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Media Flow Analysis of Single-Channel Pre-Mixed Liquid CO_2 and MQL in Sustainable Machining

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Single-channel supply of pre-mixed liquid carbon dioxide (LCO_2) and minimum quantity lubrication (MQL) represents a state-of-the-art LCO_2 assisted machining. However, to fully understand and optimize cooling and lubrication provided by the LCO_2 + MQL, a fundamental media flow analysis is essential, yet not researched enough. Therefore, in this paper, media flow velocity and oil droplet size were analysed in supplying line and at the nozzle outlet using high-speed camera and proprietary single-channel system. Results indicate that pre-mixed media flow velocity is mainly influenced by the LCO_2 expansion rate upon the nozzle outlet, wherein oil droplet size is largely dependent on the solubility between oil and LCO_2. Media flow velocity increases significantly from an average of 40 m/s in the supplying line to the excess of 90 m/s at the nozzle outlet due to the pressure drop and LCO_2 expansion. Furthermore, this volume expansion causes the oil droplet to increase to the point of critical, unstable droplet size. Afterward, the unstable oil droplet breaks up into smaller oil droplets. It was found, that nonpolar oil, with greater solubility in LCO_2, compared to the polar oil, provides droplets as small as 2 µm in diameter. Smaller oil droplets positively reflect on tool wear and tool life in LCO_2 assisted machining, as the longest tool life was achieved by using the nonpolar oil for pre-mixed LCO_2 + MQL.
Keywords: flow analysis, flow velocity, droplet size, single-channel supply, liquid carbon dioxide – LCO_2, minimum quantity lubrication – MQL, LCO_2 assisted machining

Highlights

- *LCO_2 assisted machining with single-channel supply of pre-mixed liquid CO_2 and MQL was introduced as the sustainable replacement to conventional machining with flood lubrication.*
- *Analysis of pre-mixed LCO_2 and MQL media flow was carried out.*
- *Media flow analysis was performed using high-speed camera, determining media flow velocity and media droplet size.*
- *Results of the media flow analysis were coupled with tool life experiments in LCO_2 assisted machining of Ti-6Al-4V (β).*

0 INTRODUCTION

During machining, especially of difficult-to-cut materials, excessive heat generation in the cutting zone demands adequate cooling and lubrication. Normally, conventional machining with flood lubrication and low cutting speed is applied, reflecting in lower machining productivity. In addition, conventional oil-based emulsions are found non-sustainable due to adverse impact on environment and worker's health. Studies are showing that minimum quantity lubrication (MQL) can be an alternative to flood lubrication [1]. To further emphasize the potential of MQL lubrication, innovative MQL approaches have been proposed, namely electrostatic MQL (EMQL), hybrid nano-particles immersed EMQL and electrostatic lubrication [2]. Nevertheless, the absence of MQL cooling ability demands other sustainable alternatives to allocate both – cooling and lubrication. Studies showed that combination of liquid nitrogen and MQL (N_2 + MQL) in cryogenic machining yields lower tool wear and surface roughness [3]. The use of liquid carbon dioxide (LCO_2) in combination with MQL is another approach to improve machining performance [4]. In such LCO_2 assisted machining, pre-mixed LCO_2 + MQL represents state-of-the-art, whereas LCO_2 provides cooling and MQL lubrication effects [5].

Extensive research on cooling was carried out by Pušavec et al. [6], providing a better understanding of cooling capability of LCO_2 in comparison with flood lubrication. It has been shown that even though the tool temperatures are lower when using flood lubrication, LCO_2 in combination with MQL yields longer tool life. On the other hand, however, lubrication capability of pre-mixed LCO_2 + MQL lacks in scientific research. Only a few studies can be found discussing MQL oil droplets; all of them are related to the conventional MQL or MQCL (minimum quantity cooling lubrication), where pressurized air is used as a carrier media. MQL study by Cabanettes et al. [7] discovered that oil droplets adhere to the wall of the supplying line by creating a film along the wall. At the nozzle outlet, this is followed by the film disintegration and the formation of oil droplets. In addition, the oil viscosity, as discovered by Muaz and Choudhury [8], conditions the lubrication ability of MQL. Lower viscosity oils are preferable for

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MQL, since smaller oil droplets and thus deeper penetration into the cutting zone can be achieved. Similar was reported for MQCL [9]. In addition, increase in the airflow provides higher quantity of oil droplets [10] and [11], wherein increase in the nozzle-workpiece distance provides decrease in oil droplet size. According to Maruda et al. [11], MQCL droplets of the diameter less than 5 μm can quickly evaporate from the heated surface and have the least negative effect on human health.

Presented studies show that deeper understanding of media flow leads to a better understanding of MQL / MQCL machining. Accordingly, one must be aware that state-of-the-art LCO_2 + MQL flow is not entirely understandable. In this paper, therefore, an attempt is made to advance the understanding of the pre-mixed LCO_2 + MQL media flow characteristics. The knowledge of pre-mixed LCO_2 + MQL flow characteristics can be used for deeper understanding about the cooling and lubrication abilities of this novel technology. With regard to that, media flow velocity and oil droplet size were analysed using a high-speed camera at three key locations: (i) in the supplying line; (ii) directly after the nozzle outlet; (iii) near the nozzle outlet. In addition, results obtained from this fundamental study were coupled with authors' previous tool life experiments in LCO_2 assisted milling of Ti-6Al-4V (β) [5]. Moreover, suggestions for future work and practical workshop conclusions have been drawn.

1 EXPERIMENTAL PROCEDURE

For the media flow analysis, a unique experimental setup was developed as shown in Fig. 1. The LCO_2 + MQL media flow was analysed using a high-speed camera at three positions:

- Position A: for analysing the flow in the supplying line, where the average media flow velocity was determined,
- Position B: for analysing the flow at the nozzle outlet, in the immediate vicinity of the nozzle (close to the nozzle), where the average flow velocity and average oil droplet diameter were determined,
- Position C: for analysing the expanding media flow at the nozzle outlet, at a distance from the nozzle (far from the nozzle, i.e. 3 mm from the nozzle), where the average flow velocity and average oil droplet diameter were determined.

At position A, the high-speed camera was mounted perpendicular to the supplying line, with a distance of

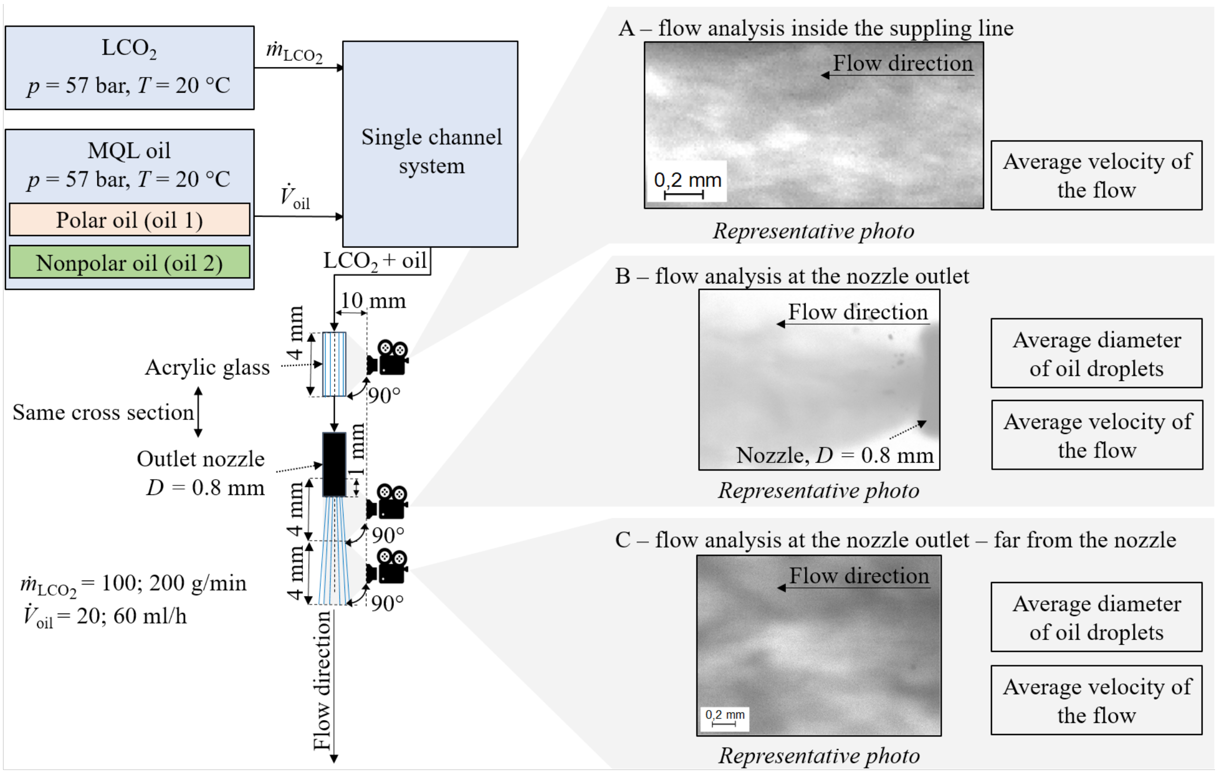

Fig. 1. *Illustration of the experimental setup*

10 mm from it. Media flow analysis at the position A was carried out using specially designed acrylic chamber with a square cross section, as shown in Fig. 2. The square cross section provided the possibility of recording of the media flow without any reflection issues. The chamber consists of two acrylic parts, which are secured together using eight screws. Two positioning holes provide the positioning accuracy of both sides. It should be noted that the cross section of the nozzle and the cross section of the supplying line chamber were identical. The identical cross-sections provide a smooth flow of the LCO_2 + MQL media, without any pressure drop due to the cross-sectional change inside the pipeline / supplying line. At position B, the high-speed camera was mounted perpendicular to the nozzle outlet, with a distance of 10 mm from the nozzle in such a manner that recording the flow of LCO_2 + MQL directly at the nozzle outlet has been performed. The high-speed camera was positioned to cover a measurement window of 4 mm × 4 mm. At position C, the high-speed camera was mounted perpendicular to the nozzle outlet, with a distance of 10 mm from the nozzle. At this position, the LCO_2 + MQL expanding flow was analysed 3 mm away from the nozzle outlet, as shown in Fig. 1.

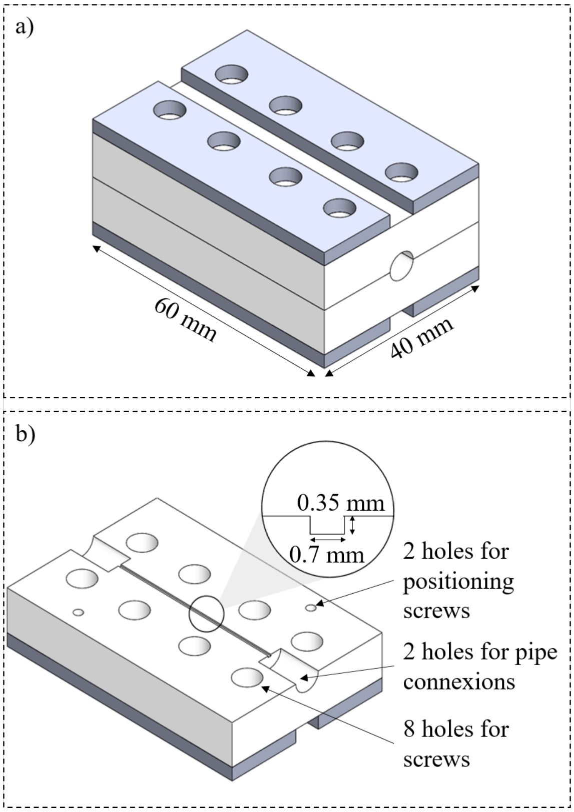

Fig. 2. *Acrylic glass chamber, a) 3D view, and b) sectional view*

Experiments have been performed separately with high-speed camera that has been moved to the desired camera positions A, B or C, with the following settings: (i) frame resolution of 512 × 384 pixels and (ii) frame rate of 67500 frames per seconds [fps]. Afterwards, Photron Fastcam Analysis software was used to extract the data from recorded videos and to analyse the media velocity and oil droplet size. Media velocity was determined by following the characteristic part of the media stream, i.e. dark areas or oil droplets in the stream. Using the analysis software, media velocity was then calculated from the change of flow path in a time period. For the sake of repeatability, every experiment was repeated five times.

A proprietary single-channel supply system ArcLub One, detailed in **[12]**, was used to supply the pre-mixed LCO_2 + MQL media under the temperature of T = 20 °C and the pressure of p = 57 bar. In this study, LCO_2 mass flow rates of $\dot{m}_{LCO2}$ = 100 g/min and 200 g/min and oil (MQL) volume flow rates of $\dot{V}_{oil}$ = 20 ml/h and 60 ml/h were used. The flow rates were selected based on the state-of-the-art studies: (i) LCO_2 flow rates from **[5]** and **[13]** and (ii) oil flow rates from **[10]** and **[14]**.

As concluded in **[5]** and **[12]**, oil polarity affects its solubility in LCO_2, which further influences the tool life. Therefore, in this study, MQL oils with different polarities were used: (i) polar MQL oil (oil 1) and (ii) nonpolar MQL oil (oil 2). Other physical and chemical properties of oils are given in Table 1.

Table 1. *Physical and chemical properties of oils (according to the oil manufacturer's specifications)*

	Oil 1	Oil 2
Physical state at 20 °C	Liquid	Liquid
Colour	Amber	Clear yellow
Odour	Weak, characteristic	Characteristic
Chemical characterization	Mixture of esters and additives	Base oil with additives
Density at 20 °C [g/cm^3]	0.90 (DIN 51757)	0.87 (DIN 51757)
Kinematic viscosity at 20 °C [mm^2/s]	N/A (22 at 40 °C) (ISO 3104)	3.5 (DIN 51562)
Polarity	Polar	Nonpolar

2 RESULTS AND DISCUSSION

2.1 High-Speed Camera Position A – Media Flow Analysis Inside the Supplying Line

Fig. 3 shows the media stream of LCO_2 + MQL inside the supplying line. As found in [5] and [12], polar oils have limited ability of mixing with LCO_2. Using the high-speed camera, this can be seen as a two-phase flow inside the supplying line. With other words, mixture of LCO_2 + MQL (oil 1), as well as unmixed portion of the oil 1 can be seen (Fig. 3a; dark spots). On the other hand, as oil 2 is nonpolar and dissolves to a greater extent in LCO_2, it is not possible to find any residual oil, which is not mixed with LCO_2. Only the flow of the mixture of LCO_2 + MQL (oil 2) can be noticed, as shown in Fig. 3b.

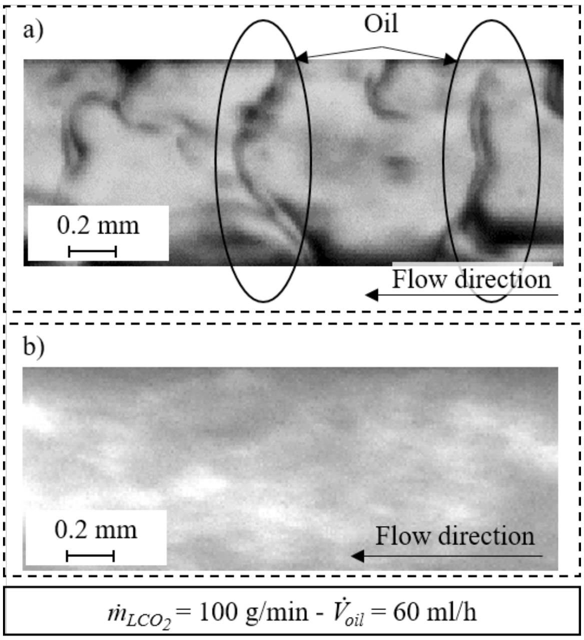

Fig. 3. *Media flow analysis inside the supplying line; a) LCO_2 + oil 1, and b) LCO_2 + oil 2*

The influence of the LCO_2 and MQL flow rates on the media flow velocity is shown in Fig. 4. Regardless of the media flow rate, it can be observed that the media flow velocity of LCO_2 + MQL (oil 2) is slightly greater than the media flow velocity of LCO_2 + MQL (oil 1). The reason can be the level of dissolution between oil and LCO_2. Namely, the oil 2 is completely soluble in LCO_2, resulting in a mixture of LCO_2 + MQL (oil 2) that has higher average flow velocity than the two-phase flow of LCO_2 and oil 1. Oil 1, which is partially mixed with LCO_2, can slow down the entire stream of the two-phase mixture. In addition, oil that is not mixed with LCO_2 (i.e. oil 1), can adhere to the walls of the nozzle and thus possibly slow down the stream of the entire media. This can be illustrated schematically with Fig. 7 in section 2.2. Considering the error bars, however, it is not possible to notice significant difference between the velocity of the mixture of LCO_2 + MQL for different LCO_2 and oil flow rates. Nevertheless, by the increase in media mass flow rate through a nozzle of the same diameter, a higher flow velocity is expected, which describes marginal average velocity increasement with the higher LCO_2 mass flow rate. For example, flow velocity increases from 44 m/s to 49 m/s when the LCO_2 flow rate is increased from 100 g/min to 200 g/min with unchanged MQL flow rate of 60 ml/h.

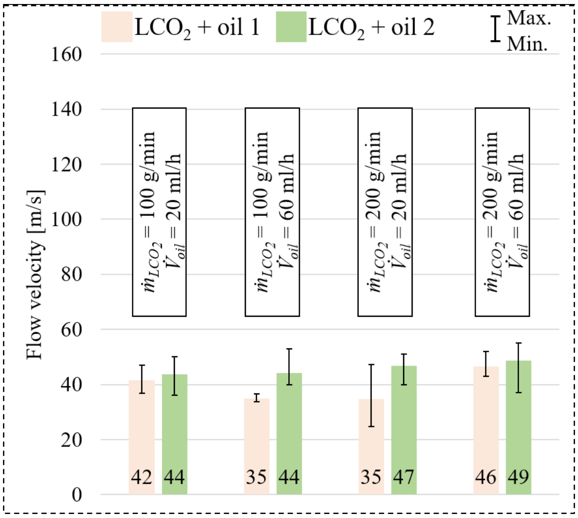

Fig. 4. *Average velocity of the media flow inside the supplying line*

2.2 High-Speed Camera Position B – Media Flow Analysis at the Nozzle Outlet

Fig. 5 shows stream of the media at the nozzle outlet. In addition, evolution of the droplet size during expansion of the mixture is visible in Fig. 6. For the mixture of LCO_2 + MQL (oil 1), oil droplets that are not part of the mixture can be observed, as they freely fly from the nozzle. Schematically, Fig. 7 illustrate this behavior of unmixed oil. It is clear that the portion of the oil, which does not mix with LCO_2, forms an oil film of variable thickness on the nozzle wall. At the nozzle outlet, the disintegration of this film occurs, resulting in a formation of oil droplets, which were captured by a high-speed camera. Similar trend was observed for conventional MQL, where oil and pressurized air are not mixed and researchers [7] observed the formation of an oil film on the nozzle wall. As illustrated in Fig. 5, the diameter of the oil droplets increases with distance from the nozzle outlet. The reason lies in the nature of the carrier media LCO_2, which evaporates and expands (expansion rate of 535:1 [15]) due to the pressure drop from 57 bar in the supplying line to 1 bar at the nozzle outlet. Therefore, its volume and thus the size increases. On the other hand, oil droplets of oil 2 in the flow of LCO_2 are not visible due to the greater solubility between the oil and LCO_2. In addition, Fig. 8, shows that the LCO_2 flow with oil 2 is slightly faster than the flow with oil 1 as a consequence of the film-formation phenomena described in previous sections. However, significant increase in media flow velocity can be observed once the LCO_2 + MQL media leaves the supplying line (Figs. 4 and 8). The increase from an average of 40 m/s in the supplying line to the excess of 90 m/s at the nozzle outlet, regardless of the LCO_2 and MQL flow rates, can be observed due to the LCO_2 expansion and phase change from liquid to gas. This results in acceleration of the flow and thus higher flow velocity at the nozzle outlet compared to the flow velocity in the supplying line.

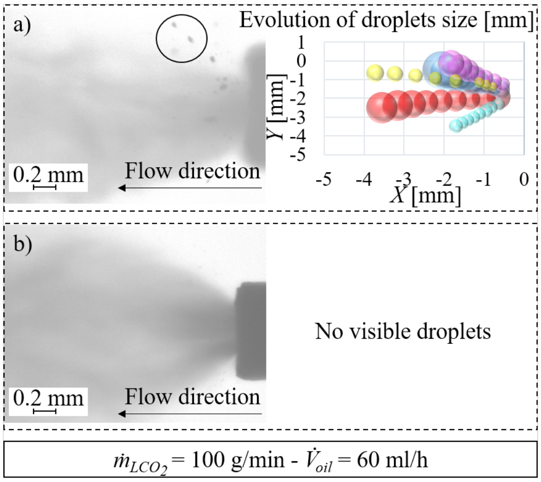

Fig. 5. *Media flow analysis at the nozzle outlet; a) LCO_2 + oil 1, and b) LCO_2 + oil 2*

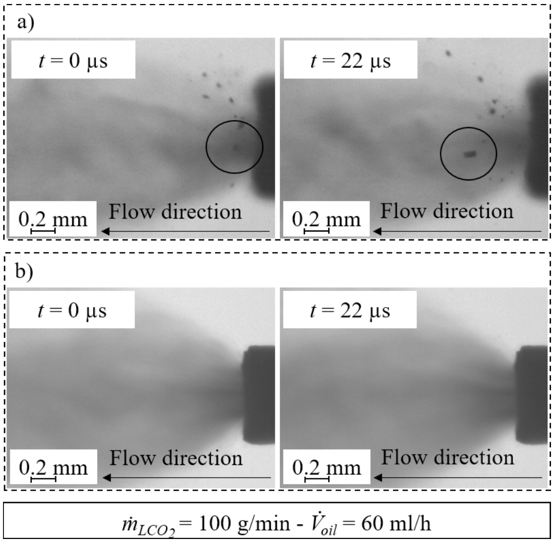

Fig. 6. *Evolution of the droplets size during mixture expansion at the nozzle outlet; a) LCO_2 + oil 1, and b) LCO_2 + oil 2*

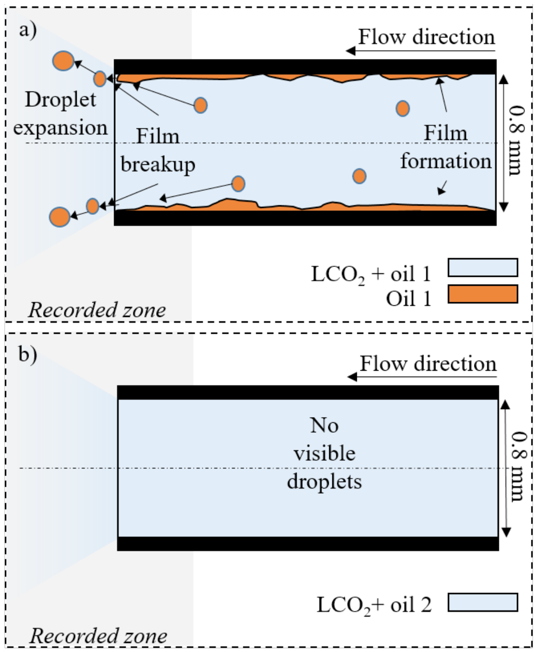

Fig. 7. *Oil behavior in the media flow at the nozzle outlet; a) LCO_2 + oil 1, and LCO_2 + oil 2*

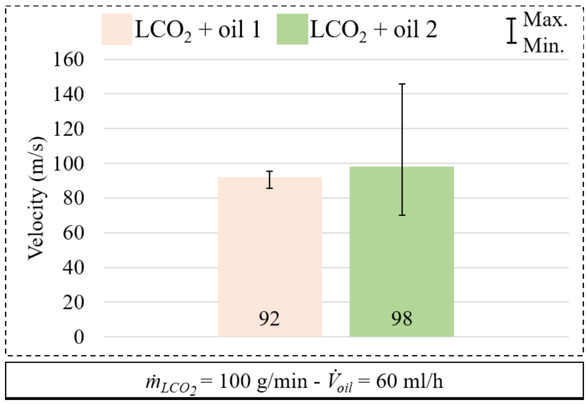

Fig. 8. *Average speed of the media flow at the nozzle outlet*

2.3 High-Speed Camera Position C – Media Flow Analysis at the Nozzle Outlet; Far from the Nozzle

Fig. 9 shows the media flow further from the nozzle outlet. The stream was recorded with a high-speed camera that was mounted at a distance of 3 mm from the outlet nozzle, as illustrated in Fig. 1. Following the observations from the high-speed camera positions A and B, the oil 2 droplets are not visible in the LCO_2 stream. Moreover, due to the spatial expansion of LCO_2, a smaller number of droplets of oil 1 can be observed in the stream. Oil droplets are smaller by comparing their size with the droplets right at the nozzle outlet (high-speed camera position B).

Illustration of the oil behavior in the LCO_2 stream is schematically shown in Fig. 10. As explained in section 2.2., the oil droplet size, after leaving the nozzle, increases due to the expansion of LCO_2. In addition, the average diameter of the droplet increases to a critical, unstable droplet size. Afterward, the decomposition of the droplet occurs, which means that the droplet breaks up into smaller droplets. It can be concluded that oil droplets entering the cutting zone are smaller than the droplets leaving the nozzle. On the other hand, no visible oil droplets in the LCO_2 flow can be seen when the oil 2 was used. This confirms that even though the oil flow rates are same, in case of oil 2, the average droplet size is significantly smaller and thus non-visible with selected camera settings. Nevertheless, our previous study [12] shows that mixture of LCO_2 and nonpolar oil (i.e. oil 2) provides oil droplets as small as 2 μm in diameter, compared to the larger oil droplets with excess of 5 μm in diameter for the mixture of LCO_2 and oil 1. In addition, due to the greater solubility of oil 2 in LCO_2, higher amount of oil enters the cutting zone. On the contrary, unmixed portion of the oil 1 is not part of the stream of LCO_2 + MQL and can freely fly from the nozzle, as observed at high-speed camera position B. This affects the amount of the oil, which has the ability to lubricate the cutting zone.

According to written, longer tool life is expected if the nonpolar oil (oil 2) is used in a mixture of LCO_2 + MQL. This observation is confirmed by tool life experiments [5], where tool life travel path of L_f = 36.6 m was achieved using single-channel supply of LCO_2 and nonpolar oil in cryogenic milling of titanium alloy Ti-6Al-4V (β). On the other hand, tool life travel path was shorter (L_f = 28.0 m) when the mixture of LCO_2 and polar oil was used. Furthermore, transition from conventional flood lubrication to LCO_2 assisted machining, if the nonpolar oil (oil 2) is used in pre-mixed LCO_2 + MQL, reflects in 44.7 % lower running costs, as the tool life is significantly prolonged (conventional flood lubrication; L_f = 13.6 m and LCO_2 assisted machining; L_f = 36.6 m) [16].

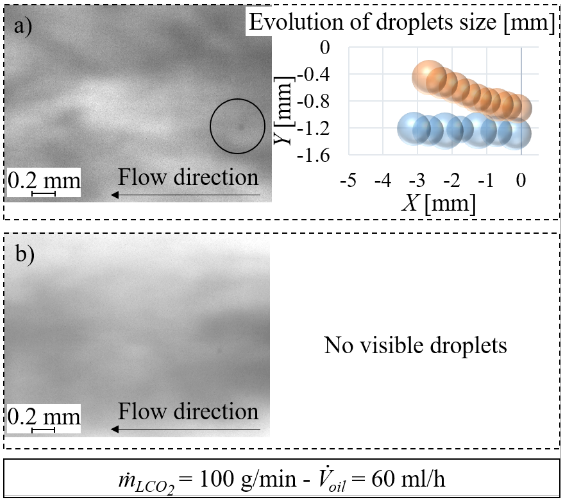

Fig. 9. *Media flow analysis at the nozzle outlet – far from the nozzle; a) LCO_2 + oil 1, and b) LCO_2 + oil 2*

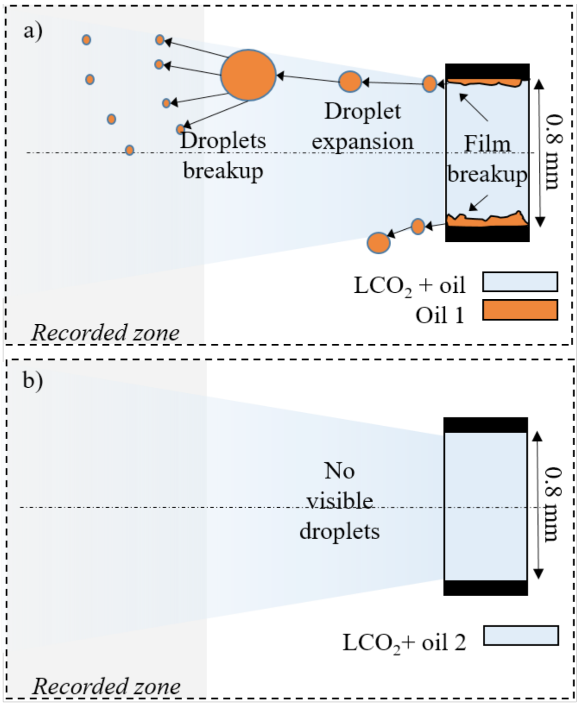

Fig. 10. *Oil behavior in the media flow at the nozzle outlet – far from the nozzle; a) LCO_2 + oil 1, and b) LCO_2 + oil 2*

3 CONCLUSIONS

In this paper, media flow analysis of pre-mixed LCO_2 and MQL (oil) was carried out. Media flow velocity and oil droplet size were analysed using high-speed camera, wherein pre-mixed media flow was analysed inside the supplying line and at the nozzle outlet. For this research, two different oils were used in a mixture of LCO_2 + oil, i.e polar MQL oil (oil 1) and nonpolar MQL oil (oil 2). Key findings can be summarized, as follows.

Flow velocity of pre-mixed LCO_2 and oil is influenced by the LCO_2 flow rate. Thus, increase in LCO_2 mass flow rate increases the flow velocity, e.g. flow velocity increases from 44 m/s to 49 m/s when the LCO_2 flow rate is increased from 100 g/min to 200 g/min with unchanged MQL flow rate of 60 ml/h. However, the flow velocity of a mixture of LCO_2 and oil is largely influenced by the pressure drop and LCO_2 expansion upon the nozzle outlet. Media flow velocity increases significantly from an average of 40 m/s in the supplying line to the excess of 90 m/s at the nozzle outlet.

LCO_2 expansion upon the nozzle outlet has an impact on oil droplet size as well. Due to the LCO_2 expansion, the size of the oil droplet increases to the point of critical, unstable droplet size. Afterward, the unstable oil droplet breaks up into smaller oil droplets. Besides, oil droplet size in the pre-mixed media is largely dependent on the solubility between oil and LCO_2. Solubility of nonpolar oil (oil 2) is greater compared to the polar oil (oil 1). Thus, mixture of LCO_2 and oil 2 provides oil droplets as small as 2 μm in diameter. On the contrary, mixture of LCO_2 and oil 1 provides oil droplets with excess of 5 μm in diameter. In addition, limited oil solubility yields towards unmixed portion of the oil 1 (oil which is not part of the LCO_2 + MQL stream), which can freely fly from the nozzle, with lower possibilities for entering the cutting zone. In combination with larger oil droplets this affects the lubrication capability in LCO_2 assisted machining, as described further in conclusions.

The contribution of this study is reflected in an enhanced understanding of LCO_2 and oil behavior for practical use of LCO_2 assisted machining. To realize the longest tool life, therefore, a nonpolar oil (i.e. oil 2) should be used in the mixture of LCO_2 + MQL. In our study, tool life travel path of L_f = 36.6 m was achieved using single-channel supply of LCO_2 and nonpolar oil in milling of titanium alloy Ti-6Al-4V (β). On the other hand, tool life travel path was shorter (L_f = 28.0 m) when the mixture of LCO_2 and polar oil was used.

Future work requires deeper investigations into LCO_2 assisted machining, wherein nonpolar oil (oil 2) should be used in the pre-mixed LCO_2 + MQL. LCO_2 and MQL flow rates should be varied and tool life experiments for other difficult-to-cut materials, such as Inconel 718, stainless steel 316 L, etc. should be investigated. In addition, surface topography and cutting forces should be analysed.

4 ACKNOWLEDGEMENTS

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5 REFERENCES

[1] Khawaja, A.H., Jahanzaib, M., Cheema, T.A. (2020). High-speed machining parametric optimization of 15CDV6 HSLA steel under minimum quantity and flood lubrication. *Advances in Production Engineering & Management*, vol. 15, no. 4, p. 403-415, **DOI:10.14743/apem2020.4.374**.

[2] Shah, P., Khanna, N., Zadafiya, K., Bhalodiya, M., Maruda, R.W., Krolczyk, G.M. (2020). In-house development of eco-friendly lubrication techniques (EMQL, Nanoparticles+EMQL and EL) for improving machining performance of 15–5 PHSS. *Tribology International*, vol. 151, p. 106476, **DOI:10.1016/j.triboint.2020.106476**.

[3] Gupta, M.K., Song, Q., Liu, Z., Sarikaya, M., Jamil, M., Mia, M., Khanna, N., Krolczyk, G.M. (2021). Experimental characterisation of the performance of hybrid cryo-lubrication assisted turning of Ti–6Al–4V alloy. *Tribology International*, vol. 153, p. 106582, **DOI:10.1016/j.triboint.2020.106582**.

[4] Jawahir, S., Attia, H., Biermann, D., Duflou, J., Klocke, F., Meyer, D., Newman, S.T., Pušavec, F., Putz, M., Rech, J., Schulze, V., Umbrello, D. (2016). Cryogenic manufacturing processes. *CIRP Annals – Manufacturing Technologies*, vol. 65, no. 2, p. 713-736, **DOI:10.1016/j.cirp.2016.06.007**.

[5] Bergs, T., Pušavec, F., Koch, M., Grguraš, D., Döbbeler, B., Klocke, F. (2019). Investigation of the solubility of liquid CO2 and liquid oil to realize an internal single channel supply in milling of Ti6Al4V. *Procedia Manufacturing*, vol. 33, p. 200-207, **DOI:10.1016/j.promfg.2019.04.024**.

[6] Pušavec, F., Grguraš, D., Koch, M., Krajnik, P. (2019). Cooling capability of liquid nitrogen and carbon dioxide in cryogenic milling. *CIRP Annals – Manufacturing Technology*, vol. 68, no. 1, p. 73-76, **DOI:10.1016/j.cirp.2019.03.016**.

[7] Cabanettes, F., Faverjo, P., Sova, A., Dumont, F., Rech, J. (2017). MQL machining: from mist generation to tribological behavior of different oils. *International Journal of Advanced Manufacturing Technology*, vol. 90, p. 1119-1130, **DOI:10.1007/s00170-016-9436-0**.

[8] Muaz, M., Choudhury, S.K. (2019). Experimental investigations and multi-objective optimization of MQL-assisted milling

process for finishing of AISI 4340 steel. *Measurement*, vol. 138, p. 557-569, **DOI:10.1016/j.measurement.2019.02.048**.

[9] Maruda, R.W., Krolczyk, G.M., Feldshtein, E., Pušavec, F., Szydlowski, M., Legutko, S., Sobczak-Kupiec, A. (2016). A study on droplets sizes, their distribution and heat exchange for minimum quantity cooling lubrication (MQCL). *International Journal of Machine Tools and Manufacture*, vol. 100, p. 81-92, **DOI:10.1016/j.ijmachtools.2015.10.008**.

[10] Park, K.H., Olortegui-Yume, J., Yoon, M.C., Kwon, P. (2010). A study on droplets and their distribution for minimum quantity lubrication (MQL). *International Journal of Machine Tools and Manufacture*, vol. 50, no. 9, p. 824-833, **DOI:10.1016/j.ijmachtools.2010.05.001**.

[11] Maruda, R.W., Feldshtein, E., Legutko, S., Krolczyk, G.M. (2015). Research on emulsion mist generation in the conditions of minimum quantity cooling lubrication (MQCL). *Tehnički vjesnik – Technical Gazette*, vol. 22, no. 5, p. 1213-1218, **DOI:10.17559/TV-20140423221850**.

[12] Grguraš, D., Sterle, L., Krajnik, P., Pušavec, F. (2019). A novel cryogenic machining concept based on a lubricated liquid carbon dioxide. *International Journal of Machine Tools and Manufacture*, vol. 145, art. ID. 103456, **DOI:10.1016/j.ijmachtools.2019.103456**.

[13] Cordes, S., Hübner, F., Schaarschmidt, T. (2014). Next generation high performance cutting by use of carbon dioxide as cryogenics. *Procedia CIRP*, vol. 14, p. 401-405, **DOI:10.1016/j.procir.2014.03.091**.

[14] Samatham, M., Sheavan, A., Vidyanand, P., Reddy, G.S. (2016). A critical review on minimum quantity lubrication (MQL) coolant system for machining operations. *International Journal of Current Engineering and Technology*, vol. 6, no. 5, p. 1745-1751.

[15] Busch, K., Hochmuth, C., Pause, B., Stoll, A., Wertheim, R. (2016). Investigation of cooling and lubrication strategies for machining high-temperature alloys. *Procedia CIRP*, vol. 41, p. 835-840, **DOI:10.1016/j.procir.2015.10.005**.

[16] Sterle, L., Grguraš, D., Kern, M., Pušavec, F. (2019). Sustainability Assesment of Advanced Machining Technologies. *Strojniški vestnik – Journal of Mechanical Engineering*, vol. 65, no. 11-12, p. 671-679, **DOI:10.5545/sv-jme.2019.6351**.