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Citation for the original published paper (version of record):
Grguraš, D., Sterle, L., Krajnik, P. et al (2019). A novel cryogenic machining concept based on a lubricated liquid carbon dioxide. International Journal of Machine Tools and Manufacture, 145.
http://dx.doi.org/10.1016/j.ijmachtools.2019.103456

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International Journal of Machine Tools & Manufacture 145 (2019) 103456

Contents lists available at ScienceDirect

International Journal of Machine Tools and Manufacture

journal homepage: http://www.elsevier.com/locate/ijmactool

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

Damir Grguraš [a], Luka Sterle [a], Peter Krajnik [b,*], Franci Pušavec [a]

[a] University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia
[b] Chalmers University of Technology, Department of Industrial and Materials Science, Gothenburg, Sweden

ARTICLE INFO

Keywords:
Cryogenic machining
Carbon dioxide
Single-channel MQL
Solubility
Cooling
Lubrication

ABSTRACT

A novel single-channel supply of pre-mixed (a) liquid carbon dioxide (LCO_2) 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_2 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_2. 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_2) 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_2 and MQL) due to (i) LCO_2 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_2 consumption (up to 650 g/min) due to: (i) external CO_2 pre-heating and pressurizing to achieve supercritical CO_2 [6,7], (ii) the application of gas and liquid CO_2 phases simultaneously (under pressure) to control the media delivery [8], and (iii) external oil pressurizing to ensure oil flow into the CO_2 [9]. This necessitates the need of developing a less complex, single-channel method for integrated delivery of pre-mixed LCO_2 and oil under typical LCO_2 conditions ($p = 57$ bar $= 5.7$ MPa, $T = 20\,^\circ\mathrm{C} = 293.15$ K). The requirement specifications for this technique are ease of implementation, moderate CO_2 consumption (up to 250 g/min) and no need for CO_2 pre-heating.

The objective of this paper is to report the technical details of the single-channel delivery of lubricated LCO_2 with respect to achieving the required solubility of oil and droplet size/distribution. The research background concerning oil solubility in CO_2 [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_2 using a high-pressure mixing chamber; (ii) solubility of different oils in LCO_2 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_2 is illustrated schematically in Fig. 1. The system enables a continuous supply of lubrication media into the LCO_2 flow, wherein the LCO_2 is supplied directly from the LCO_2 cylinder. In this system, a mixture of LCO_2 and lubrication media is obtained, wherein the flow of LCO_2 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

* Corresponding author. Hörsalsvägen 7B, SE-412 96 Gothenburg, Sweden.
E-mail address: peter.krajnik@chalmers.se (P. Krajnik).

https://doi.org/10.1016/j.ijmachtools.2019.103456
Received 11 July 2019; Received in revised form 30 August 2019; Accepted 1 September 2019
Available online 5 September 2019

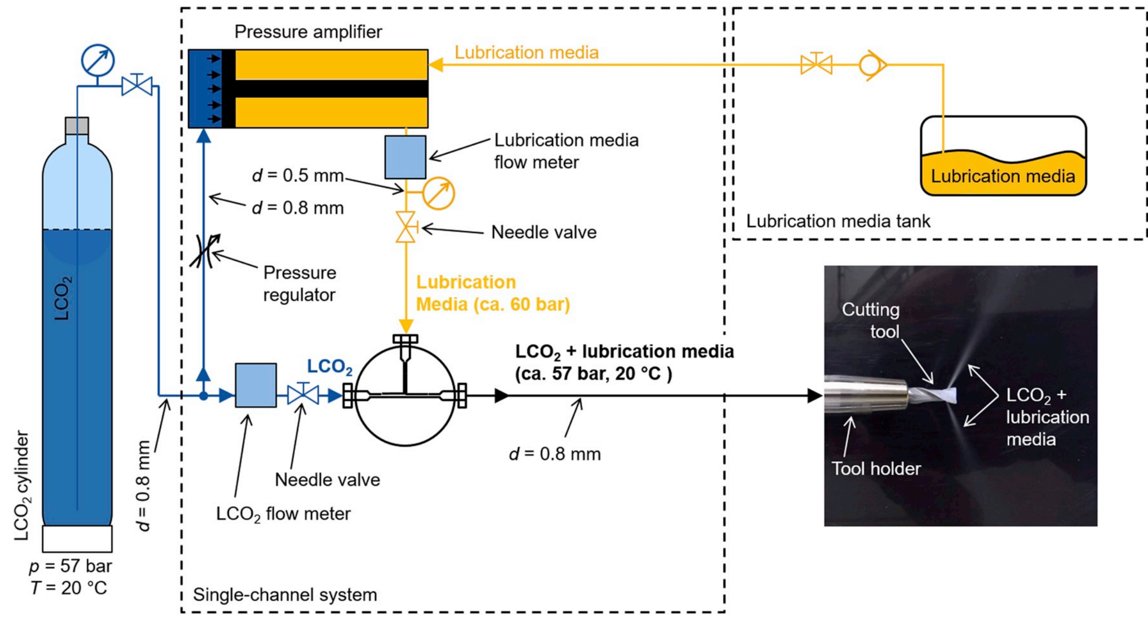

Fig. 1. Schematic illustration of a novel cryogenic machining system based on single-channel, lubricated, liquid carbon dioxide (patent pending, EU-LU101232, Luxembourg, 2019).

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_2 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_2 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_2 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_{solute} is the mass of the solute, which is uniformly dissolved in the solution, and m_{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_2 is expected to be influenced only by polarity of the oil because the temperature is governed by the liquid state of CO_2 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_2. 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_2 and oils.

	LCO_2	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[a]	Mixture of esters and additives	N/A
Density at 20 °C in g/cm^3	0.77	0.91	0.83	0.90 ISO 279	0.87 ISO 279
Kin. viscosity in mm^2/s	0.09	72 (20 °C)	30.5 (40 °C)	22 (40 °C) ISO 3104	3.5 (20 °C) ISO 3104
Polarity	Nonpolar	Polar	Nonpolar	Polar	Nonpolar

[a] PAO - Polyalphaolefin.

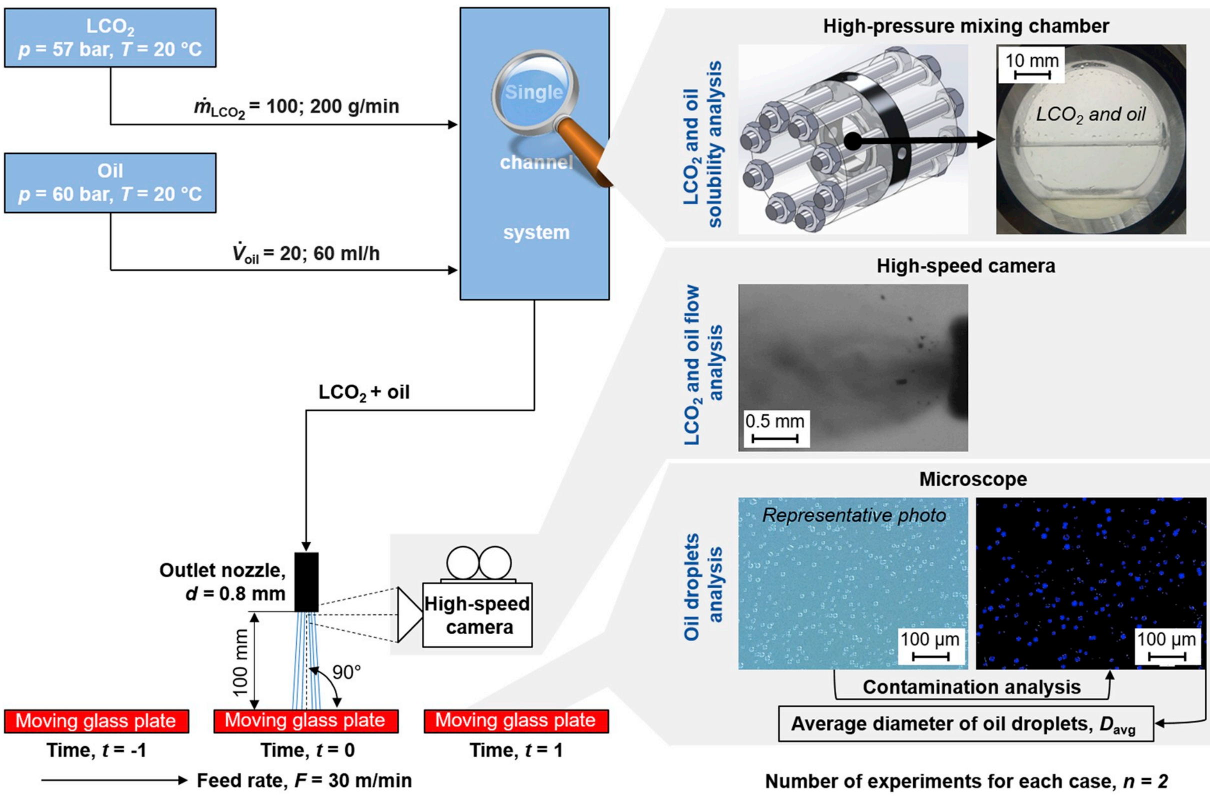

Fig. 2. Illustration of the experimental setup.

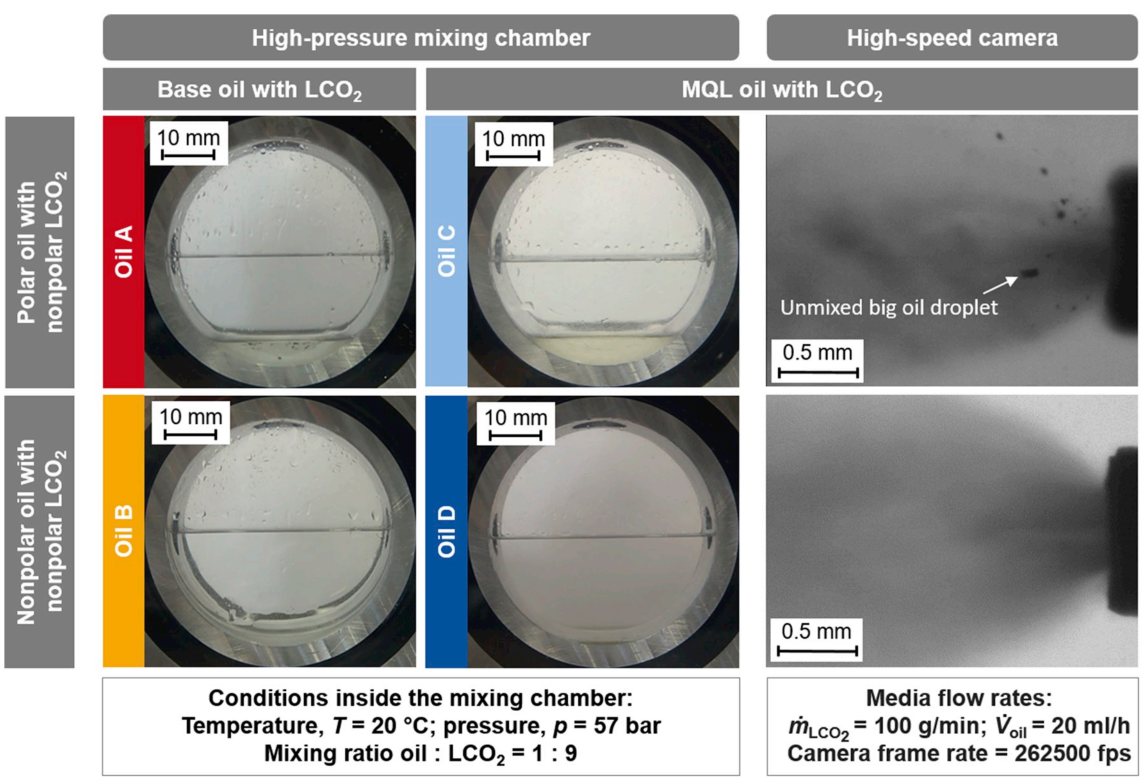

Fig. 3. Investigation of oil polarity on solubility of liquid oil in LCO_2 using high-pressure mixing chamber and high-speed camera.

volume ratio of oil to LCO_2 was 1:9. To investigate solubility, oil was first added to the mixing chamber, followed by LCO_2 (at $p = 57$ bar $= 5.7$ MPa; $T = 20\,°C = 293.15$ K), up to the total volume of $V = 16$ 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_2 was

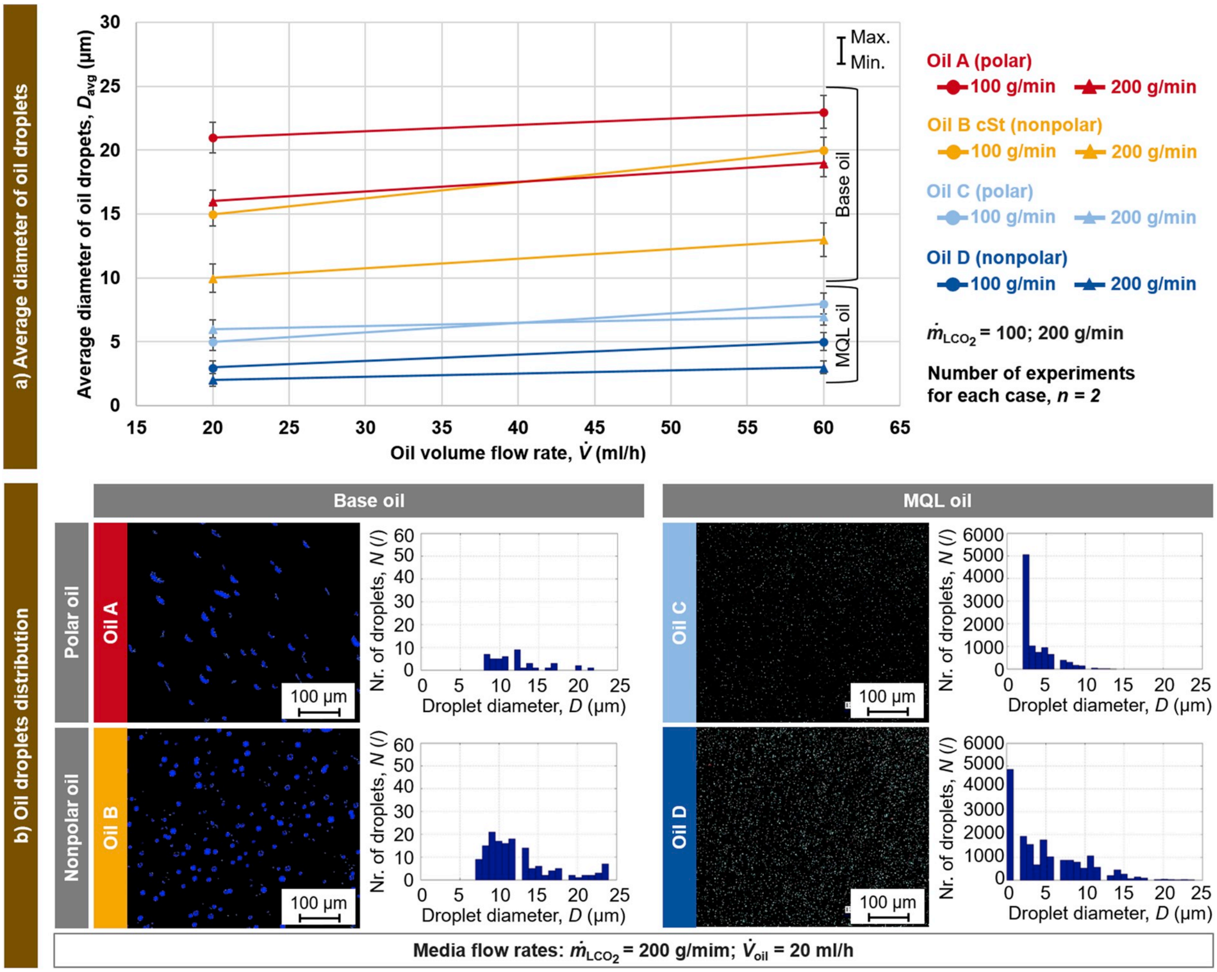

Fig. 4. Influence of LCO_2 mass flow rate and oil volume flow rate on a) average diameter of oil droplets; and b) oil droplets distribution.

added to the chamber (see Fig. 3 showing the effect of oil polarity on solubility). As expected, nonpolar oils are more soluble in LCO_2. Moreover, nonpolar base oil (oil B) and nonpolar MQL oil (oil D) are completely soluble in LCO_2 (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_2 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_2 mass flow rates were $\dot{m}_{LCO2} = 100$ and 200 g/min, based on a typical operation [4,19]. Oil volume flow rates were set to $\dot{V}_{oil} = 20$ and 60 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 × 384 pixels; frame rate of 67500 fps). Here, the superior solubility of nonpolar oil in LCO_2 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 $L = 100$ 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 $F = 30$ m/min crossing the (vertical) LCO_2 + oil flow. As the LCO_2 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_2 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_2 can further split droplets into multiple smaller droplets; which occurs at higher mass flow rates of LCO_2. This is caused by higher velocity of the LCO_2 carrier media, which results in a higher velocity of the pre-mixed LCO_2 and oil at the nozzle outlet. In addition, with the increase of mass flow rate of LCO_2 at constant volume flow rate of oil, the oil concentration inside the LCO_2 decreases, whereas the velocity and expansion ratio of LCO_2 (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_2 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_2, 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 µm to 23 µm for base oils without additives and from 2 µm to 8 µm for special MQL oils (smaller for nonpolar oils). Previous studies reported an average oil droplet diameter between 10 µm and 15 µm for conventional MQL [13]

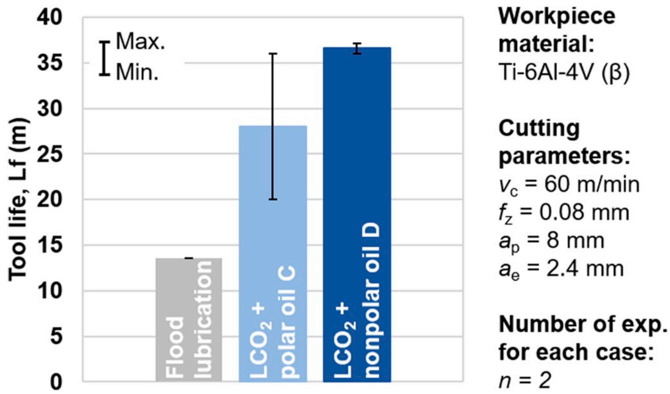

Fig. 5. Influence of different cooling-lubrication on tool life (summarized from Ref. [4]).

and an average emulsion droplet diameter between 15 μm and 26 μm for conventional minimum-quantity cooling lubrication (MQCL) [14]. Therefore, the capability of oil to be dissolved in LCO_2 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 *Lf* 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_2 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_2 + 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_2. This new technique enables the introduction of any liquid lubrication media into a liquid CO_2 flow without the requirement of additional CO_2 pre-preparation. The proof of concept is based on an experimental investigation of oil solubility in LCO_2 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 μm in diameter can be generated, which is much smaller than those generated using conventional MQL, where oil droplets are typically larger than 10 μm in diameter. Furthermore, it was proved that oil polarity clearly affects its solubility in LCO_2, which influences the achievable oil-droplets size and distribution. Nonpolar oils are fully soluble in LCO_2 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_2 [26]) mixed with LCO_2, with the goal of achieving a completely dry cryogenic machining process.

Acknowledgements

The work was funded by the Slovenian Research Agency (ARRS) via research project L2-8184 and research program P2-0266. The authors would also like to acknowledge Rhenus lub and Mrs. Daniele Kleinmann for supporting this work.

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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