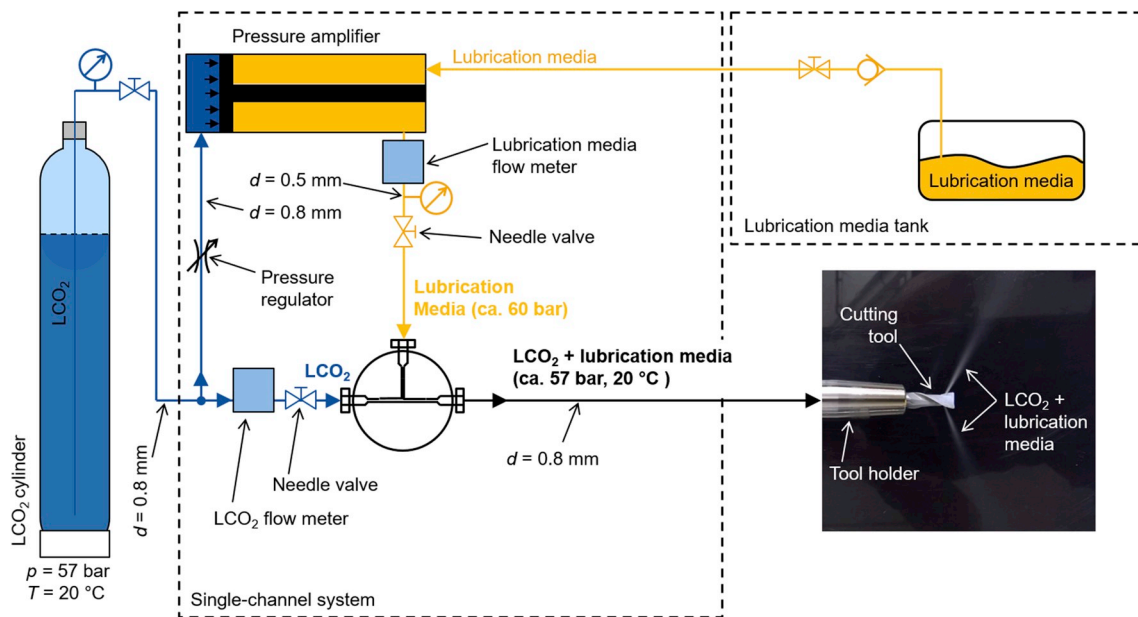


Fig. 1. Schematic illustration of a novel cryogenic machining system based on single-channel, lubricated, liquid carbon dioxide (patent pending, EU-LU101232, Luxembourg, 2019).

or solid lubricant. For the proof of the concept here, oil in liquid state was used. To obtain a flow of the lubrication media into the LCO<sub>2</sub> at room temperature (20 °C = 293.15 K) and pressure (57 bar = 5.7 MPa), the lubrication-media pressure needs to be at least 60 bar (6.0 MPa). This is achieved by the innovative solution for pressure regulation and amplification, which uses the available pressure of LCO<sub>2</sub> to shift the lubrication media to a higher pressure without any external energy source. Both media are then simultaneously delivered into the mixing zone before exiting the system as a controlled mixture of LCO<sub>2</sub> and lubrication media in a single-phase flow.

### 3. Theoretical background

Solubility characterizes the amount of a gaseous or liquid substance (solute) that can dissolve in a solvent to form a solution. Solubility depends on each substance involved, i.e. the physical and chemical properties of the solute and the solvent. In general, liquids with similar solubility parameters are more compatible – and a better solubility is expected between substances with similar polarity. Solubility can be defined as  $S = m_{\text{solute}}/m_{\text{solution}}$ , where  $m_{\text{solute}}$  is the mass of the solute, which is uniformly dissolved in the solution, and  $m_{\text{solution}}$  is the mass of a mixture, in which the solute is uniformly distributed within the solvent. Solubility is typically expressed as grams of solute per gram of solution. Other commonly used units include g/l (grams of solute per liter of solution) and mol/l (moles of solute per liter of solution).

Solubility is not affected by viscosity. However, the dissolution rate – i.e. how quickly the dissolution occurs can be affected by viscosity. In general, a higher viscosity leads to a decrease in the dissolution rate but does not change the solubility. Moreover, solubility is temperature dependent. In case of gases, solubility typically decreases with increasing temperature because of the higher kinetic energy of the molecules at higher temperature. In contrast, the solubility of solids and liquids increases with increasing temperature due to higher energy “stored” in the solution. Finally, the pressure dependency of solubility for solids and liquids is typically weak and, in practice, is usually neglected [17,18].

Based on the fundamentals described above, the solubility of liquids is influenced by polarity and temperature. However, solubility of liquid oil in liquid CO<sub>2</sub> is expected to be influenced only by polarity of the oil because the temperature is governed by the liquid state of CO<sub>2</sub> before cryogen expansion, i.e. at a constant temperature of 20 °C (293.15 K).

### 4. Experimental proof of concept

The purpose of the experimental work was to demonstrate proof-of-concept, where four different types of oil (in liquid state) were used as a lubrication media and mixed with LCO<sub>2</sub>. The properties of the oils are given in Table 1.

The experimental setup is shown in Fig. 2. A high-pressure mixing chamber consists of an aluminum base with two acrylic glass covers. The

Table 1  
Physical and chemical properties of LCO<sub>2</sub> and oils.

	LCO <sub>2</sub>	Base oils without additives		Special oils designed for MQL use	
		Oil A	Oil B	Oil C	Oil D
Physical state at 20 °C	Liquid (at 57 bar)	Liquid	Liquid	Liquid	Liquid
Color	Colorless	Light yellow	Clear and Bright	Amber	Clear yellow
Odor	Odorless	Faintly perceptible	Characteristic	Weak, characteristic	Characteristic
Chemical characterization	Liquid gas	Vegetable oil, low in erucic acid	Highly branched isoparaffinic PAO <sup>a</sup>	Mixture of esters and additives	N/A
Density at 20 °C in g/cm <sup>3</sup>	0.77	0.91	0.83	0.90	0.87
Kin. viscosity in mm <sup>2</sup> /s	0.09	72 (20 °C)	30.5 (40 °C)	ISO 279 22 (40 °C)	ISO 279 3.5 (20 °C)
Polarity	Nonpolar	Polar	Nonpolar	ISO 3104 Polar	ISO 3104 Nonpolar

<sup>a</sup> PAO - Polyalphaolefin.

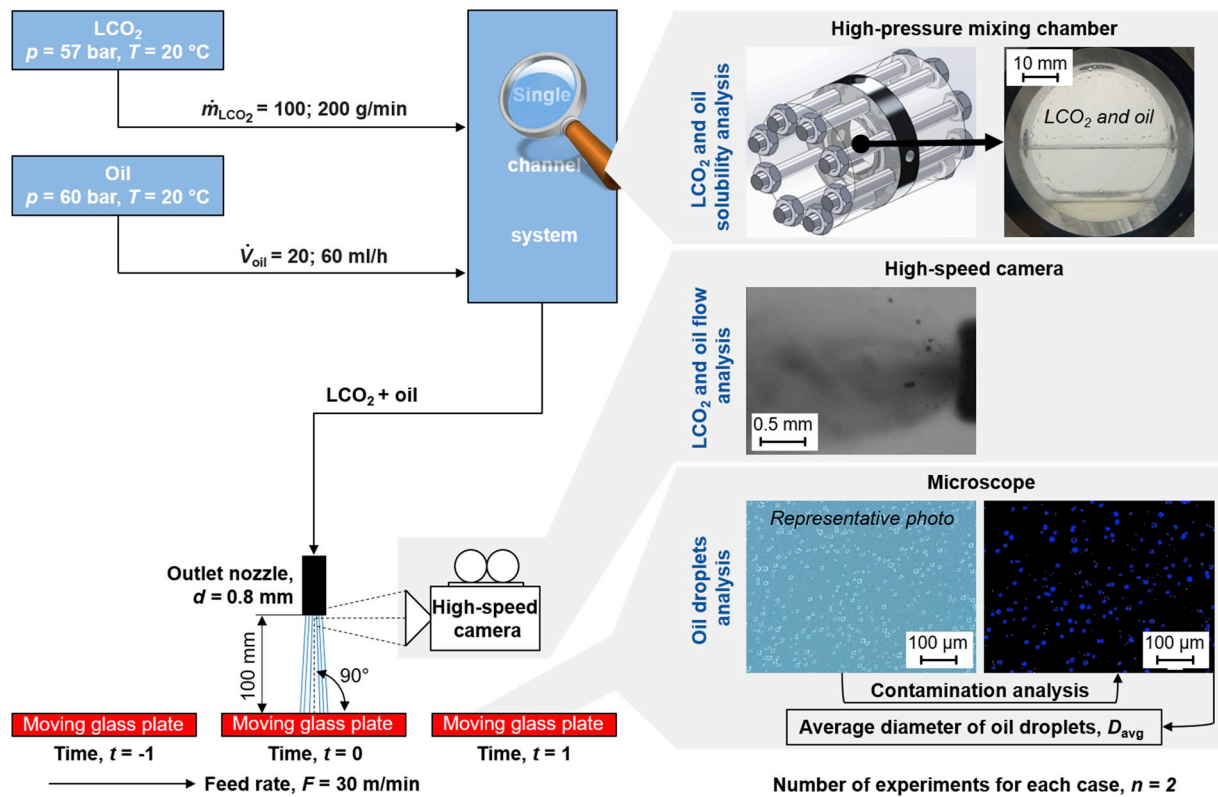


Fig. 2. Illustration of the experimental setup.

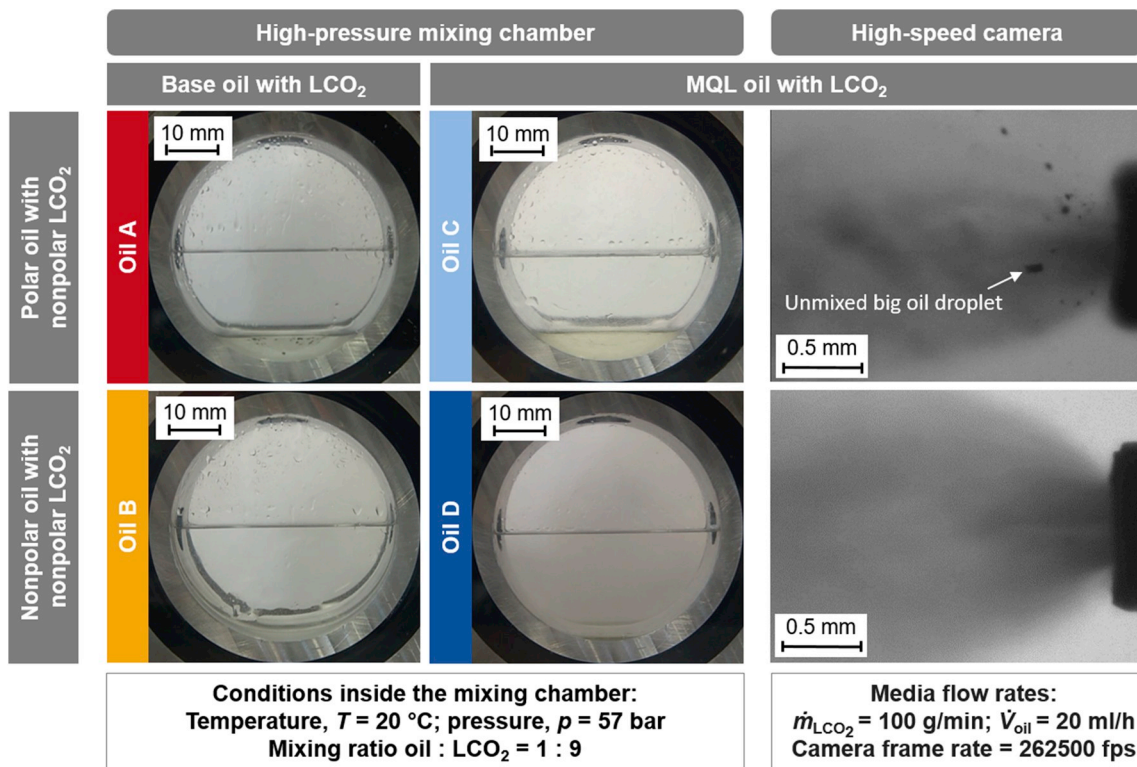


Fig. 3. Investigation of oil polarity on solubility of liquid oil in LCO<sub>2</sub> using high-pressure mixing chamber and high-speed camera.

volume ratio of oil to LCO<sub>2</sub> was 1:9. To investigate solubility, oil was first added to the mixing chamber, followed by LCO<sub>2</sub> (at  $p = 57 \text{ bar} = 5.7 \text{ MPa}$ ;  $T = 20 \text{ °C} = 293.15 \text{ K}$ ), up to the total volume of

$V = 16 \text{ ml}$ , which is half of the maximum capacity of the chamber.

For the first assessment, the solubility of oil was examined visually through images that were captured immediately after the LCO<sub>2</sub> was

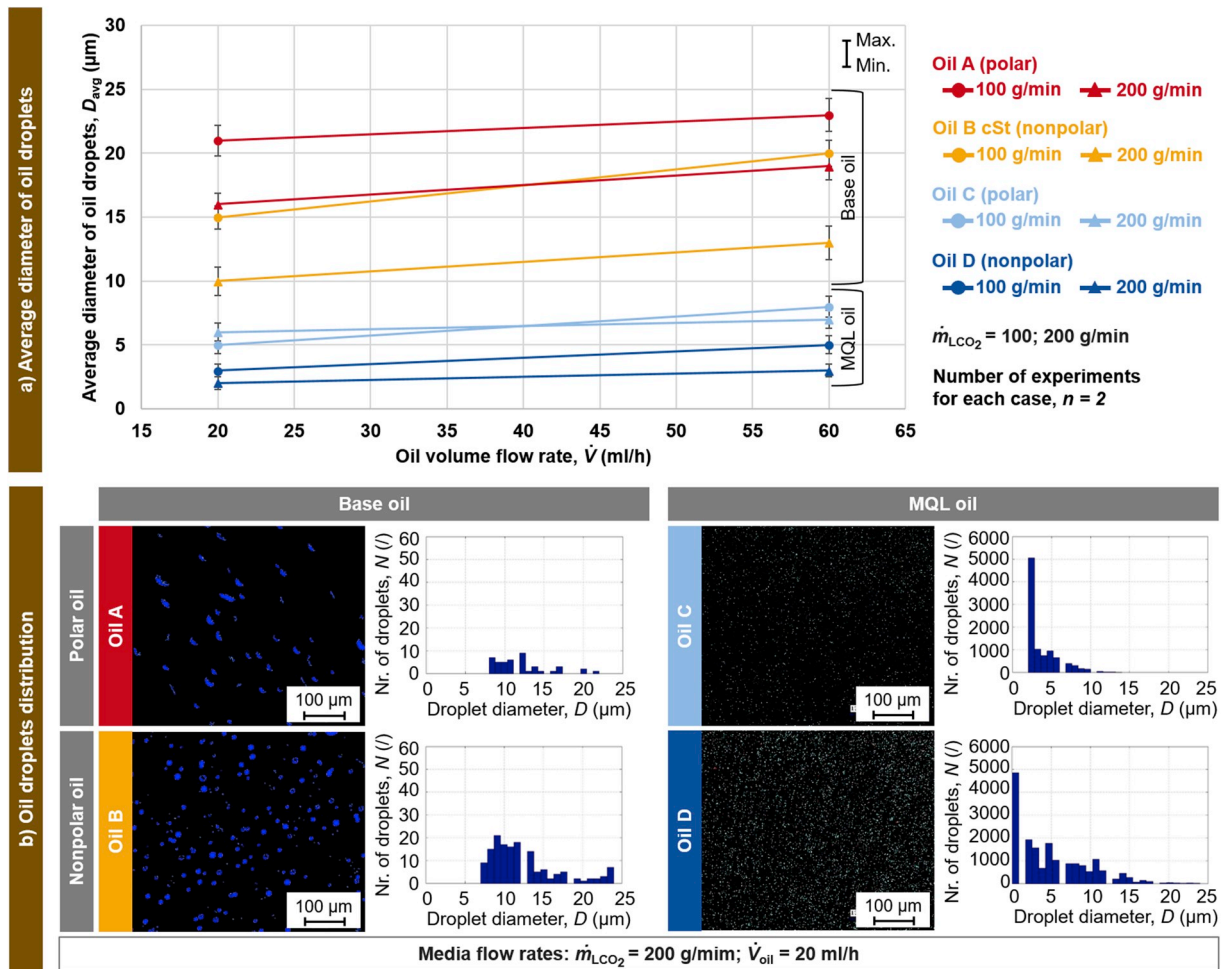


Fig. 4. Influence of LCO<sub>2</sub> mass flow rate and oil volume flow rate on a) average diameter of oil droplets; and b) oil droplets distribution.

added to the chamber (see Fig. 3 showing the effect of oil polarity on solubility). As expected, nonpolar oils are more soluble in LCO<sub>2</sub>. Moreover, nonpolar base oil (oil B) and nonpolar MQL oil (oil D) are completely soluble in LCO<sub>2</sub> (i.e. totally miscible). However, it can be seen on the bottom of the mixing chamber that a small portion of the oil B is left unmixed, indicating saturation. In contrast, saturation has not been observed for nonpolar oil D that includes additives. This is indicating that certain additives (confidential) can increase oil solubility in LCO<sub>2</sub> and prevent saturation.

A more comprehensive proof of concept involves solubility in a real application, i.e. the outlet nozzle for cryogenic machining. Here, the selected LCO<sub>2</sub> mass flow rates were  $\dot{m}_{\text{LCO}_2} = 100$  and  $200 \text{ g/min}$ , based on a typical operation [4,19]. Oil volume flow rates were set to  $\dot{V}_{\text{oil}} = 20$  and  $60 \text{ ml/h}$ , according to the usual MQL oil consumption [13,20,21], in a variety of machining operations, including grinding. The solubilities of oils were first investigated at the outlet nozzle using a high-speed camera (measuring area  $512 \times 384$  pixels; frame rate of 67500 fps). Here, the superior solubility of nonpolar oil in LCO<sub>2</sub> is visible as it is not possible to spot fragments of unmixed oil droplets in the flow, as opposed to polar oils. Next, the outlet nozzle was mounted inside a machine and positioned vertically at a distance of  $L = 100 \text{ mm}$  from the center of a moving glass plate (mounted on the XY table of the machine). The glass plate was moved with a feed rate of  $F = 30 \text{ m/min}$  crossing the (vertical) LCO<sub>2</sub> + oil flow. As the LCO<sub>2</sub> immediately evaporated, the remaining oil droplets on the glass surface were analyzed using a digital microscope.

To further investigate the influence of system parameters on achievable oil droplets, the LCO<sub>2</sub> and oil flow rates were varied as shown

in Fig. 4a. It can be seen that a higher oil-volume flow rate results in larger oil droplets. Upon hitting the surface, the droplets can merge with each other and form clusters with a large diameter. On the other hand, LCO<sub>2</sub> can further split droplets into multiple smaller droplets; which occurs at higher mass flow rates of LCO<sub>2</sub>. This is caused by higher velocity of the LCO<sub>2</sub> carrier media, which results in a higher velocity of the pre-mixed LCO<sub>2</sub> and oil at the nozzle outlet. In addition, with the increase of mass flow rate of LCO<sub>2</sub> at constant volume flow rate of oil, the oil concentration inside the LCO<sub>2</sub> decreases, whereas the velocity and expansion ratio of LCO<sub>2</sub> (expansion ratio = 535:1) both increase, thus generating smaller oil droplets. In addition, the media splitting angle at the nozzle outlet also increases with increasing LCO<sub>2</sub> mass flow rate, as observed in Ref. [22]. A larger media splitting angle ensures that the droplets do not interact with each other in the air and consequently do not merge, as evidenced by the observed smaller average diameter. A similar trend was reported in Ref. [14]. Moreover, oils with better solubility in LCO<sub>2</sub>, i.e. nonpolar oils, produced smaller oil droplets as they are more evenly distributed in the pre-mixed flow, resulting in smaller oil droplets at the nozzle outlet. However, special oils for MQL use are designed to disperse well due to the addition of additives. This is confirmed here as well, as the oil droplets of both special MQL-oils were smaller than the oil droplets of base oils without additives, regardless of the oil polarity. Smaller oil droplets were also more evenly distributed, as shown in Fig. 4 b).

The average diameter of oil droplets varied from  $10 \mu\text{m}$  to  $23 \mu\text{m}$  for base oils without additives and from  $2 \mu\text{m}$  to  $8 \mu\text{m}$  for special MQL oils (smaller for nonpolar oils). Previous studies reported an average oil droplet diameter between  $10 \mu\text{m}$  and  $15 \mu\text{m}$  for conventional MQL [13]

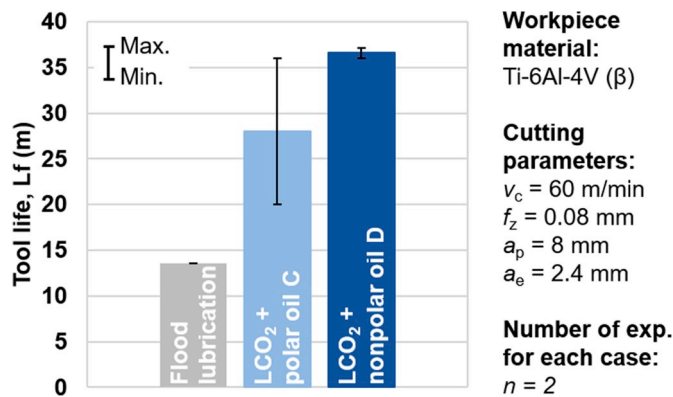


Fig. 5. Influence of different cooling-lubrication on tool life (summarized from Ref. [4]).

and an average emulsion droplet diameter between 15  $\mu\text{m}$  and 26  $\mu\text{m}$  for conventional minimum-quantity cooling lubrication (MQCL) [14]. Therefore, the capability of oil to be dissolved in LCO<sub>2</sub> by using the novel single-channel technique allows the opportunity of achieving much smaller oil droplets in comparison to existing MQL/MQCL systems. This capability could have significant impact on machining performance as smaller droplets are superior to larger droplets due to their better ability of penetrating into the cutting zone [23].

Tool-life experiments employed milling of Ti-6Al-4V alloy using uncoated solid-carbide end mills: 8 mm-diameter, four cutting edges, K20–K40 substrate with submicron grain size in a 12% cobalt binder, 1570 HV30 hardness. The horizontal machining center enabled a through-spindle and through-tool supply of cooling lubricant. The lubricated liquid carbon dioxide was delivered in the single-channel supply described here. The cutting parameters are given in Fig. 5. The machinability criteria used was the achievable tool life – measured as a travel path  $L_f$  in meters when the critical flank wear of 0.2 mm was reached. The results in Fig. 5 show that the longest tool life was achieved using the pre-mixed LCO<sub>2</sub> and (nonpolar) oil D, presumably due to better lubrication. Moreover, minimal scatter within the tool-life measurements was observed in this case due to a more even distribution of oil droplets leading towards more consistent lubrication. Moreover, significant tool-life prolongation is achieved under both cryogenic conditions in comparison to the reference conditions, i.e. conventional flood lubrication. The uncertainty of the LCO<sub>2</sub> + polar oil C results would be reduced by more extensive tool-life testing, but this is beyond the scope of the current proof-of-concept study. While this experiment is not limited to the Ti-6Al-4V alloy milled here, the largest cost benefits are expected from difficult-to-machine materials, such as nickel-based superalloys with a wide range of applications [24,25].

## 5. Conclusions and future work

The paper demonstrates a significant development in cryogenic-machining technology: the efficacy of a single-channel MQL-delivery system using lubricated LCO<sub>2</sub>. This new technique enables the introduction of any liquid lubrication media into a liquid CO<sub>2</sub> flow without the requirement of additional CO<sub>2</sub> pre-preparation. The proof of concept is based on an experimental investigation of oil solubility in LCO<sub>2</sub> using a high-pressure mixing chamber and a high-speed camera. The solubility results are further coupled with the measurement of oil-droplet size and distribution. It is found that droplets as small as 2  $\mu\text{m}$  in diameter can be generated, which is much smaller than those generated using conventional MQL, where oil droplets are typically larger than 10  $\mu\text{m}$  in diameter. Furthermore, it was proved that oil polarity clearly affects its solubility in LCO<sub>2</sub>, which influences the achievable oil-droplets size and distribution. Nonpolar oils are fully soluble in LCO<sub>2</sub> and therefore can achieve smaller droplet sizes with more even distribution; this gives

better lubrication in comparison to polar oils. This is further verified in machining tests, where prolonged tool life is achieved when applying a nonpolar oil.

Future work will provide more extensive experimental testing, especially in view of tool-life evaluation, and will further focus on exploring the use of solid lubricants (e.g. MoS<sub>2</sub> [26]) mixed with LCO<sub>2</sub>, with the goal of achieving a completely dry cryogenic machining process.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijmachtools.2019.103456>.

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