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Characterising resource usage for a supercritical carbon dioxide cooling and lubricating system used in machining processes

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Abstract

Cryogenic or sub-zero media are increasingly used for cooling and lubrication (CL) of machining processes. Supercritical carbon dioxide ($scCO_2$) shows potential in both CL functions, being able to carry dissolved lubricant (MQL) into the cutting zone.
Evaluating environmental performance for different CL options requires detailed supporting information, via characterising system resource use. This represents a knowledge gap.
In this research a $scCO_2$ plus MQL delivery system was characterized for its consumption of CO_2 and MQL, system electrical energy and pneumatic air resources, in response to CO_2 exit nozzle orifice diameters. 72 flowrate tests were run with multiple repeats to assess variability. At 13.1 MPa (131 bar) supply pressure, as the nozzle diameter increased from 0.15 to 0.30 to 0.45 mm, the CO_2 flowrate increased from 5.2 to 17.0 then to 34.0 kg per hour. Pneumatic air flow through the system also increased, approximately in proportion to nozzle diameter, whilst system electric power consumption barely changed.
Calculated emissions were dominated (over 98 percent) by two resource flows: the direct release of CO_2 through the nozzle, plus the electricity driving pneumatic air input. MQL resources accounted for less than 1 percent of emissions. Annual projected running costs were dominated by the use of CO_2.
The efficient use of CO_2 is important to best deploy this promising CL technology into industry. This can be realised via means such as post-system CO_2 delivery design, and lowering system pressure. Future work will characterise $scCO_2$ plus MQL in full machining systems to optimize the process performance.

Keywords: machining; cooling; supercritical carbon dioxide; emissions; consumption; lubrication.

1. Introduction

Nomenclature

CE	carbon emissions
CL	cooling and lubricating
MQL	minimum quantity lubrication
$scCO_2$	supercritical carbon dioxide

1.1. Assessing cooling and lubricating media in machining

Cryogenic or sub-zero-temperature media have increasingly gained attention due to their capability for cooling and lubricating (CL) the cutting zone in support of machining processes. Potential benefits include (1) the avoidance of coolant liquid and mist which can be hazardous; (2) chilling the

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near-surface region of the workpiece to make it more machinable; and (3) interacting with the workpiece and tool materials in such a way as to reduce tool wear rates. More details on the nature and benefits of cryogenic cooling can be found in dedicated review articles [1, 2].

This research paper focusses on the use of carbon dioxide, mainly in the supercritical ($scCO_2$) state, functionalised as a coolant and as a carrier of a small dose of dissolved oil, referred to as minimum quantity lubrication (MQL). Resource flows, resource consumption and environmental impact are the focus of this work, so research findings on that subject have been investigated.

In pursuit of the 'typical' flowrate for CO_2 in CO_2-assisted machining, a meta-analysis has been done from publications to date [3 to 17]. Considering these 15 CO_2 machining papers which include delivery systems running at any supply pressure, the minimum CO_2 flowrate found was 7 kg/hour and the maximum was 55 kg/hour, with an average of 19.5 kg/hour flowrate. For comparison, in a prior meta-analysis Supekar et al. [18] compiled flowrates for multiple CL media across 29 published studies and found a median CO_2 flowrate at a higher level of 42 kg/hour.

In terms of consumption data for status quo liquid emulsion coolants, the prior literature [18, 19, 20] contains useful information regarding for instance standard sump sizes, coolant concentration and fluid pumping power. Calculations of carbon emissions for machining CL systems should also take into account the life cycle of the CL media. The UKLA [21] has produced a useful guide to the make-up of metalworking lubricants, and treatment options at the end of life.

In 2006 Narita et al. [20] calculated carbon emissions for machining based on the use of (a) machine electricity, (b) cutting tools, (c) coolants, (d) cut metal chips and (e) machine lubricants, by compiling relevant greenhouse gas emissions factors from various sources. They then applied their calculations to three case studies, which tentatively pointed to higher cutting speeds incurring lower process emissions.

Pusavec et al. [22, 23] carried out life cycle assessment for a turning process, to compare liquid nitrogen performance against that of standard and high-pressure emulsion coolant. Six environmental impact categories including greenhouse gas emissions were evaluated, as well as financial costs, with the pros and cons of each option discussed. Li et al. [24] calculated carbon emissions for machining based on the process resources (a) to (d) as above. They used resource emissions factors compiled from sources including the Intergovernmental Panel on Climate Change (IPCC).

Pereira et al. [25] tested dry, MQL and cryo-type CL to assist the turning of 304 stainless steel. They used life cycle assessment to evaluate environmental impact in nine categories. They argued that MQL, liquid nitrogen and sub-critical CO_2 alone were not the best-performing options, so MQL should be combined with cryo-type CL. Kim et al. [26] compared emissions for different CL strategies in the turning of steel. They compared dry and wet strategies against liquid nitrogen based cryogenic cooling. The lowest carbon emissions were for the case where the liquid nitrogen jet was applied to the tool flank. The authors made use of emissions factor data from prior research literature. Emissions factors from the literature were also used by Khan et al. [27] in their calculations to find that nitrogen-based cryo-MQL CL led to greater carbon emissions than the use of flood-delivered emulsion in titanium turning, with the nitrogen use accounting for a significant percentage of the process's emissions. Khanna et al. [28] compared eight different CL strategies in the turning of stainless steel. Tool wear was not considered in their study. The outcomes showed MQL with hybrid nanoparticles having the largest negative environmental impact, and liquid nitrogen having a lower environmental impact than liquid CO_2.

Meanwhile the UK government and other governments [29, 30] have published resource emissions factors for organisations to use in carbon reporting, including release of gases and the production of mains water, mineral oil and plastics. Data is useful for life cycle modelling of manufactured products. The UK's carbon intensity from electricity production was 149 g CO_2 per kWh in 2023 as reported by the National Grid [31].

Li et al. [32] calculated carbon emissions for an aluminium ball end milling process, based on electricity and cutting tool consumption, in order to optimise the milling tool path to minimise emissions. They eliminated workpiece material and cut chips (swarf) from their studies with justification. Coolant was eliminated due to dry cutting. Jiang et al. [33] reviewed previous carbon emissions optimisation research for machining. Furthermore they produced their own optimisation of a turning process. Resources accounted for as emissions sources were (a) to (d), as per the review of Narita et al. above.

1.2. Quantifying global warming impact of cooling and lubricating systems

The comparison of environmental performance for different machining process CL options requires detailed supporting information and analysis in terms of resource impact and aggregated resource usage. For various CL technologies this represents a knowledge gap.

The motivation for this study is thus to investigate the system resource use and the environmental and economic impact for supercritical carbon dioxide plus minimum quantity lubrication ($scCO_2$ plus MQL) based CL in detail, as a function of the CO_2 outlet nozzle diameter. The environmental impact focusses on global warming and incurred greenhouse gas emissions. Multi-resource consumption data have been collected for the system, and CO_2 equivalent emissions data have then been calculated.

The carbon emissions from the CL system, *CEme*, are based on the consumption of CL media and electricity. *CEme* is defined as the sum of the carbon emissions within the analysed boundary.

$$CEme = CEelec\_p + CEelec\_s + CEc + CEo + CEw \quad (1)$$

$$CEelec_p = Vpneu.Cpneu.CEFelec. \quad (2)$$

Where *CEelec* is the carbon emissions from generation of electricity for pneumatic air supply (*_p*), and for direct supply to the supercritical CO_2 system (*_s*). *CEc* is the direct CO_2 emissions released from the nozzle. *CEo* and *CEw* are emissions due to mineral oil and water use respectively, in the form of the MQL lubricant spray.

CEelec_p is consumed by the factory's pneumatic compressor supplying air to the CL system, based on the air flow rate *Vpneu* into the system and calculated via the specific pneumatic energy factor *Cpneu* and the carbon intensity of the electricity supply which is *CEFelec*.

Modelling points to note are as follows.

- Each CE carbon emissions value is equal to the mass or amount of each resource, multiplied by a case-specific carbon emissions factor.
- Of the various environmental impacts specified in ISO 14040, global warming potential and greenhouse gas emission (CO_2 equivalent) is studied in this work.
- Over 80 percent of industrial CO_2 supplied (sold) in Europe has been captured from industrial chemical processes [34]. In that sense the market for captured industrial CO_2 improves the environmental performance of those chemical processes. Considering the upstream pre-processing of the CO_2 as a separate activity in terms of scope, and in line with various governments' greenhouse gas reporting guidelines [29, 30], this study assumes that 1 kg CO_2 released through the scCO_2 delivery system out to the atmosphere via an exit nozzle is a release equivalent to 1 kg CO_2 equivalent emissions.
- By accounting for the system's CO_2 release in a science-based framework, a useful driver is created to reduce such emissions if they are found significant.
- Inclusion of CO_2 up-stream compression, purification, storage and transportation activities in supply would increase the assumed emissions factor for industrial CO_2, however this increase is expected to be small relative to the two points above.
- MQL fluid is used in its undiluted form as supplied. Based on [21], the condition of supply is assumed to contain 75 % mineral oil, and a volume of functional additives assumed small, with the balance being water.
- It is furthermore assumed that carbon emitted due to maintaining CO_2-based delivery systems in good working order, and provision of support equipment such as CO_2 concentration monitors, are minimal in their relative impact.
- The scope and focus in this work is the fundamental characterization of the scCO_2 plus MQL CL system. Thus the effect of the system on the quality and productivity of a machining process and the machined parts are not considered in this study.

2. Experimental work

2.1. Hardware

The following hardware was used in trials, with reference to Figures 1 and 2. The patent-protected method for delivery of scCO_2 for CL of machining processes is the Fusion Coolant Systems Pure-Cut Plus system. The system has a top and bottom unit which include the functions of increasing the CO_2 pressure, heating the CO_2, injecting an MQL oil and adjusting and monitoring the media flow rates.

On the input side of the system, CO_2 was supplied from a pallet containing 500 kg of BOC industrial-grade bottled CO_2. On the output side was an 11 m long hose with 6 mm internal diameter, ending in a manifold and an 80 mm long pipe of 2 mm internal diameter, which terminated with exchangeable M3-threaded grub screw style CO_2 nozzles. The nozzles have internals made of wear-resistant sapphire, and exit orifices in the diameter range 0.15 to 0.45 mm [35].

Two flow meters were fitted to the scCO_2 delivery system by the manufacturer: a coriolis mass flow meter for CO_2, and a volumetric flow meter for MQL.

A Fluke 1732 power meter was used for measuring and averaging the scCO_2 delivery system's power draw over time. The system's top and bottom units each have a separate 50 Hz AC mains power cable and plug. The Fluke logged the power drawn by both units combined.

The system uses a pneumatic air-driven pump to increase the CO_2 input pressure (5 MPa, where 1 MPa equals 10 bar) up to an adjustable supercritical level (i.e. at least 7.4 MPa). An in-line IFM SD6000 unit measured the flow rate versus time of pneumatic compressed air into the system from the factory's 0.7 MPa supply.

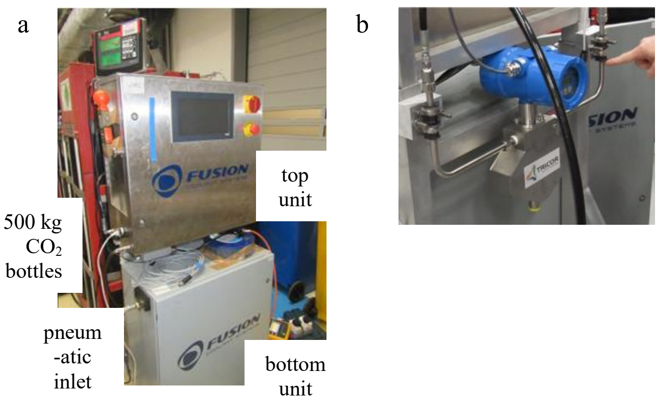

Fig. 1. scCO_2 plus MQL delivery system: (a) front view showing units plus CO_2 pallet, and; (b) rear view showing coriolis meter.

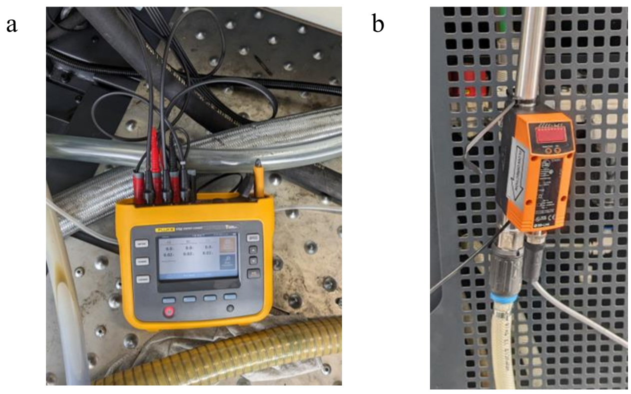

Fig. 2. Flow measurements: (a) electrical power meter, and; (b) pneumatic air flow meter.

2.2. Method

In these tests the $scCO_2$ system exit pressure was controlled to 13.1 MPa ± 1 %, by varying the pneumatic air pressure using a valve. Slight air pressure modifications were required from run to run to counteract the effect of environmental temperature and mass reduction in the CO_2 bottles. Nozzles with four different exit hole diameters were screwed in and out of the system's threaded exit pipe, with PTFE tape applied to the threads to avoid CO_2 leakage.

The system's CO_2, MQL, pneumatic air and electrical energy flowrates were measured against time, and average values found for the appropriate time interval (see section 3). The CO_2 system was started, then flowrate was measured, then the system was stopped, in total 72 times in order to test for variability. CO_2 monitors and an air extraction system were used to ensure that CO_2 levels remained below the safe exposure limit 5000 parts per million.

3. Results

Figures 3 to 6 convey consumption data versus nozzle size for the $scCO_2$ delivery system in terms of (Figures 3 and 6) CO_2, (Figure 4) system electrical energy and (Figure 5) pneumatic air. With reference to Figure 3, flow variables for the system are transient at first, then are time-varying later but with a steady and cyclic repeating pattern. The transient period lasts for tens of seconds from observation, with a duration partly dictated by the delivery hose length and the exit nozzle size. Figure 3 shows the initially high flow period then 'steady repeating' CO_2 flowrate, as measured against time from the moment of system start. Due to the transient period, average CO_2 flow values were collected over several minutes of the system running, with the first minute after system start being discounted.

Summary values and findings from Figures 4 to 6 are as follows. The electrical consumption of the $scCO_2$ delivery system was minimally affected by the exit nozzle size and the resulting CO_2 flow rate. The time-averaged mains power draw for the system's top and bottom units combined was 311 W with ±6 % variation.

At the same time, the system drew air from the factory's pneumatic supply. Air flow was found to change significantly in response to a change in nozzle size. When the nozzle diameter was 0.15 mm, the average pneumatic flowrate was 7.25 m^3/ hour. When the nozzle diameter tripled to 0.45 mm, the average flowrate almost tripled to be 21.0 m^3/ hour of air. As per Equation 2, the pneumatic electrical power consumption increases in proportion to the air flowrate.

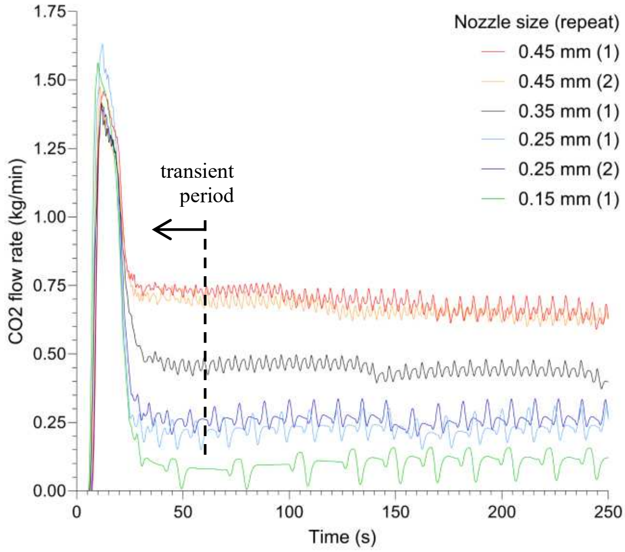

Fig. 3. System CO_2 flow rate against time for four nozzle sizes.

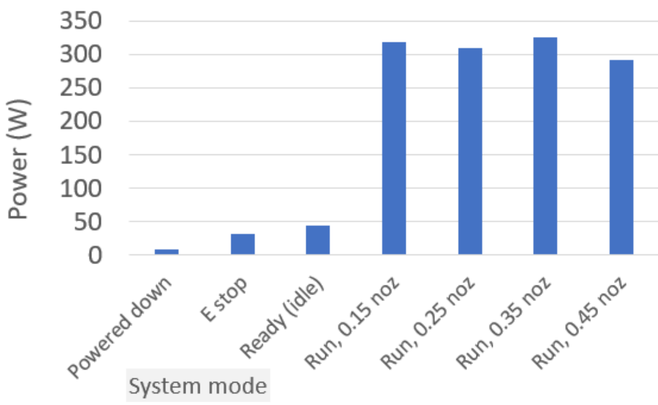

Fig. 4. System electrical power consumption. 'noz' is nozzle diam (mm).

In terms of CO_2 released, when using a 0.15 mm diameter nozzle the average CO_2 flowrate was measured to be 5.2 kg/ hour. For a 0.45 mm nozzle diameter, the average CO_2 flowrate was measured to be over six times higher at 34.0 kg/ hour. At the same time the MQL flowrate was set at the same level throughout flowrate testing, and was measured in all cases to be 40 ml/ hour to within ±4 percent.

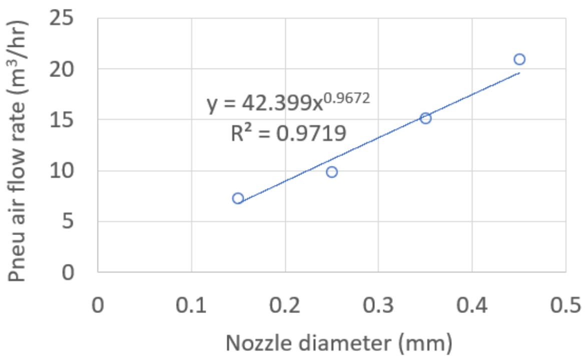

Fig. 5. System pneumatic air consumption versus nozzle size.

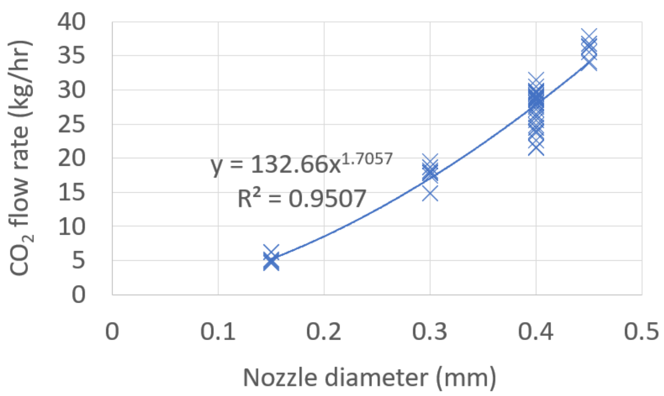

Fig. 6. System CO_2 flow rate against nozzle size: results from 72 tests.

4. Assessment of emissions and cost

Using the data collected as above and in Table 1, annual projected carbon emissions were calculated via Equations 1 and 2 for the CL system. Relatively small, medium and large nozzle cases are analysed.

Table 1. Carbon emission factors, constants and assumptions in calculations.

CO2 gas release, 1 kgCO2e/kg [29]
Water supply, 0.000153 kgCO2e/litre [29]
Mineral oil manufacturing, 1.4 kgCO2e/kg, or 1.2 kgCO2e/litre [29]
Assume mineral oil makes up 75% of coolant concentrate [21]
Cpneu, pneumatic system electrical energy factor, 0.11 kWh/ m^3 [36]
CEFelec, carbon intensity for electricity production, 0.149 kgCO2e/kWh [31]
Assume 2000 hrs machining per year. Delivery systems switched off at other times

Table 2. Calculated carbon emissions from $scCO_2$ CL delivery system.

scope: scCO2 delivery system electricity, CO2 and MQL	**nozzle cases**		
	Low	Med	High
Nozzle d (mm)	0.15	0.30	0.45
CO2 flowrate for nozzle size (kg /hr)	5.22	17.02	33.98
CEc, nozzle CO2 emissions annually (kg/ year)	10433	34033	67960
Pneumatic air throughput rate (m^3/ hr)	6.77	13.23	19.59
Pneumatic air throughput rate (m^3/ year)	13536	26464	39172
Pneumatic elec consumption rate (kWh/ year)	1489	2911	4309
CEelec_p, pneumatic elec emissions (kg/ year)	221.86	433.75	642.02
System elec consumption rate (W)	311	311	311
System elec consumption (kWh/ year)	622	622	622
CEelec_s, system elec emissions (kg/ year)	92.68	92.68	92.68
MQL mineral oil consumption (ml/ hr)	30	30	30
MQL mineral oil consumption (l/ year)	60	60	60
CEo, MQL mineral oil emissions (kg/ year)	72	72	72
MQL water consumption (ml/ hr)	10	10	10
MQL water consumption (l/ year)	20	20	20
CEw, MQL water emissions (kg/ year)	0.0031	0.0031	0.0031
CEme, summed CO2e emissions (kg/year)	**10820**	**34631**	**68767**

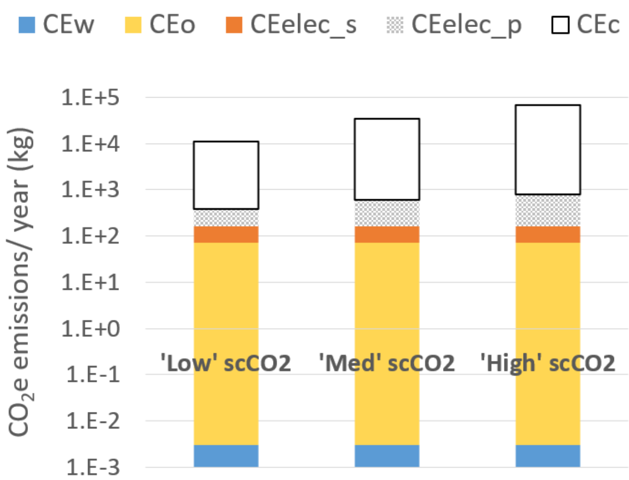

Fig. 7. Emissions versus nozzle size, for $scCO_2$+MQL CL system.

Table 2 and Figure 7 present the same data, in tabular and graphical format respectively. Low, medium and high CL consumption cases are itemized for the specified scope, with summed annual carbon equivalent emissions. Note that Figure 7 is logarithmic, to show numbers of different magnitudes. The table and figure show that calculated emissions were dominated by firstly the direct release of CO_2 through the nozzle, and secondly by the pneumatic power requirement. These two resources account for over 98 percent of calculated emissions. As can be appreciated from Figure 7, if the 'nozzle CO_2' *CEc* contribution (the unfilled bar area) was omitted from consideration due to use of CO_2 which is mostly recaptured upstream, $scCO_2$ CL fares better in emissions terms. In this work *CEc* is considered within the emissions scope, for the reasons provided in section 1.2.

System electrical power and MQL fluid account for the remaining emissions. Mineral oil use and system electrical power generate emissions of a similar magnitude, whilst water use causes a relatively very low contribution. MQL is responsible for less than 1 percent of the total greenhouse gas emissions.

Table 3. Running cost calculations for $scCO_2$ plus MQL CL resources.

	Annual costs (£)		
Resource	Low	Med	High
CO_2	10433	34033	67960
MQL lubricant	1400	1400	1400
Pneumatic elec	313	611	905
System elec	131	131	131
Combined (sum)	**12277**	**36175**	**70396**

CO_2, £1 per kg Electricity, £0.21 per kWh
MQL lubricant, £17.50 per litre

5. Discussion

Considering an average of at least 19.5 kg/hour CO_2 flowrate from recent literature, for sub-critical and supercritical CO_2 machining research (section 1.1), Table 2 provides an interesting comparison. For context 19.5 kg/hour is slightly higher than the medium $scCO_2$ flowrate case of Table 2.

To be clear, this study's scope and focus for investigation is the $scCO_2$ plus MQL CL system itself, and thus the effect of $scCO_2$ plus MQL on performance in machining is not integrated into the analysis. Cutting tool wear/ tool life performance will vary with $scCO_2$ plus MQL flowrates, and has often been seen to improve versus the status quo when cryo-type CL media are applied [5, 7, 37]. This effect would potentially drive reduced emissions within the wider system based on lower tool and machine power consumption, to offset the use of CL media. Notably CO_2 machining has some important industrial niches where surface cleanliness and lack of contamination or greasiness are paramount for health and safety or hardware compatibility reasons, meaning that liquid-based CL media are not always an option.

Table 2 argues for an economical mentality towards the use of the CO_2. For instance it may be wise to start at the lower end of the available nozzle cross-section options at the system exit point, and the lower-end system pressure, when proving out machining processes for $scCO_2$ plus MQL.

Different machining (subtractive processing) technologies will require different CO_2 delivery and CO_2 exit options in terms of geometry. Whilst turning operations tend to have a small tool-workpiece interface zone suited to coolant applied to a point in space (nozzle use), a milling or grinding setup will likely work better with coolant applied along a line-like geometry. For solid milling tools and drills, through-tool holes are common for coolant delivery. In each case the cross-sectional area at exit will determine the flow rate of the medium. Through-spindle and through-tool CO_2 delivery are slightly harder to achieve than external delivery in terms of hardware design and manufacture, but through-tool supply will make more efficient use of the CO_2, which as has been seen is important for emissions.

The trials of this study were run at 13.1 MPa. A minimum of 7.4 MPa is required for the supercritical state, so the pressure could be reduced.

The system's running costs are now discussed. These have been evaluated in Table 3, based on Table 2 usage plus billing and invoice data from UK suppliers. MQL is costed in terms of the formulated product, as sold. Purchasing bottled CO_2 on a relatively small scale (around 1500 kg per annum) leads to an all-in service cost of approximately £1 per kg. Whilst MQL causes less emissions than the system's electrical requirement, it incurs more cost than the required electricity. Bottled CO_2 represents the greatest consumable cost for running the CL system.

Finally, accurate emissions calculations depend on good input data, including resource emissions factors. Further research towards granularity for the emissions factors in the literature would be of value. This is expected to require a globally distributed effort over time, due to different configurations and practices occurring with different locations and technology providers.

6. Conclusions

- Experiments carried out on a supercritical CO_2 ($scCO_2$) plus minimum quantity lubrication (MQL) delivery system for machining, operating at 13.1 MPa (131 bar), demonstrated that as the exit nozzle diameter increased from 0.15 (lowest) to 0.30 then to 0.45 mm (highest), the flowrate of CO_2 increased from 5.2 to 17.0 then to 34.0 kg/hour respectively.
- The flowrate order of magnitude is as per prior CO_2 machining literature, where an average of 19.5 kg/hour was extracted.
- The pneumatic air flow rate through the system also increased with nozzle diameter, roughly in proportion, whilst system electric power consumption barely changed.
- Carbon equivalent emissions were calculated for the use of media plus electricity. Calculated emissions were dominated (over 98 percent) by two resources: the direct release of CO_2 through the nozzle, plus electricity to drive pneumatic air through the system.
- MQL resources accounted for less than 1 percent of system emissions.
- Annual projected system running costs were dominated by the use of CO_2.
- The above suggests that the efficient use of the CO_2 is important to best deploy this promising cooling and lubricating technology. Efficient use can be realised via numerous means, such as nozzle size optimisation and through-tool CO_2 delivery.
- Future work will include building on this characterisation activity by integrating the system into various machining processes, and varying delivery parameters to test the associated benefits.

Acknowledgements

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References

[1] Jawahir IS, Attia H, Biermann D, Duflou J, Klocke F, Meyer D, Newman ST, Pusavec F, Putz M, Rech J, Schulze V. Cryogenic manufacturing processes. CIRP Ann 2016 Jan 1;65(2):713-36.

[2] Proud L, Tapoglou N, Slatter T. A review of CO_2 coolants for sustainable machining. Metals 2022 Feb 5;12(2):283.

[3] Jerold BD, Kumar MP. Experimental comparison of carbon-dioxide and liquid nitrogen cryogenic coolants in turning of AISI 1045 steel. Cryogenics 2012 Oct 1;52(10):569-74.

[4] Stephenson DA, Skerlos SJ, King AS, Supekar SD. Rough turning Inconel 750 with supercritical CO_2-based minimum quantity lubrication. J Mater Process Technol 2014 Mar 1;214(3):673-80.

[5] Sadik MI, Isakson S, Malakizadi A, Nyborg L. Influence of coolant flow rate on tool life and wear development in cryogenic and wet milling of Ti-6Al-4V. Procedia CIRP 2016 Jan 1;46:91-4.

[6] Bergs T, Pušavec F, Koch M, Grguraš D, Döbbeler B, Klocke F. Investigation of the solubility of liquid CO_2 and liquid oil to realize an internal single channel supply in milling of Ti6Al4V. Procedia Manuf 2019 Jan 1;33:200-7.

[7] Wika KK, Litwa P, Hitchens C. Impact of supercritical carbon dioxide cooling with Minimum Quantity Lubrication on tool wear and surface integrity in the milling of AISI 304L stainless steel. Wear 2019 Apr 30;426:1691-701.

[8] Wika KK, Gurdal O, Litwa P, Hitchens C. Influence of supercritical CO_2 cooling on tool wear and cutting forces in the milling of Ti-6Al-4V. Procedia CIRP 2019 Jan 1;82:89-94.

[9] Courbon C, Sterle L, Cici M, Pusavec F. Tribological effect of lubricated liquid carbon dioxide on TiAl6V4 and AISI1045 under extreme contact conditions. Procedia Manuf 2020 Jan 1;47:511-6.

[10] Gross D, Blauhöfer M, Hanenkamp N. Milling of Ti6Al4V with carbon dioxide as carrier medium for minimum quantity lubrication with different oils. Procedia Manuf 2020 Jan 1;43:439-46.

[11] Sterle L, Krajnik P, Pušavec F. The effects of liquid-CO_2 cooling, MQL and cutting parameters on drilling performance. CIRP Ann 2021 Jan 1;70(1):79-82.

[12] Arafat R, Madanchi N, Thiede S, Herrmann C, Skerlos SJ. Supercritical carbon dioxide and minimum quantity lubrication in pendular surface grinding–a feasibility study. J Clean Prod 2021 May 10;296:126560.

[13] Taylor E. Characterisation of cryogenically assisted drilling of titanium alloy. Doctoral dissertation, University of Sheffield 2021.

[14] Jamil M, Zhao W, He N, Gupta MK, Sarikaya M, Khan AM, Siengchin S, Pimenov DY. Sustainable milling of Ti–6Al–4V: a trade-off between energy efficiency, carbon emissions and machining characteristics under MQL and cryogenic environment. J Clean Prod 2021 Jan 25;281:125374.

[15] Khosravi J, Azarhoushang B, Barmouz M, Bösinger R, Zahedi A. High-speed milling of Ti6Al4V under a supercritical CO_2+ MQL hybrid cooling system. J Manuf Process 2022 Oct 1;82:1-4.

[16] Proud L, Tapoglou N, Wika KK, Taylor CM, Slatter T. Role of CO_2 cooling strategies in managing tool wear during the shoulder milling of grade 2 commercially pure titanium. Wear 2023 Jul 15;524:204798.

[17] Wika KK, Litwa P, Maurotto A. Effect of cutting parameters and CO_2 flow rate on surface integrity in milling AISI 316L steel using supercritical CO_2. Procedia CIRP 2024 Jan 1;123:1-6.

[18] Supekar SD, Graziano DJ, Skerlos SJ, Cresko J. Comparing energy and water use of aqueous and gas-based metalworking fluids. J Ind Ecol 2020 Oct;24(5):1158-70.

[19] Martínez Herrero E, Pereda Pereda L, Huidobro Fernández F, Monje Pardo JC, Urquidi Sandoval B. An environmental evaluation of a milling machine range: a case study on reconfigurable approach. SN Appl Sci 2019 Nov;1:1-0.

[20] Narita H, Kawamura H, Norihisa T, Chen LY, Fujimoto H, Hasebe T. Development of prediction system for environmental burden for machine tool operation (1st report, proposal of calculation method for environmental burden). JSME Int J Ser C 2006;49(4):1188-95.

[21] United Kingdom Lubricants Association (Chipasa K), Best Practice Guide for the Disposal of Water-mix Metalworking Fluids, UKLA, 2011 [cited 2024 Aug 18]. Available from: https://www.ukla.org.uk/wp-content/uploads/UKLA-PERA-Best-Practice-Guide-for-the-Disposal-of-Water-mix-Metalworking-Fluids.pdf

[22] Pusavec F, Krajnik P, Kopac J. Transitioning to sustainable production–Part I: application on machining technologies. J Clean Prod 2010 Jan 1;18(2):174-84.

[23] Pušavec F, Kopač J. Sustainability assessment: cryogenic machining of Inconel 718. Strojniški vestnik-J Mech Eng 2011 Sep 15;57(9):637-47.

[24] Li C, Tang Y, Cui L, Li P. A quantitative approach to analyze carbon emissions of CNC-based machining systems. J Intell Manuf 2015 Oct;26:911-22.

[25] Pereira O, Rodríguez A, Fernández-Abia AI, Barreiro J, De Lacalle LL. Cryogenic and minimum quantity lubrication for an eco-efficiency turning of AISI 304. J Clean Prod 2016 Dec 15;139:440-9.

[26] Kim DM, Kim HI, Park HW. Tool wear, economic costs, and CO_2 emissions analysis in cryogenic assisted hard-turning process of AISI 52100 steel. SM&T 2021 Dec 1;30:e00349.

[27] Khan AM, Zhao W, Li L, Alkahtani M, Hasnain S, Jamil M, He N. Assessment of cumulative energy demand, production cost, and CO_2 emission from hybrid CryoMQL assisted machining. J Clean Prod 2021 Apr 10;292:125952.

[28] Khanna N, Shah P, Sarikaya M, Pusavec F. Energy consumption and ecological analysis of sustainable and conventional cutting fluid strategies in machining 15–5 PHSS. SM&T 2022 Jul 1;32:e00416.

[29] UK Government, GHG Emissions Reporting Guidance (Emissions Factors), UK Gov, 2024 [cited 2024 Aug 18]. Available from: https://www.gov.uk/government/publications/environmental-reporting-guidelines-including-mandatory-greenhouse-gas-emissions-reporting-guidance

[30] USA Environmental Protection Agency, GHG Emissions Factors Hub, EPA, 2024 [cited 2024 Aug 18]. Available from: https://www.epa.gov/system/files/documents/2024-02/ghg-emission-factors-hub-2024.pdf

[31] UK National Grid, Renewable Energy, UKNG, 17/01/2024 [cited 2024 Aug 18]. Available from: https://www.nationalgrid.com/stories/energy-explained/how-much-uks-energy-renewable#:~:text=2023%20was%20the%20greenest%20year,achieved%20on%2018%20September%202023

[32] Li L, Deng X, Zhao J, Zhao F, Sutherland JW. Multi-objective optimization of tool path considering efficiency, energy-saving and carbon-emission for free-form surface milling. J Clean Prod 2018 Jan 20;172:3311-22.

[33] Jiang Z, Gao D, Lu Y, Shang Z, Kong L. Optimisation of cutting parameters for minimising carbon emissions and cost in the turning process. J Mech Eng Sci 2022 Feb;236(4):1973-85.

[34] European Industrial Gases Association, The Carbon Dioxide Industry and the Environment, EIGA, 2020 [cited 2024 Aug 18]. Available from: https://www.eiga.eu/uploads/documents/DOC101.pdf

[35] MVT Micro Technologies, Sapphire screw-in nozzle specifications, MVT, 2024 [cited 2024 Aug 18]. Available from: https://www.mvt.ch/en/products/sapphire-screw-in-nozzles

[36] Gontarz AM. Energy assessment of machine tools within manufacturing environments. Doctoral dissertation, 2015, ETH Zurich, Switzerland.

[37] Xu N, Taylor CM. Latest performance findings in milling of three titanium based alloys, using supercritical CO_2 and MQL for cooling and lubrication. Presentation at Advanced Cooling event, 21/09/2023, Nuclear AMRC, Sheffield, UK.