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The impact of airborne emissions from coolants and lubricants on machining costs

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ABSTRACT

A novel aerosol evaluation cell was employed to measure particle number and mass concentration, with a size distribution from nano to micro scale. Different cooling/lubrication and airflow extraction scenarios were tested on a CFRP/Ti6Al4V case study, and the particle concentrations were measured to evaluate their effect on productivity and cost per hole, if current occupational exposure limits are respected. Aspects to achieve sustainable machining like tool life, consumption of coolant and energy, and standby time required to safely open the machine-tool doors were considered. LCO_2 delivered the best productivity and cost results as it improved the tool life by 40 % compared to MQL, while eliminating the need for standby time to evacuate particles.

1. Introduction

Coolants and lubricants play an essential role in machining, as they reduce temperature and friction in the tool-chip contact area and help evacuate the chips. This in turn, improves industry outcomes such as part quality or tool life. However, coolants and lubricants pose several hazards to the environment and human health, as they release pollutants into the water, soil and air [1]. Moreover, the production, use, and disposal costs of emulsion coolants can account for up to 15 % of the manufacturing cost [2]. This has driven the development of sustainable alternatives such as minimum quantity lubrication (MQL), or sub-zero cooling using liquified gases like nitrogen (LN_2) or carbon dioxide (LCO_2) [3].

Sustainability of coolants is often assessed through economic and environmental aspects like energy and resource consumption [4]. To achieve sustainable manufacturing, however, social aspects such as worker health and safety should also be considered [5].

One of the most common health hazards for workers is exposure to mists. Since coolants atomise when impacting the tool or workpiece [6], they are one of the greatest sources of airborne pollution in machining (12–80 times more than in dry cutting) [7]. Exposure to coolant mists has been linked to several cancer types, respiratory illness and skin problems [1]. Therefore, Occupational Exposure Limits (OELs) and Recommended Exposure Limits (RELs) are established by industrial hygiene bodies worldwide to ensure Occupational Health and Safety (OHS) [8].

Adhering to these limits can affect the cost of machining processes, as mist collection systems might be needed to purify the workshop air [9]. The cycle time can also be affected, since particle concentrations may need to be extracted from the machine-tool enclosure, before opening the doors. Despite the obvious impact of OHS regulations on industrial production, this matter has received scant attention in the literature. In fact, no studies were found which measure the standby time required to extract the hazardous airborne particles from the work area, and combine it with tool and coolant consumption to achieve a holistic cost analysis.

This study employs a novel aerosol evaluation cell that simultaneously measures particle mass and size concentrations from nano to micro scale at high rates (1 Hz) for an industrial case study of aeronautical CFRP/Ti6Al4V stack drilling. The main contribution of this work is combining tool life and standby time required to open the doors of the machine tool at OHS safe particle concentration levels, to analyse the effect of different coolants and airflow extraction on the environmental impact and cost per hole.

2. Methodology

2.1. Overview of the experimental setup and plan

The CFRP/Ti6Al4V drilling case study was selected, since it presents machinability challenges due to mixed wear mechanisms and fluctuating loads [10], and includes several hazardous airborne emission sources. As composites can be degraded from moisture absorption when using emulsions [11], sustainable coolants such as MQL or LCO_2 may be employed when drilling composite/metal stacks [10]. Despite these alternatives minimise the use of coolant, they can create high oil mist concentrations or oxygen depletion in the workplace, and thus their effect on health must be analysed [7,8]. Additionally, the ultrafine dust-like chips from composite machining also cause pulmonary diseases [11].

The experiments were conducted in a LAGUN GVC1000-HS, equipped with through-tool emulsion and LCO_2+MQL delivery (Fig. 1a). An oil mist extractor (Filtermist FX5000) and an on-tool extractor (Nederman 216A EX – NE52) were used to evacuate the particles from the machine workspace (Fig. 1a). The machine was enclosed on all sides, and access to the work area was via sliding doors. The particle concentration was measured: (i) inside the machine-tool workspace with tubes inserted through a small hole next to the spindle to observe the peak values and settling times (blue marker in Fig. 1a), and (ii) outside to evaluate the exposure for

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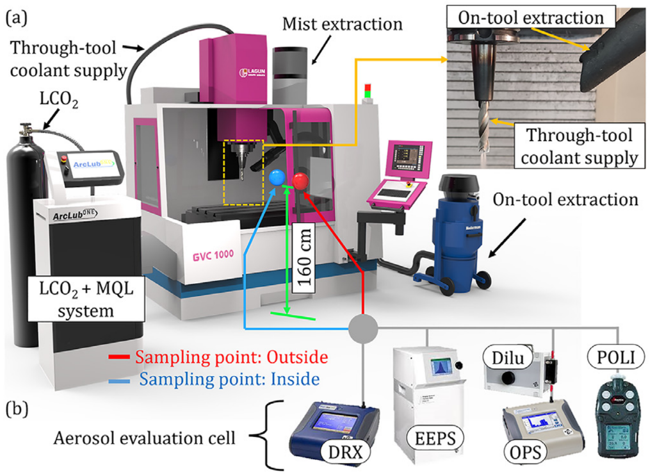

Abbreviation	Equipment name	Particles detected	Units	Channels
DRX	TSI DustTrak DRX 8533EP	PM1 – PM10	[mg/m^3]	5
EEPS	TSI EEPS 3090	5.6 – 500 nm	[#/cm^3]	32
OPS	TSI OPS 3330	300 – 10,000 nm	[#/cm^3]	16
Dilu	TSI Diluter 3332 1:10	Decreases sampled particle amount	-	-
POLI	WatchGas POLI	CO$_2$, CO	ppm	2

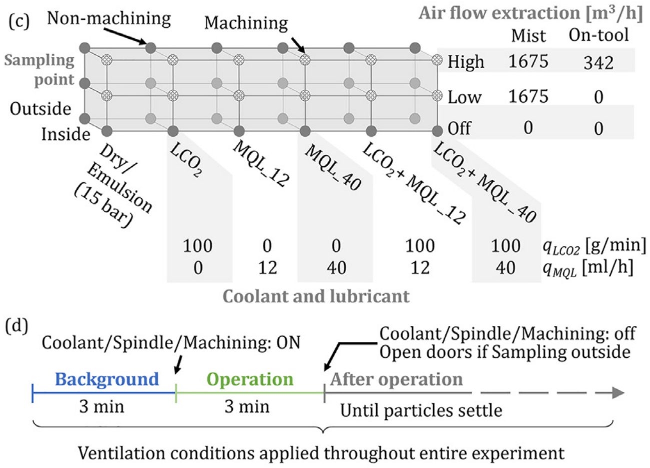

Fig. 1. (a) Experimental setup and sampling points; (b) Aerosol evaluation cell devices; (c) Tested conditions; (d) Experimental procedure.

a worker when opening the doors (red marker in Fig. 1a). Both sampling points were located next to the machine tool doors 160 cm from the ground to simulate the height of the respiratory tract of the operator (green arrow in Fig. 1a).

The aerosol evaluation cell was composed of several devices (Fig. 1b). The DustTrak DRX 8533EP measured particle mass concentration (mg/m^3), in accordance with EN 481. However, as mass concentration evaluations often underestimate nano scale particles due to their small mass [12], particle number concentration (#/cm^3) and their size distribution were also monitored. A TSI EEPS 3090 and TSI OPS 3330 were used for this latter purpose, with a particle size range of 5.6 nm to 10 μm, and sampling based on the ISO 28439 and CEN/TS 16976 standards.

The TSI OPS 3330 was equipped with a TSI Aerosol Diluter 3332 1:10 to prevent particle saturation. Since LCO$_2$ cooling was used, a Watchgas POLI CO$_2$ and CO detector was also employed to measure CO$_2$ concentrations in compliance with ISO 16000-26. All devices acquired samples at 1 Hz rate, to observe the evolution of particle concentration throughout the machining operation.

Non-machining tests (full dots in Fig. 1c) were combined with machining tests (hatched dots in Fig. 1c) to evaluate the contribution of coolants and lubricants to the total particle concentration when drilling the CFRP/Ti6Al4V stacks. In the machining tests, dry cutting particle emissions and tool life were compared to those when using sustainable cooling/lubrication, namely LCO$_2$, MQL and LCO$_2$+MQL. In the non-machining experiments, emulsion cooling was tested to compare the particle concentration generated by sustainable alternatives to that of conventional coolants. The emulsion contained Blaser Vasco 7000 oil at a 7 % concentration, and was supplied at 15 bar and 32 l/min. A non-polar oil (Bellini Harolbio 0) was used for the MQL and LCO$_2$+MQL tests.

The LCO$_2$ flow rate (q_{LCO2}) was 100 g/min, while MQL flow rates (q_{MQL}) were tested on two levels (12 ml/h and 40 ml/h). Oil mist and on-tool extraction technologies were combined to vary airflow extraction conditions. The oil mist extractor was activated to obtain the low condition (1675 m^3/h), and both extractors were used for the high condition (1675 + 342 = 2017 m^3/h).

The fixed experimental inputs included machining parameters (V_c = 75 m/min; f_n = 0.1 mm/rev), tool geometry (SECO SD203A-10.0-31-10R1-T), and workpiece dimensions (CFRP and Ti6Al4V plates of 350 mm × 250 mm × 5 mm).

All tests were carried out following the procedure defined in Fig. 1d. First, the background particle concentration was measured to ensure outside pollution did not affect the measurements. Then, a three-minute operation was performed, in which the coolant was activated and the stacks were drilled (for machining tests). The non-machining experiments utilized air cutting (N = 2378 rpm). In the experiments with an outside sampling point, the doors of the machine were opened immediately ($<$ 2 s) after the operation finished. When sampling inside the machine, the doors were kept closed after the operation to observe the settling of the particles.

For the machining experiments, 30 holes were drilled every test resulting in a three-minute operation under the given parameters. Particle concentrations were measured for the first 60 holes, and no variation was detected due to tool wear. A reduced experimental plan was carried out for machining experiments, following the results observed in the non-machining tests. Each test was repeated three times to determine the uncertainty.

2.2. Output evaluation methodology

The aerosol evaluation cell measured the particle mass and number concentrations, with their size distribution, as well as the CO$_2$ concentration every second. The results obtained from the EEPS and OPS were merged to obtain the size distribution curve from 5.6 nm to 10 μm, and the total particle number concentration was calculated by integrating the area below such curve (Fig. 2a).

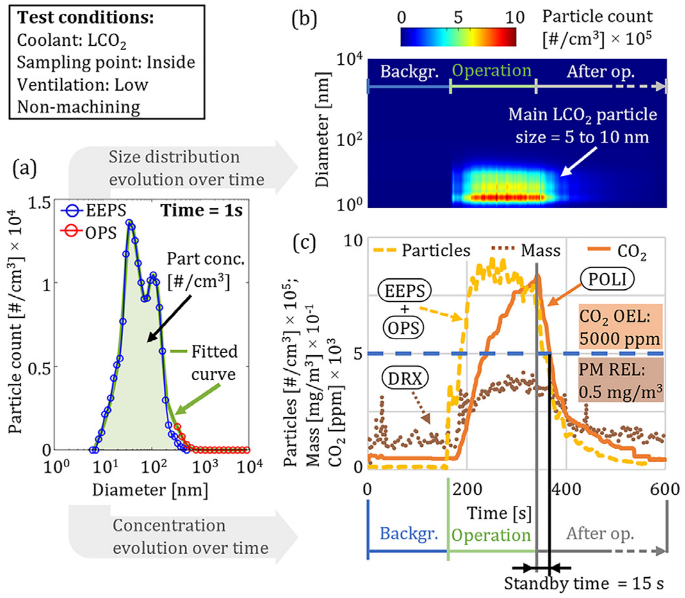

Fig. 2. (a) Particle size distribution and concentration; (b) Size distribution evolution; (c) Particle number, mass, and CO$_2$ concentration evolution.

The distributions sampled every second were combined to obtain the size distribution evolution over time (Fig. 2b). The total particle number concentration calculated in Fig. 2a, was plotted together with particle mass and CO$_2$ concentration, to observe their evolution and determine if OHS values were exceeded (Fig. 2c). Workplace OELs and RELs for particulate matter and CO$_2$ concentration vary from country

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to country. Currently, the most restrictive REL for particulate matter is that established by the American NIOHS at 0.5 mg/m^3 [8], and was thus selected for this study. The OEL of 5000 ppm set by the German IFA [13] was applied for CO_2 exposure. Although these values are for a time weighted average of 8 h, it was assumed that a process repeatedly exceeding OELs in short operations, would exceed OELs in 8-h shift. The standby time required to open the doors of the machine was calculated from the end of the operation, until both mass and CO_2 concentrations were below their respective thresholds. Fig. 2c shows how the CO_2 concentration was above the OEL after the operation, causing a standby time of 15 s, until the level dropped below the OEL.

Tool wear was monitored every 15 holes. Flank wear (VB) was measured using a Leica DMS1000 microscope (× 2 magnification) and an Alicona IF G4 optical 3D microscope (× 5 magnification) was used to examine the wear on the margin and rake face. The tool life criterion was set at VB = 300 μm, as per ISO 3685.

3. Results and discussion

3.1. Particle concentrations

Fig. 3 illustrates the particle concentrations of a non-machining LCO_2+MQL_q40 test, sampled both inside and outside the machine. It can be seen that the peak values for particle number, mass, and CO_2 concentration inside the machine-tool, and outside of the enclosure just after opening the doors coincide. This was observed in other non-machining tests. It was thus assumed that a worker opening the doors would be exposed to the particle concentration inside the machine at that exact moment. Based on this, sampling outside the enclosure was omitted for the machining tests.

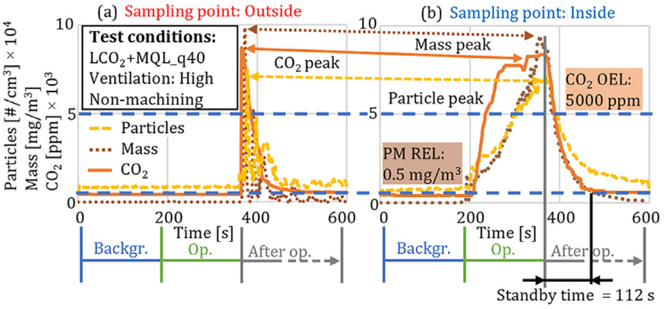

Fig. 3. Particle concentrations: (a) Outside; (b) Inside the machine-tool.

In Fig. 4 the maximum particle number (yellow bars), mass (brown bars), and CO_2 concentrations (orange bars) are plotted for all the conditions detailed in Fig. 1c, when sampling inside the machine. The standby time until the concentrations dropped below the OHS thresholds, is also shown in Fig. 4c and d. The non-machining tests demonstrate that when no airflow extraction is used, the mass and/or CO_2 concentrations do not go below OHS limits, even after 1000s (hatched bars in Fig. 4c) Thus, machining tests without airflow extraction were omitted (Fig. 4b and d).

In non-machining tests with pure LCO_2 cooling, the mass concentration stayed at background levels (0.1−0.15 mg/m^3), despite a high particle number concentration (red arrow in Fig. 4a). The size distribution of LCO_2 tests in Fig. 2b indicated that the main particle diameter ranges from 5 to 10 nm. This shows the relevance of measuring particles in number concentration, to avoid underestimating sub-micron particles due to their small mass. Similar results were reported by other researchers [9,12].

When employing emulsion or MQL, the mass concentration exceeded the REL (brown bars in Fig. 4a except LCO_2, and Fig. 4b except dry and LCO_2 with high airflow extraction). MQL created a greater particle concentration than emulsion cooling, likely due to greater coolant atomisation [7]. The MQL mist inside the machine tool created long standby times (see example in Fig. 3b). However, low MQL flow rates (q_{MQL} = 12 ml/h), greatly reduced the particle concentration and standby time (blue arrows in Fig. 4a and b).

The particle mass concentration when machining under dry and LCO_2 conditions report CFRP dust, which was below 0.5 mg/m^3 when using high airflow extraction (red arrows in Fig. 4b). The particle number concentration was higher than in the non-machining tests (green ellipses in Fig. 4b). This could greatly affect cycle time, however, as there is no regulated limit for particle number concentration, the standby time could not be calculated.

High airflow extraction (mist and on-tool) yielded the lowest particle concentrations. In the machining tests, 0 s standby time was achieved when no oils were used (dry and LCO_2). For the conditions that created high particle concentrations (MQL_q40 and LCO_2+MQL_q40), the high airflow extraction reduced the standby time by half compared to the low one (red lines in Fig. 4d).

3.2. Tool life and productivity

Flank wear for CFRP/Ti6Al4V stack drilling with different coolants is shown in Fig. 5a. The wear at the flank (Leica DMS1000) and tool margin (Alicona IF G4) are also shown, for certain conditions. Dry drilling yielded the worst tool life, exceeding 300 μm flank wear at 60 holes. Using LCO_2 and LCO_2+MQL helped prolong tool life considerably, as the cold temperature of the LCO_2 prevented adhesion wear in the drill margin and corner (Fig. 5a). This could be due to reduced thermal shrinkage when drilling the Ti6Al4V phase with sub-zero cooling, as reported by [14].

In Fig. 5b the productivity of each experimental condition is evaluated with tool life and standby time. Although high MQL flow rates ensured long tool life, they also caused long standby times. Pure LCO_2 cooling or LCO_2+MQL cooling/lubrication at q_{MQL} = 12 ml/h are potentially the most productive. Even if the longest tool life was not achieved, it was double that of dry drilling, and short standby times were possible when using high airflow extraction.

3.3. Implications of airborne emissions in machining costs

To understand the impact of workshop air quality on economic and environmental outputs, the standby time required to evacuate high airborne emissions must be considered. The effect of coolant, energy and cutting tool consumption were calculated according to [15], considering the obtained tool life and standby time results.

The carbon footprint (Fig. 6a) was calculated considering the eco-properties of the consumed materials (obtained from Granta EduPack 2023), and the average Carbon Emission Signature (CES) of the energy consumption in Europe (0.0575 kg CO_2/MJ) [15].

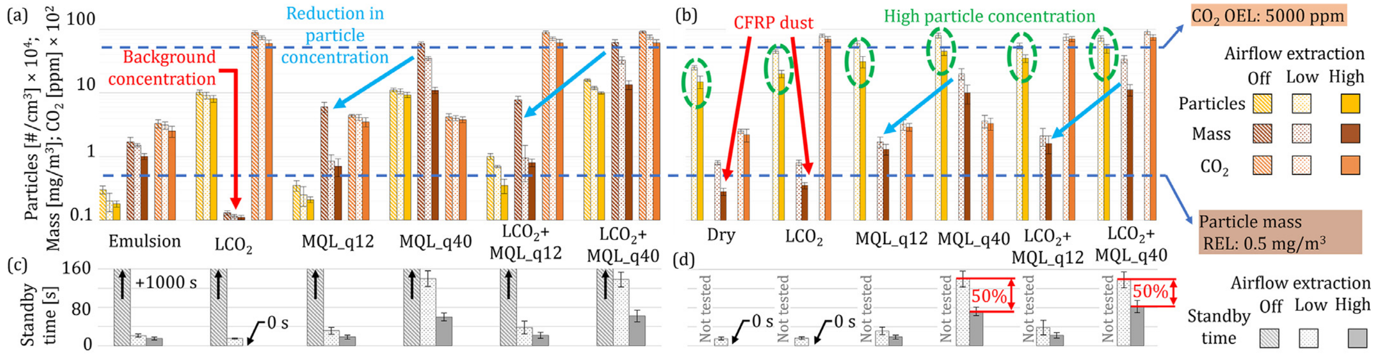

Fig. 4. Maximum particle, mass and CO_2 concentration: (a) Non-machining; (b) Machining, and door opening standby time: (c) Non-machining; (d) Machining.

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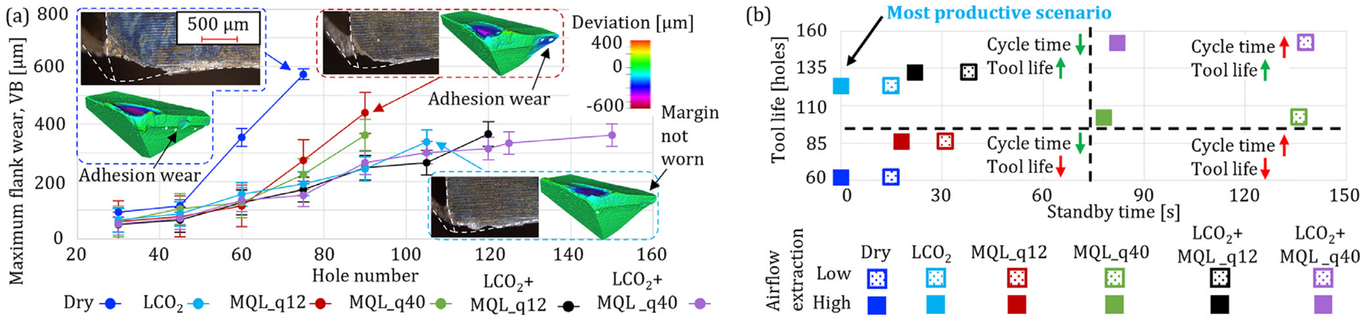

Fig. 5. (a) Flank wear evolution of drilling for each cooling and lubrication technique; (b) Tool life and standby time comparison.

Even if most CO_2 used by industry is a by-product of other processes, it must be liquified to use it as LCO_2 for cooling. Thus, an energy demand of 120 kWh/t was considered following [16].

Regarding the machining cost analysis (Fig. 6b), investments of 10,000 €, 20,000 €, and 40,000 € were assumed for the MQL, LCO_2, and LCO_2+MQL equipment, respectively. A cost of 20,000 € was assigned for the oil mist extraction, and 10,000 € for the on-tool extractor. Coolant cost was 6.7 €/kg for the LCO_2 and 50 €/litre for the MQL. The tools were costed at 20 € per drill bit. All these were based on average market values. The power consumption of the machine-tool was measured via internal signals, and the one of the extraction systems and cooling/lubrication equipment was approximated from their nominal power. The tool changing time was based on experimental data for shrink fit tool-holders (360 s).

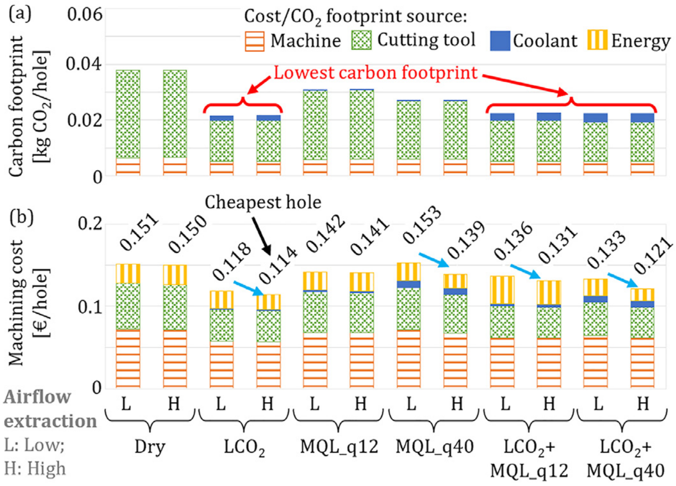

Fig. 6. (a) Carbon footprint and (b) Machining cost per hole.

The cutting tool was the most significant carbon footprint source (Fig. 6a). This might be due to tool life being low for CFRP/Ti6Al4V machining [10]. Thus, the coolants that ensured the longest tool life generated the lowest carbon footprint (red arrows in Fig. 6a). Despite the higher initial cost and energy consumption of the high extraction, the cost per hole was less than with the low one, due to shorter cycle times and less standby costs (blue arrows in Fig. 6b).

The results also show that pure LCO_2 cooling with high extraction produced the cheapest holes. In addition to LCO_2 having a smaller coolant cost than MQL and LCO_2+MQL, it lowered machine and cutting tool costs through fewer tool changes and standby time (0 s with high extraction, for existing OSH limits).

4. Summary and conclusions

A novel aerosol evaluation cell was employed to analyse airborne particle number, mass, and CO_2 concentrations, as well as their size distribution, in accordance with OHS regulations. A new procedure to monitor particle emissions from machining (cooling/lubrication and chips) was employed in a CFRP/Ti6Al4V stack drilling case study. Most relevant particle emission sources were identified, and the effect of air quality on machining costs was estimated.

The particle concentration results demonstrate that despite the small coolant consumption of MQL, high oil mists are generated due to atomisation. Reducing the amount of oil and maximising the extraction capacity are crucial to minimising oil mist concentration, and reducing the standby time to open the machine-tool doors at OHS safe levels.

When dry cutting and using pure LCO_2 cooling with mist and on-tool extraction no standby time was needed to evacuate particles and CO_2 from the machine-tool enclosure. Moreover, when using LCO_2, tool life was doubled in comparison to dry cutting, and a 30–40 % improvement was achieved compared to MQL at q_{MQL} = 12 m/h. This can therefore be considered an effective solution to increase productivity and reduce cost per part in CFRP/Ti6Al4V drilling without polluting the workshop air.

CRediT authorship contribution statement

Iñigo Rodriguez: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Pedro J. Arrazola:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing. **Franci Pušavec:** Conceptualization, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

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