



Comparison of dry and liquid carbon dioxide cutting conditions based on machining performance and life cycle assessment for end milling GFRP

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Received: 15 April 2022 / Accepted: 22 July 2022 / Published online: 17 August 2022

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Abstract

In the present scenario, citizens' concern about environment preservation creates a necessity to mature more ecological and energy-efficient manufacturing processes and materials. The usage of glass fiber reinforced polymer (GFRP) is one of the emerging materials to replace the traditional metallic alloys in the automotive and aircraft industries. However, it has been comprehended to arise a sustainable substitute to conventional emulsion-based coolants in machining processes for dropping the destructive effects on the ecosystem without degrading the machining performance. So, in this study, the comparison of the two sustainable cutting fluid approaches, i.e., dry and LCO₂, has been presented based on machining performance indicators like temperature, modulus of cutting force, tool wear, surface roughness, power consumption, and life cycle assessment (LCA) analysis for end milling of GFRP. The cutting condition of LCO₂ has been found to be superior in terms of machining performance by providing 80% of lower cutting zone temperature, tool wear, 5% lower modulus of cutting force, and reduced surface roughness with 9% lower power consumption that has been observed in the case of LCO₂ in comparison with dry machining. However, to compress the CO₂ for converting in liquid form, a higher amount of energy and natural resources is consumed resulting in a higher impact on the environment in comparison with dry machining. Considering the 18 impact categories of ReCiPe midpoint (H) 2016, 95% higher values of impacts have been observed in the case of LCO₂ in comparison with dry machining.

Keywords GFRP · End milling · Liquid carbon dioxide · Life cycle assessment · Machinability indicators

Nomenclature

LCA Life cycle assessment
FRS Fossil resource scarcity
FPMF Fine particulate matter formation

WC Water consumption
ME Marine eutrophication
MET Marine ecotoxicity
SD Stratospheric ozone depletion

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MS	Mineral resource scarcity
OFTE	Ozone formation, terrestrial ecosystems
HNCT	Human non-carcinogenic toxicity
GFRP	Glass fiber reinforced polymer
TA	Terrestrial acidification
OFHH	Ozone formation, human health
IR	Ionizing radiation
FE	Freshwater ecotoxicity
LU	Land use
HCT	Human carcinogenic toxicity
GW	Global warming
TE	Terrestrial ecotoxicity

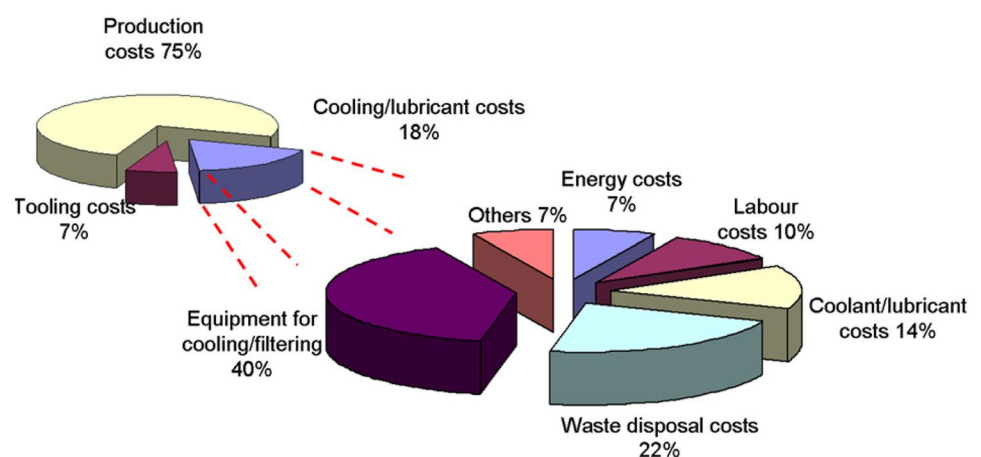
1 Introduction

Glass fiber reinforced polymer (GFRP) is one of the composites materials in which glass is used as reinforced material while thermosetting plastic, phenol–formaldehyde, and vinyl ester are generally used as matrix materials [1, 2]. The GFRP possesses an exceptional specific strength, resistance to corrosion, fatigue, microorganisms, and chemical along with its lightweight which is the prime requirement in aviation and automobile industries. Thus, their applications are extensively found in aerospace, automobile, spaceships, and marine sectors. All the parts needed to be assembled in these sectors are required to have a good dimensional accuracy and surface finish. However, the machinability of GFRP is poor due to its non-homogeneity, anisotropy, and excessive hardness of abrasive fibers [3]. Carbon-based cutting fluids can be an alternative to combat the adverse impact of tool wear due to the machining of harder abrasive fibers. It has been observed that the cooling and lubrication cost comprises 7–17% of total machining cost which can go up to 20% for cutting difficult-to-cut material [4]. This cost includes the labor cost to handle the lubricant/coolant, energy cost for recirculation, coolant/lubricant cost, cost of equipment

required to circulate coolant/lubricant, and waste disposal [5]. Figure 1 describes the bifurcation of costs involved in machining as well as cutting fluids used in machining operations of automobile industries [6]. Thus, the usage of conventional cutting fluid is not economical. Besides, their usage is restricted for machining GFRP due to the absorption of water present in cutting fluids by the fibers lowering its strength and in-service performance. The best available option to replace the cutting fluid is not to use the cutting fluid absolutely, i.e., dry machining. Dry machining evolves as a low-price clean machining process due to the absence of cutting fluid. It is found to be favorable and competent to open-faced machining operations like milling operations. In the open-faced machining operation, the chip evacuates easily from the tool interface. In the end milling operation, one of the open-faced machining processes, the only one cutting edge is not involved continuously in the cutting action and the generated heat can be managed without the usage of cutting fluid up to a certain level of process parameters [7]. The usage of cryogenic coolants has been found to cut hard-to-machine alloys like superalloys, titanium-based alloys, and steel alloys. They can also be used for machining GFRP to reduce the pullout of fibers by lowering the cutting zone temperature. Besides, they are sustainable and not required to recycle unlike in conventional carbon-based cutting fluids. Also, the recycling of chips is not an environmental issue in cryogenic machining as they do not leave any residue on machined surface and chips [8]. So, the cryogenic coolant can be used as another alternative of carbon-based coolant, apart from dry machining for machining of GFRP.

Naresh and Prasad [9] investigated the effect of wet and cryogenic conditions for turning unidirectional GFRP through analysis of surface roughness, tool wear, and fiber pullout at various combinations of cutting process parameters. The cryogenic condition has been found as the superior condition in terms of surface roughness, tool wear, and pullout of fibers. It has been also observed that

Fig. 1 Bifurcation of machining and cutting fluid costs associated with automotive industries for machining processes [6] (Copyright reserved from Elsevier)



the machined surface required approximately 24 h to dry the fiber. Azmi et al. [10] investigated the cutting force, tool wear, and surface quality with the change in cutting process parameters, i.e., cutting speed and feed rate. The abrasion wear mechanisms were found to be predominant tool wear mechanisms for all combinations of process parameters. The higher tool life was observed at the lowest cutting speed and feed rate, i.e., 150 m/min and 0.16 mm/rev, respectively, and when the fibers are oriented at 0°. In another study, Azmi et al. [11] investigated the effect of process parameters, i.e., cutting speed, feed rate, and depth of cut on the cutting force, tool wear, and surface roughness quantitatively. Among the three cutting process parameters, feed rate has been emerged as the most affecting parameter on all three machinability indicators, i.e., cutting force, tool wear, and surface roughness. Razfar and Zadeh [12] formed a model-based genetic algorithm optimized neural network system to predict the surface roughness and delamination factor for end milling GFRP. A good agreement was found between the experimental and predicted results for surface roughness and delamination factor. It was also found that the higher cutting speed and lower feed rate resulted in lower delamination factor and surface roughness. Sheikh-Ahmad et al. [13] developed a mechanistic model based on committee neural (CN) network and multiple regression to predict specific cutting energy for end milling GFRP. The CN network-based model was found to be more accurate than the multiple regression-based models. Davim and Reis [14] statistically investigated the impact of cutting speed and feed rate through L_9 array on cutting force, delamination factor, and surface roughness for end milling of two composites of GFRP, i.e., Viapal VUP 9731 and ATLAC 382–05. However, the feed rate has been found as a significant parameter affecting three machinability indicators for both GFRP composites. Koklu et al. [15] compared dry and cryogenic LN₂ based on hole quality indicators for drilling S2 glass fiber composites at various feed rate and cutting speed. It has been observed oversized holes in the case of cryogenic environment with less deviation in circularity and cylindricity of holes in comparison with dry machining. With the results of ANOVA, it was observed that the circularity at the top of hole was affected by the feed rate and cooling condition, respectively, in decreasing order as the cylindricity was significantly (60%) influenced by the cutting conditions. However, the deviation in the hole size was found a greater than 20 μm in the case of cryogenic cooling. Kumar and Gururaja [16] compared dry and cryogenic machining using LN₂ for milling uni-directional carbon fiber reinforced polymer (UD-CFRP) at various feed rate, cutting speed, and fiber orients. In the cryogenic environment, a higher cutting force was observed in the comparison of dry machining at all fiber orientations and

process parameters. Surface quality of UD-CFRP with 0°, 45°, 90°, and 135° fiber orientations were improved by 8.60%, 26.71%, 22.53%, and 4.45%, respectively, under cryogenic conditions. Machining UD-CFRP with 45° fiber orientation produces rougher surface, whereas smoother surface was achieved while machining of 135° oriented UD-CFRP. In the dry machining, bending-based failure mechanism was observed for all orientations of fiber as shear-based, tensile-based, and combination of tensile and compression-based failures of fibers were observed for the fiber orientations of 135°, 90°, and 45°, respectively. The 3D surface topography of machined surface indicated that the higher surface quality was observed in the case of cryogenic machining. The attachment of dust particles of fiber/matrix, fracture of fiber, fiber-matrix de-cohesion, and cavities were found in dry condition as only and fiber pull-outs were observed in cryogenic condition. Khanna et al. [17] compared cryogenic LN₂ and dry machining for drilling CFRP at various feed rate, cutting speed, and tool. The superior machining performance in terms of damage factor at entry and exit were observed using four facet drill and cryogenic cutting condition at combinations of process parameters. Approximately, 14–38% and 5–68% lower values of R_a and damage factor were observed in the case of cryogenic machining in comparison of dry machining considering all combinations of process parameters.

In 2019, as per the report of Carbon Disclosure Project (CDS), a total of 8446 industries revealed the data for the environmental impact they generated. By the first look, this number is very small but if we compare with 2003 when around 228 companies participated, the trend of revealing environmental impact is remarkably improved [18]. To evaluate the environmental impact, life cycle assessment (LCA) analysis is a generally employed approach. Its usage is popular because it follows the (ISO:14040–14044:2006) and Environment Management System (EMS) [19]. However, it has been found a little literature that compares the machining performance as well as LCA analysis of end milling of GFRP. In this context, this study compares the cutting temperature, cutting force, power consumption, surface profile, and LCA for end milling GFRP under the two sustainable cutting conditions, i.e., dry and cryogenic coolant of LCO₂.

2 Experimental setup

Slot milling tests were carried out in a Kondia HS1000 high-speed machining center. The material used during the tests was glass fiber characterized for presenting:

- Tex 600 ± 10% at 90°
- Tex 1200 ± 10% at 0°
- Glass fiber content: 47.2 ± 0.5%

In particular, the layers of Tex 600 and 1200 are oriented at alternatively 0° and 90° , respectively; that is, layers of 600 g per kilometer of yarn (g/km yarn) and 1200 g/km yarn were overlapped at 0° and 90° , respectively, until obtain the part. The tool used was an indexable mill TECCOR[®] of 14 mm in diameter with 4 teeth. The tool holder used was a special tool holder NIKKEN[®] anti-vibration HSK63A. The 4 uncoated PCD inserts, TECOOR[®] D14X15X100Z4, were used. During the tests, the cutting conditions used were 350 m/min of cutting speed, 0.05 mm/tooth of feed, axial depth of 6.5 mm, and each slot had a length of 100 mm. Regarding cooling conditions, dry conditions and LCO₂ were compared. In the case of CO₂ cryogenic cooling, it was injected at 14 bars with a BeCold[®] device and a special way injection system was designed. The 2 nozzles having 1.5 mm diameter have been used to provide LCO₂ at the cutting zone. The total flow rate of LCO₂ has been fixed as 1.6 kg/min. The nozzle to workpiece distance has been kept as 25 mm with an orientation of 45° to used end mill.

In particular, a methacrylate box was manufactured which was connected with the suction pipe of the industrial vacuum cleaner on one side and at the bottom side; a perimetral brush to absorb the glass fiber generated during the slotting tests was added. This box was also provided with two cylinders which are in the center of setup and has a LCO₂ nozzle injection with the aim of adjusting the injection angle and of fitting the LCO₂ towards the cutting zone.

During the tests, cutting forces were measured with a Kistler[®] 9255. Besides, the power consumption of the spindle was measured with a Vydas UPC-E power cell. Also, cutting temperature at 0.5 mm from the bottom was measured with a K-type thermocouple. Furthermore, several stops were carried out to measure edge tool wear with a PCE-200 optical tool maker microscope. Stop test criterion was established at 1000 mm of cutting length. Each test was carried out 3 times with the aim of reducing the variability of the results obtained. Finally, once tests were carried out, a Leica[®] confocal microscope was used to analyze surface roughness of the bottom slots maintaining sampling length and cutting filter as 1 mm and Gaussian 0.8 mm respectively. Figure 2 presents the experimental setup employed in the study.

3 Discussion on obtained results

3.1 Analysis of cutting zone temperature

The application of GFRP is often found as an insulator requiring the utmost thermal stability and expansion. It is quite often that the deviation in dimensional changes is introduced during machining processes due to the higher

heat at the cutting zone. The cutting zone temperature is a controlling factor of machining performance in the case of GFRP materials. The higher tool life is found with lower cutting zone temperature. Besides, the surface quality is also affected by the cutting zone temperature. So, it is highly required to examine the cutting zone temperature during machining of GFRP [20]. In this context, Fig. 3 presents the temperature at 0.5 mm from the bottom of a plate using a K-type thermocouple to compare the cutting zone temperature after machining a 100-mm slot in dry and LCO₂ cutting conditions. The purpose of analyzing the temperature after the very first slot is to exclude the effect of tool wear as at the initial stage of machining, the tool wear is similar in both cutting conditions. From Fig. 3, it is clear that the 88% lower cutting zone temperature has been observed in the case of LCO₂ in comparison with dry machining. It is attributed to the lower temperature (194.5 K) provided by the LCO₂ at the cutting zone when it exits from the nozzle. The important service performance indicator for machining GFRP like fiber pullout and thermal ablation are highly controlled by the cutting zone temperature. The reason for these issues is the higher cutting zone temperature generated due to the friction between cutting tool and workpiece which also leads to rapid tool wear too [21]. However, the usage of LCO₂ reduces the cutting zone temperature and controls the fiber pull-out and thermal ablation. Besides, at a higher temperature, the smearing of matrix and fiber burning is also observed for machining FRP [22]. It changes the phenomenon of breaking the fiber from shearing observed in the case of cryogenic machining to the bending found for dry machining.

Finally, in Fig. 4 is shown the initial and final slot carried out with each technique. In this picture can be shown that when dry machining is used, in the first slot, small burrs already appear in the first slot that increased until the last one in which have a considerable size. Nevertheless, when LCO₂ is applied, this effect is mitigated, appearing in the final slots burrs, but smaller in comparison with the obtained with dry machining, what implies that the use of LCO₂ enhances the thermal control avoiding fiber pull-out and thermal ablation effect.

3.2 Cutting force and tool wear analysis

Figure 5 presents the comparison of end milling GFRP in dry and LCO₂ cutting conditions based on the modulus of cutting force. The value of modulus of cutting force has been obtained using Eq. 1.

$$\text{Modulus of cutting force} = \sqrt{(F_x^2 + F_y^2 + F_z^2)} \quad (1)$$

Here, the F_x , F_y , and F_z present the component of cutting force in the direction of x , y , and z , respectively.

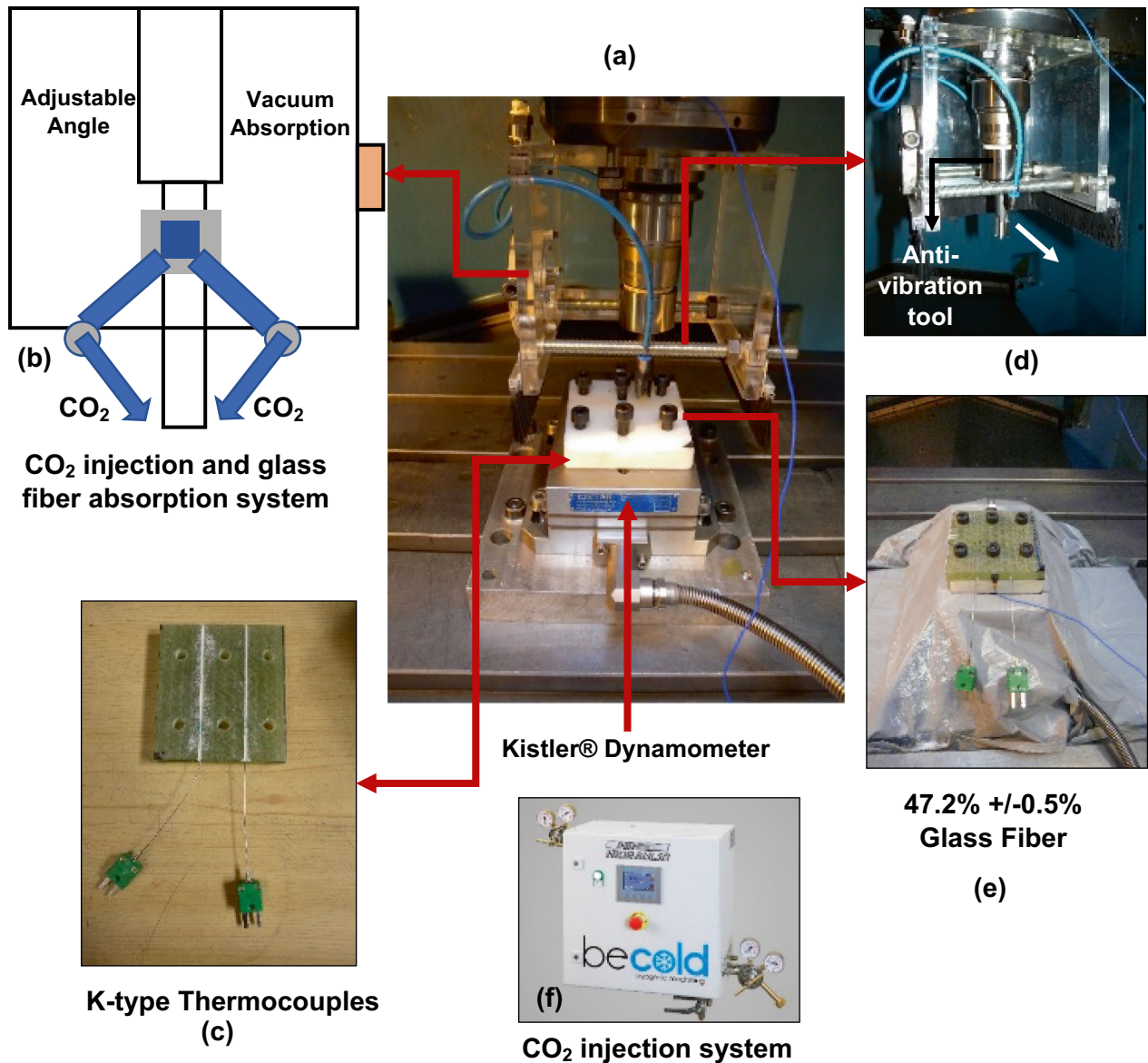


Fig. 2 An image of **a** experimental setup, **b** a schematic for CO₂ injection and glass fiber absorption system, **c** image of used K-type thermocouples, **d** image of anti-vibration tool, **e** image of workpiece material, and **f** image of CO₂ injection system

In Fig. 5, the cutting force modulus obtained in slots 1, 5, and 10 in each test are shown to analyze its evolution. In particular, each test was carried out 3 times and in Fig. 5 is shown the average values obtained in each slot. In this line, it must be taken into account that the use of LCO₂ implied a reduction in the first stages of 7%, and in the last one slot was reduced until 5%. This behavior is due to in the first stages, when the inserts were not worn and the cooling effect implied a brittleness of the glass fiber that enhanced the cutting process. However, this difference is reduced at the last stage due to the mechanical effects stemming from the slight wear that appeared on the cutting edge. Regarding the

absolute values, in both cases, the modulus of cutting force increases by 40% in comparison with the slot 1 and 10 for both cutting conditions.

One of the reasons for observing a lower cutting force at cryogenic condition is the reduction in fracture strain and embrittlement of material which leads to lower cutting force. Besides, as shown in Fig. 6, marginally higher tool wear observed in the case of dry machining also contributed to a higher cutting force modulus in comparison with cryogenic machining. In particular, after finishing the tests, inserts used under dry machining presented flank wear of 18 μm, which is the double of the flank

Fig. 3 Comparison of cutting zone temperature for end milling GFRP in dry and LCO₂ cutting conditions

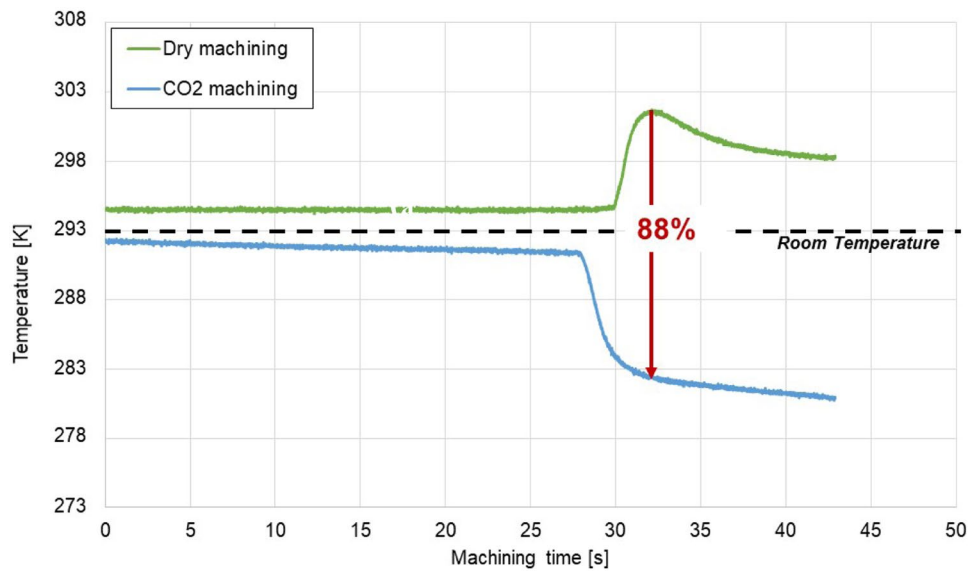


Fig. 4 Initial and final slot carried out with each technique. **a** Dry machining. **b** CO₂ machining

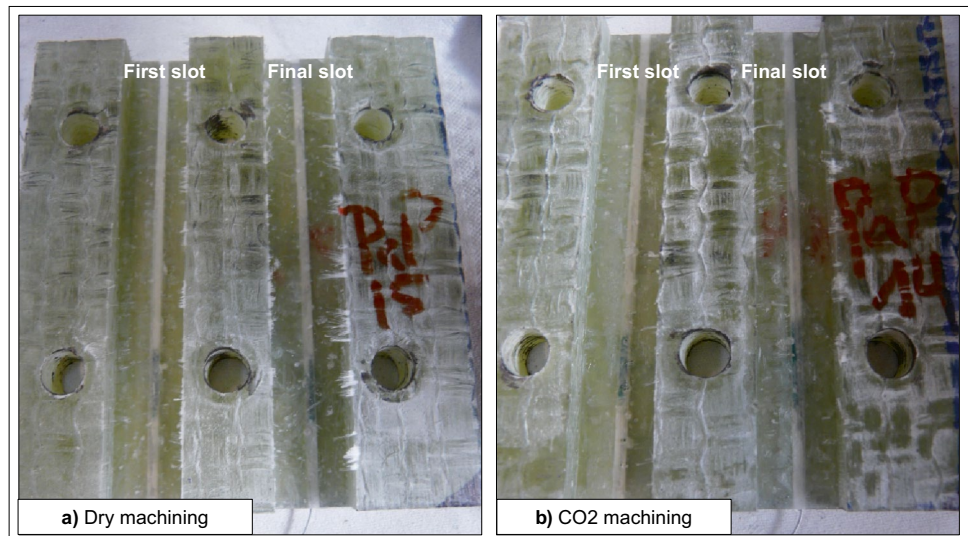
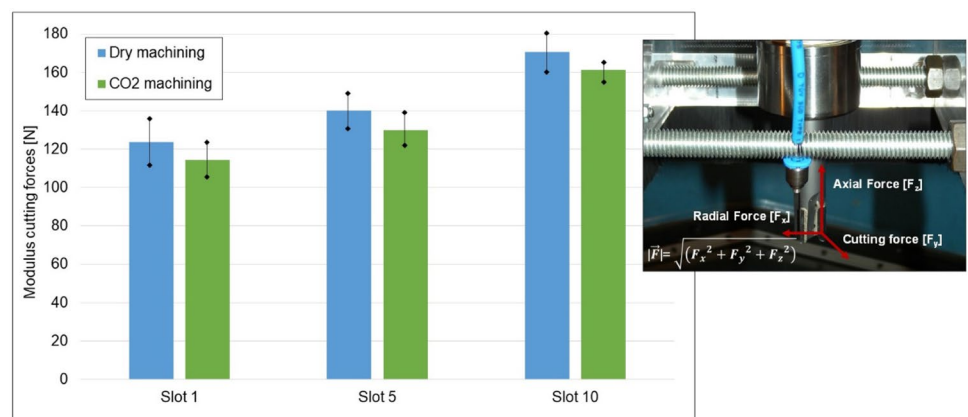


Fig. 5 Comparison of modulus of cutting force for end milling GFRP in dry and LCO₂ cutting conditions



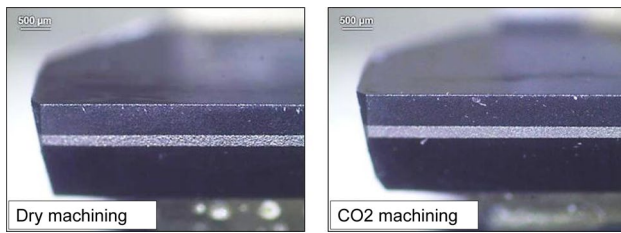
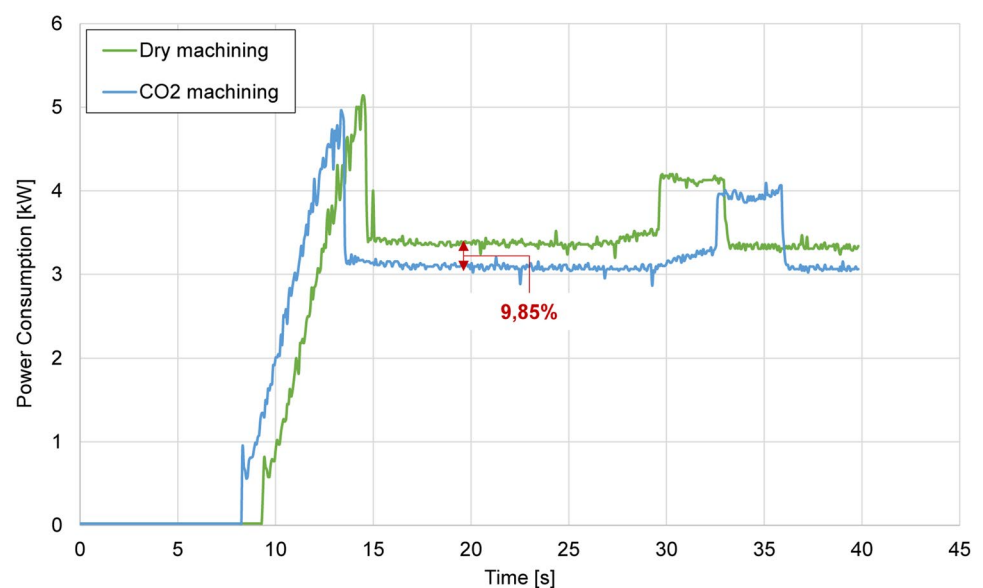


Fig. 6 Comparison of dry and LCO₂ machining based on tool wear generated after the last slot produced

wear obtained when cryogenic cooling is used where the value was 8 µm. This difference in combination with the reduction in fracture strain and embrittlement of material due to LCO₂ application implied that the use of cryogenic machining as coolant technique lower cutting forces is obtained.

The wear mechanism in the GFRP material is quite different from the metallic materials wherein the adhesion wear is very common. In composite material, the abrasion of cutting edge can be seen in Fig. 6 due to intermittent contact of harder reinforced fibers for both cutting conditions, i.e., dry and cryogenic LCO₂ [10]. In addition, particularly in the end milling process, alternating cutting action generates cyclic stresses due to contact of cutting edge with various phases of GFRP materials. Thus, in GFRP, the material is being cut by the combined mechanism of bending and shearing resulting in abrasive and microchipping tool wear [23]. However, marginally higher abrasive marks can be observed on the cutting edge employed for the dry machining due to the lack of any provision to escape the heat generated in the machining process.

Fig. 7 Comparison of dry and LCO₂ machining-based power consumption during 1000 mm slot produced on GFRP



3.3 Power consumption analysis

A higher energy efficiency reflects that the same process can be accomplished using less energy, denoting lesser energy waste. This fetches numeral advantages such as reduced greenhouse emissions, energy imports, and cost for machining. Hence, it is safe to conclude that energy efficiency and environment-friendliness go hand in hand. In this regard, the comparison of power consumption has been made for end milling GFRP in dry and LCO₂ cutting conditions as shown in Fig. 7. In this case, the use of CO₂ as coolant implies a reduction in power consumption of ≈10%, which supposes an improvement in the slotting process from both economic and environmental points of view due to this reduction.

A similar trend as observed for cutting force modulus has been observed for power consumption; i.e., lower power consumption has been observed for LCO₂ in comparison with dry end milling. In dry cutting, the generation of higher heat makes a long contact of the cutting tool with chip. This increases the friction at the interface of tool-chip which eventually raises the power consumption. Besides, the marginally higher tool wear observed in the case of dry machining also contributed to higher power consumption in the case of dry machining in comparison with the LCO₂ condition [24].

3.4 Surface roughness analysis

Figure 8 presents the comparison of dry and LCO₂ cutting conditions based on surface roughness obtained for machining GFRP at the first slot. In the case of machining under dry conditions, the surface arithmetical mean height (S_a) was 5.28 µm and the sum of the largest peak height value and

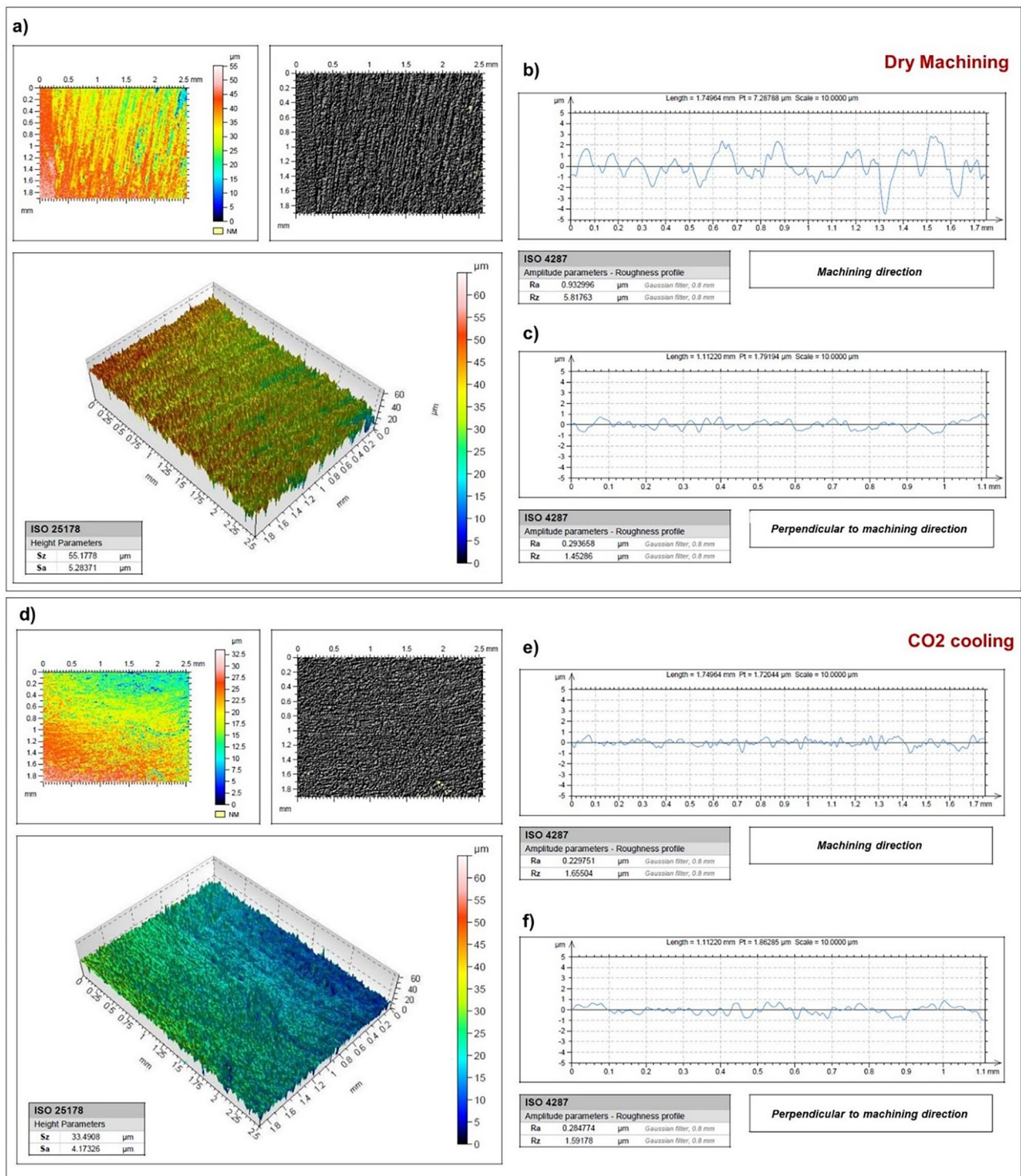


Fig. 8 Comparison of dry and LCO₂ machining–based on surface roughness produced on GFRP. Dry machining: **a** 3D surface roughness, **b** surface roughness machining direction, **c** surface roughness

perpendicular to surface roughness. LCO₂ cooling: **d** 3D surface roughness, **e** surface roughness machining direction, and **f** surface roughness perpendicular to machining direction

the largest pit depth value within the defined area (S_z) was 55.18 μm . These values, when CO₂ was used, were reduced 20% in the case of Sa and 39% in S_z , obtaining 4.17 μm and

33.49 μm , respectively. Similar behavior is obtained when the surface roughness is analyzed in machining direction and perpendicular to it which implies that the use of CO₂ has an

impact on surface roughness, improving it in comparison with dry machining conditions.

It has been observed that the reduction in the sharpness of the cutting edge generates a higher heat ensuing in severe damage to the machined surface. This damage is done in the form of failure of matrix, pullout, and protrusion of fibers [25]. Thus, comparatively a larger tool wear observed in the dry machining is a cause for higher tool wear. Besides, the cutting zone temperature also plays a vital role to control the surface roughness. At lower temperatures, uniform material removal has been observed. As the cutting zone temperature raises, the amount of uncut reinforced fiber is increased due to the elongation of fiber length at a higher temperature. This also attributes to raising the surface roughens in the case of dry machining in comparison with the LCO₂ environment [26]. Besides, at lower temperature, the effect of thermal degradation is found at a limited level. It resulted in the increment of shear strength, tensile strength, and stiffness of a matrix resisting the delamination of fiber in the matrix. In addition, at lower temperature, the differences of thermal co-efficient of expansion induce the stresses in the interior of matrix. It enhanced the inter-laminate strength of laminates and reduced the surface damage of machined surface in the case of machining using LCO₂ in comparison with dry condition [16].

4 LCA analysis

In the current study, influences associated with the end milling of GFRP assigned with two cutting fluid conditions are measured with the Ecochain Mobius online platform. This examination can reasonably differentiate the efficacy of cryogenic CO₂ and dry machining using the

harm caused to human health, ecosystem, and resources. Besides it, the executed LCA model is following the steps described in the ISO 14040 and 14044: 2006 for the investigation [27]. In this regard, the LCA has been presented following the order of subsections as goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results obtained.

4.1 Goal and scope definition

The aim of this study is the investigation of the environmental performance of end milling GFRP under dry and cryogenic CO₂. In this context, the designation of system boundaries of the parameters specified for the cutting fluid strategies is vital. The pivot of the study is to equate the dry and cryogenic CO₂ environments in a “gate-to-gate” method, abolishing the mining of material, usage of the final product, and its disposal. This macro-level impact valuation often called the streamlined LCA (SLCA) assesses only the environmental loads rising from the energy consumption of the process, production, and utilization of the coolant/lubricant [28].

The functional unit (FU) is a noticeable standard for the evaluation of substitute processes (here, employed coolant) in the SLCA method. In the current LCA analysis, the average energy consumption and LCO₂ for machining a slot having 100 mm have been selected as an FU. Such an FU enables a clear collation of the cutting conditions for their environmental impact, creating an essential link for relating the LCI data with the LCIA results signified. Figure 9 indicates the system boundaries along with input–output flows of considered materials for dry and LCO₂ cutting conditions.

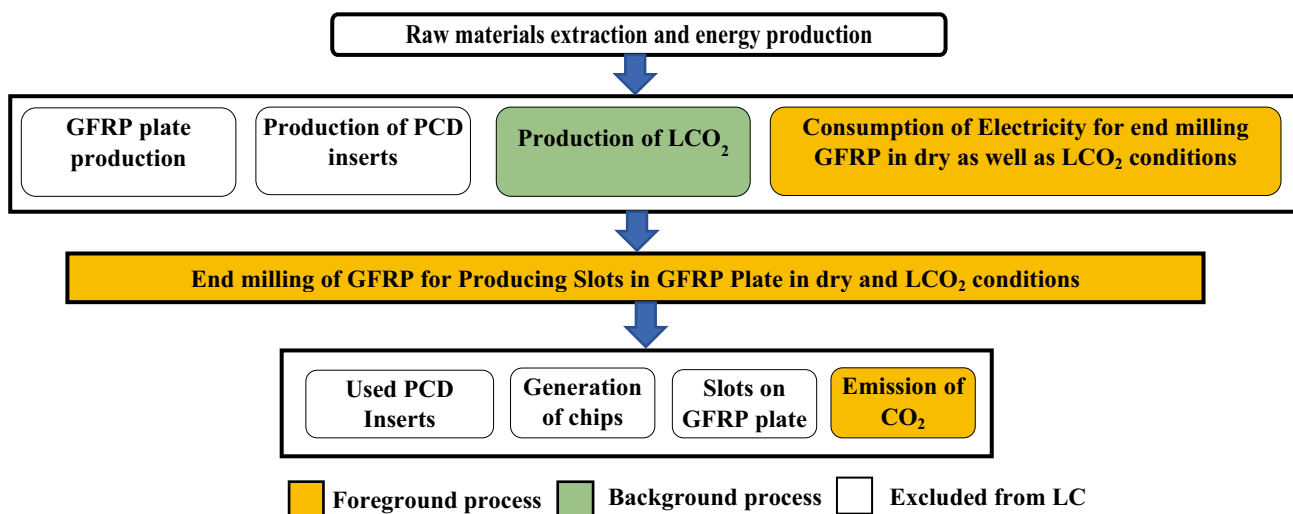


Fig. 9 Image showing the boundary conditions considering the input and output flows

Table 1 Details of inventory

Particular	Dry	LCO ₂
Workpiece	GFRP plate	
Cutting tool	4 uncoated PCD inserts, TECOOR® D14X15X100Z4	
Consumption of coolant (g)	NA	90
Average electrical energy required for cutting (Wh)	2.41	2.23

The elementary proposals and assumptions are considered for conquering the possible confines of the LCA performed as detailed below [29, 30]:

- Electricity consumption was considered according to Gujarat, India, production mix.
- The transport of workpiece material and depreciation of devices has not been analyzed owing to their negligible effect.
- The tool geometry, the flow of the coolants, vibrations of the machinery, and atmospheric humidity are taken as constants.
- The vertical machining center (VMC), air compressor, and other equipment used for end milling are considered to have a trivial impact due to their frequent usage lately.
- The impact due to leakage of the coolants is not considered. The chip recycling and remelting are omitted.
- The effects of LCO₂ evaporation are emitted considering the derivation of LCO₂ as a by-product.

4.2 Life cycle inventory analysis

This section quantifies the flows between input and output elements of the considered boundary system. The collected data on the consumption of electricity and LCO₂ has been referenced for end milling GFRP to produce a slot having 1000 mm. The consumption of electrical energy during end milling has been gained from the values of power consumption obtained from a Vydas UPC-E power cell and cutting time duration. The values of inventories generated during end milling have been presented in Table 1. Table 2 describes the Ecoinvent 3.5 database used in the study.

Table 2 Data source for LCI

Element	Database
Electricity generation	ELCD 3.2 Green Delta V2.18: electricity consumption mix at consumer
Liquid carbon dioxide production	Ecoinvent database 3.5: CO ₂ production, LCO ₂

4.3 Life cycle impact analysis

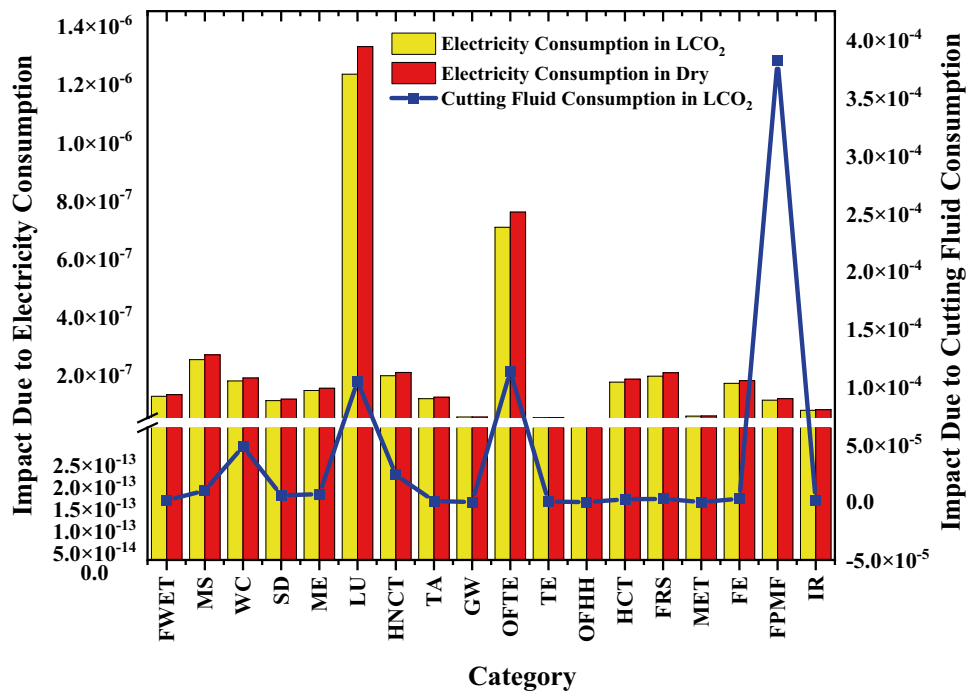
This phase of LCA establishes a relation between the process under study and its potential impacts. It is a comprehensive derivation of the innovative models for risk assessment. Although it is unable to forecast an absolute value of the risk, it is often helpful to gain an insight into the relative threats posed by one or more alternative processes. The assessment model for LCIA can be either midpoint or endpoint, based on the goals and scope defined for the study and the data collected in the inventory [31].

From the literature, it is observed that the midpoint impact assessment model has lesser assumptions and complications, along with a provision of more extensive understanding when compared with that of the endpoint model. The LCA allows identifying the areas where the negative environmental impacts can be potentially reduced. CML 2002 and Eco-indicator 99 have been widely used methods for LCIA, while the ReCiPe method is a refurbished model of the previously mentioned methods. Although the amalgamation of the midpoint and the endpoint impact categories in a single rating is a functional tool for comparing alternatives, ReCiPe midpoint (H) is often implemented in scientific studies for its homogeneity and uniformity [32]. Taking these rulings into consideration, the normalized score for each of the 18 impact categories was evaluated by the ReCiPe midpoint (H). The sustainability assessment was carried out by analysis of damage to the ecosystem, human health, and resources. These three factors are distinguished for those they provide an outlook for the identification of areas of improvement in terms of environmental performance.

4.4 Life cycle result interpretation

Figure 10 presents the comparison of dry and cryogenic LCO₂ machining based on the normalization values of 18 impact categories of ReCiPe midpoint (H) 2016. This comparison makes possible the two sustainable cutting fluid approaches dry and LCO₂ firmed on LCA. Due to exclusion of cutting fluid in dry machining, the environmental impacts generated due to cutting fluid is zero but the higher energy consumption involved in the dry machining makes more burden on the environment in comparison with LCO₂. So, it will be interesting to compare the cutting fluid strategies based on the total effect, i.e., due to cutting fluid and energy consumption. From Fig. 10, it is confirmed that the higher value of impact values has been found

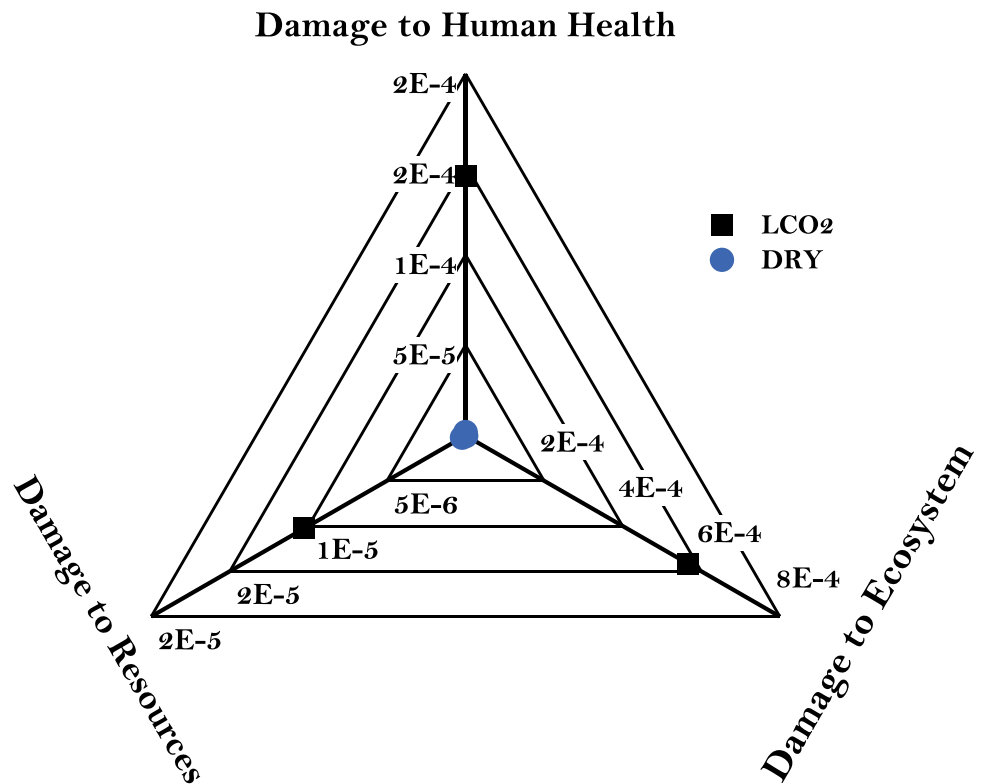
Fig. 10 Comparison of dry and LCO₂ based on normalized values results of ReCiPe 2016 (H) midpoint impact categories



for the LCO₂ in comparison with dry considering the impact due to fluid consumption and energy consumption. However, it is also observed that the higher values of impact category due to energy consumption have been found for the dry machining in comparison with LCO₂ cutting condition. So, it is confirmed that the contribution to environmental impact is higher due to

cutting fluid in comparison with the energy consumption during the machining process. Considering all impact categories, more than 95% higher impacts have been generated in the case of LCO₂ condition due to cutting fluid consumption in comparison with dry machining. The higher differences in terms of 10⁴ times impacts have been generated in FPMF category

Fig. 11 Comparison of dry and LCO₂ cutting conditions based on damage categories, i.e., human health, resources, and ecosystem



as 60 times impacts have been generated in ME considering the lower differences between the impacts generated in the dry and LCO₂ cutting conditions. Thus, the LCO₂ emerges as a “hotspot” in comparison with dry machining in terms of generating environmental impact.

In the context of a more applicable comparison of dry and LCO₂ cutting conditions, the normalized values of midpoint impact categories have been clustered into the three damage categories, i.e., damage to natural resources, ecology, and human resources. Figure 11 presents this comparison of dry and LCO₂ based on damage to natural resources, ecology, and human resources. From Fig. 11, it is directly visible that the higher impacts have been generated for LCO₂ in comparison to dry cutting condition. It is attributed to exclusion of cutting fluid involved in the dry machining. Though the obtained CO₂ is a by-product of the chemical process, the production of LCO₂ requires compression of gaseous CO₂ to approximately 60 bars to convert it into liquid form. This process consumes more electricity and natural resources [33, 34]. Thus, a higher value of impacts has been found in the case of LCO₂ in comparison with the dry machining process.

5 Conclusions

This novel study presents the comparison of dry and LCO₂ based on machining performance indicators like cutting zone temperature, tool wear, modulus of cutting force, power consumption, and surface roughness based on end milling GFRP. The conclusive remarks made based on the discussion on results are presented below.

- The lower temperature (194.5 K) provided by LCO₂ reduces the cutting zone temperature by 88% in comparison with dry machining considering the first 100 mm length slot what implies a cutting temperature control which minimizes burrs formation.
- In the first slot, a 7% lower value for modulus of cutting force was observed in the case of LCO₂ in comparison with dry machining. This difference is reduced until the last slot in which was established at 5%. This implies that cutting force evolution is similar with both techniques, presenting a slight improvement when LCO₂ is applied as cutting fluid.
- Regarding tool life, the use of LCO₂ implies doubling tool life in comparison with dry machining once the tests are finished. Besides, this lower tool wear necessitates 9% lower power consumption considering the 1000 mm slot length reducing friction at the tool-chip interface.
- In the case of machining under dry conditions, the surface arithmetical mean height (S_a) was 5.28 μm and the sum of the largest peak height value and the largest pit

depth value within the defined area (S_z) was 55.18 μm . These values, when CO₂ was used, were reduced 20% in the case of S_a and 39% in S_z , obtaining 4.17 μm and 33.49 μm , respectively.

- Considering all impact categories, more than 95% higher impacts have been generated in the case of LCO₂ condition due to cutting fluid consumption in comparison with dry machining. So, as per it, the LCO₂ emerges as a “hotspot” in comparison with dry machining in terms of generating environmental impact.

Therefore, taking into account technical and environmental issues, the use of liquefied CO₂ as cutting fluid instead of dry machining implies not only a tool life improvement with lower power consumption and better surface roughness but also a real improvement from an environmental point of view which becomes this technique in a suitable alternative to be applied industrially in GFRP milling processes.

Acknowledgements The executed work is as per the MOU signed between the Advanced Manufacturing Laboratory (IITRAM, India) and the Advanced Manufacturing Research Group (UPV/EHU, Bilbao, Spain). Thanks are due to Spanish Project Ministerio de Ciencia e innovation PDC2021-121792-I00 (DPI2016-74845-R) because of some result analysis and to project, and to former one PID2019-109340RB-I00 Iteneo for the help in CO₂ device development and optimization.

Author contribution Navneet Khanna and Prassan Shah performed the life cycle analysis; Adrian Rodriguez, L. N. López de Lacalle, and Octavio Pereira carried out the drilling experiments at university; meanwhile, Antonio Rubio and Txomin Ostra did at Tecnalia. Result discussion was a common task of all the group. Cryogenic device was patented by O. Pereira, I. N., López de Lacalle, and Tecnalia researchers.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. The authors received financial support from Basque Government in the Excellence University Group system call, grant IT 1573–22.

Declarations

Ethics approval Authors agree with paper publication and consent to it. Data are in author’s database. There are not ethical issues with the work.

Conflict of interest The authors declare no competing interests.

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