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In pursuit of sustainable cutting fluid strategy for machining Ti-6Al-4V using life cycle analysis

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ABSTRACT

The need for developing sustainable manufacturing processes which should have a good balance between economic viability and environmental protection is one of the key challenges against manufacturers. The conventional carbon-based cutting fluids used in machining processes are found to be unsustainable in terms of a higher impact on ecology and hence it is required to develop alternative sustainable cutting fluid strategies. However, the research that compares conventional, cryogenic and Minimum Quantity Lubrication (MQL) machining based on all pillars of sustainability i.e., machining performance, environmental impact and human health is still lacking. With this view, this novel study on Ti-6Al-4V machining compares conventional flood coolant with MQL and liquid carbon dioxide (LCO_2) as a cryogenic coolant based on the machining performance and Life Cycle Assessment (LCA) analysis. Though lower impacts on the environment are observed for MQL machining, it is not sustainable as it has been observed 75% reduced tool life with a higher cutting force and surface roughness in comparison with flood and cryogenic machining. The flood machining is found to be non-sustainable as it has more than 50% of total impacts generated for most of the ReCiPe 2016 (H) midpoint categories. Thus, cryogenic machining is emerged as sustainable machining to have a good balance between machining performance and impacts on the environment for turning Ti-6Al-4V.

1. Introduction

Titanium (Ti) alloys are used widely in the aerospace, medical, and automobile sectors due to their higher specific strength (50% lower density than steel), good corrosion, and fatigue resistance even at elevated temperatures [1,2]. It attributes to a requirement of 1,36,000 tons of Ti for every year [3]. Among these Ti-based alloys, Ti-6Al-4V, an $\alpha + \beta$ alloy, comprises 50% of total Ti-based alloys applications because heat treatment and aging can be done on it [4]. The 80% applications of Ti-6Al-4V Grade 5 was found in the aerospace parts like exhaust ducts, landing gear as Ti-6Al-4V ELI (Extra Low Interstitials) can be found in the applications of the medical sector due to its low reactivity with tissues in addition to exceptional mechanical and metallurgical properties [5–7]. However, the following reasons lead to poor machinability of Ti-6Al-4V [5,8,9].

- A low thermal conductivity hinders heat flow from the cutting zone to chips and increases the temperature of cutting region up to 1000 °C promoting various tool wear mechanisms rapidly.
- In the case of Ti coated cutting tools, adhesion and diffusion wear mechanisms promote rapidly due to the affinity of Ti present in coating towards the chips of Ti-6Al-4V.
- Attainment of higher strength and hardness even at higher temperatures raises the required amount of torque and cutting force.

To avoid these issues, currently, additive manufacturing is taking relevance. Besides, it makes possible personalized surfaces with this alloy [10]. Nevertheless, this technology at this moment still presenting defects in surface integrity related to porous and internal cracks [11]. Besides, additive manufacturing needs finishing operations carried out by machining to achieve surface roughness requirements. In this line, Markopoulos et al. [12] developed a three-stage process for manufacturing knee prosthesis. Azzam et al. [13] studied the viability of automatizing surface polishing of this kind of prosthesis. Le Roux et al. [14] analyzed different cutting speeds in turning operations to improve the residual stress and concluded that a balance between residual stress values and the cycles of fatigue failure was achieved when the cutting speed is over 40 m/min. However, in all these cases oil emulsions were used, and therefore, ecological issues were not taken into account.

The carbon-based conventional cutting fluids in the form of emulsion are generally used to overcome these tool wear-related problems

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Nomenclature

LCO_2	Liquid carbon dioxide
v_c	Cutting speed (m/min)
LCA	Life Cycle Assessment
f	Longitudinal feed (mm/rev)
MQL	Minimum Quantity Lubrication
a_p	Axial depth of cut (mm)
R_a	Mean height of roughness profile in micron within sampling length
R_z	Maximum height of roughness profile between peak to valleys in micron
ME	Marine ecotoxicity (kg 1,4-DCB)
SOD	Stratospheric ozone depletion (kg CFC11 eq)
IR	Ionizing radiation (kBq Co-60 eq)
OFH	Ozone formation, human health (kg NOx eq)
MEu	Marine eutrophication (kg N eq)
TA	Terrestrial acidification (kg SO_2 eq.)
HCT	Human carcinogenic toxicity (kg 1,4-DCB)
TE	Terrestrial ecotoxicity (kg 1,4-DCB)
MRS	Mineral resource scarcity (kg Cu eq)
GW	Global warming (kg CO_2 eq)
LU	Land use (m^2a crop eq)
FE	Freshwater ecotoxicity (kg 1,4-DCB)
OFT	Ozone formation, terrestrial ecosystems (kg NOx eq)
FEu	Freshwater eutrophication (kg P eq)
HNCT	Human non-carcinogenic toxicity (kg 1,4-DCB)
WC	Water consumption (m^3)
FPMF	Fine particulate matter formation (kg PM2.5 eq)
FRS	Fossil resource scarcity (kg oil eq)
EC	Electricity consumption
CFC	Cutting fluid consumption
FU	Functional unit
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

by escaping the heat [15]. Its massive use is dangerous for air, soil and water resources [16]. Besides, approximately, 80% of total skin-related issues due to occupational activities are registered due to usage of conventional coolants [17]. Also, they are not capable of removing heat quickly from the cutting area when the low thermally conductive material is being cut and the coolant maintenance and disposal cost implies an increase of manufacturing costs [18]. So, they are not sustainable due to the creation of environmental, economic and worker's health-related issues [16,19–21]. In this regard, as an alternative to the above coolants, various cutting fluid approaches viz., Minimum Quantity Lubrication (MQL), cryogenic coolants (LN_2 and LCO_2), and high-pressure coolant (HPC) are being developed to provide sustainable solutions [15,22–24].

Several studies were identified in the literature analyzing the comparison of cutting fluid strategies based on machining performance for turning Ti-based alloys. Sartori et al. [25] compared dry, flood, MQL, cryogenic, and CryoMQL machining using LCO_2 and LN_2 for turning Ti-6Al-4V ELI based on flank and crater tool wear; surface roughness, and surface integrity in terms of deformed layer thickness. Hybrid cutting fluid strategies in terms of LCO_2 + MQL eliminate crater wear mechanism in comparison with other cutting fluid approaches and provided better machining performance than others. Jerold and Pradeep Kumar [26] compared dry, flood, LCO_2, and LN_2 based on cutting temperature, cutting force, tool wear, surface roughness, and chip morphology for turning Ti-6Al-4V. Cryogenic coolants especially LCO_2 provided better results for machining performance in terms of 48% and 40% improvement in surface roughness and tool life respectively in comparison with LN_2. Gupta et al. [27] compared dry, cryogenic using LN_2, CryoMQL using LN_2, and Ranque-Hilsch vortex tube (RHVT) assisted MQL machining based on machinability indicators for turning Ti-6Al-4V. A superior machining performance in terms of lower tool wear, surface roughness, and discontinuous chips was observed using CryoMQL machining in comparison with others. The higher microhardness was observed using LN_2 and CryoMQL in comparison with others as embrittlement of material occurred at a lower temperature. Agrawal et al. [28] compared machining performance, machining cost, and carbon emission for turning Ti-6Al-4V when flood and cryogenic coolant of LN_2 was employed at various cutting speeds. The cryogenic machining provided better machining performance in terms of tool wear, surface roughness, and power consumption; a lower total cost and carbon emission especially at the higher cutting speed viz., 110 m/min. Biermann et al. [29] analyzed machining performance for cryogenic machining using LCO_2, CryoMQL using LCO_2, flood, and HPC coolants based on tool life for turning Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo. The LCO_2 provided better results in terms of higher tool life for Ti-6Al-4V as CryoMQL resulted in longer tool life for Ti-6Al-2Sn-4Zr-6Mo.

Due to stricter government restrictions to reduce the negative impacts of manufacturing processes on ecology, the aim of industrialists is changing from mere profit-making to sustainable. So, it is highly desirable to calculate the impacts on ecology due to various alternatives [30]. With this view, some literature was identified comparing LCA analysis of turning process employing different cutting fluid approaches like Pereira et al. [31] compared cutting fluid strategies such as dry, flood, MQL, LN_2, LCO_2, and CryoMQL using LN_2 and LCO_2 based on machining performance and LCA analysis using TRACI method for turning AISI 304. However, a comparable machining performance was noticed for hybrid cutting fluid strategies in comparison with flood coolant while CryoMQL machining emerged as the most ecological process. Mia et al. [32] compared dry, and cryogenic coolant using LCO_2 using mono and dual jet each for machinability indicators like cutting force, cutting temperature, surface roughness, and specific cutting energy; and LCA analysis employing EPS 2000 and Impact 2002+ methods when Ti-6Al-4V grade 5 was turned. The better machining performance and lower ecological impact were seen when LN_2 was injected at the flank as well as rake faces of a cutting tool.

The above literature survey affirms that cryogenic machining has a higher potential to provide a sustainable solution for machining Ti-based alloys. However, no study was identified comparing machining performance and Life Cycle Assessment (LCA) analysis for turning Ti-6Al-4V ELI considering MQL, flood, and cryogenic machining using LCO_2. In this regard, this study aims to compare flood, MQL, and cryogenic using LCO_2 based on machinability indicators like cutting force, tool wear, and surface roughness; and LCA analysis for turning Ti-6Al-4V ELI to identify the most balanced cutting fluid strategy in terms of machining performance and impact on the environment.

2. Experimental setup

In this study, turning tests were carried out using a CMZ made TCB25BTY turning center having a capacity of 35 kW engine power. VNMG110404 FN carbide inserts having TiAlN coating were used to

Table 1
Elemental composition and mechanical properties of Ti-6Al-4V ELI.

<table>
<tr><td colspan="8">Chemical composition</td></tr>
<tr><td>Ti</td><td>V</td><td>Al</td><td>O</td><td>Fe</td><td>C</td><td>N</td><td>H</td></tr>
<tr><td>Bal.</td><td>4.2%</td><td>6.1%</td><td>0.1%</td><td>0.12%</td><td>0.03%</td><td>0.01%</td><td>0.008%</td></tr>
<tr><td colspan="8">Mechanical properties</td></tr>
<tr><td colspan="2">Yield strength</td><td colspan="3">Ultimate tensile strength</td><td colspan="2">Elasticity modulus</td><td>Hardness</td></tr>
<tr><td colspan="2">930 MPa</td><td colspan="3">970 MPa</td><td colspan="2">116 GPa</td><td>32 HRC</td></tr>
</table>

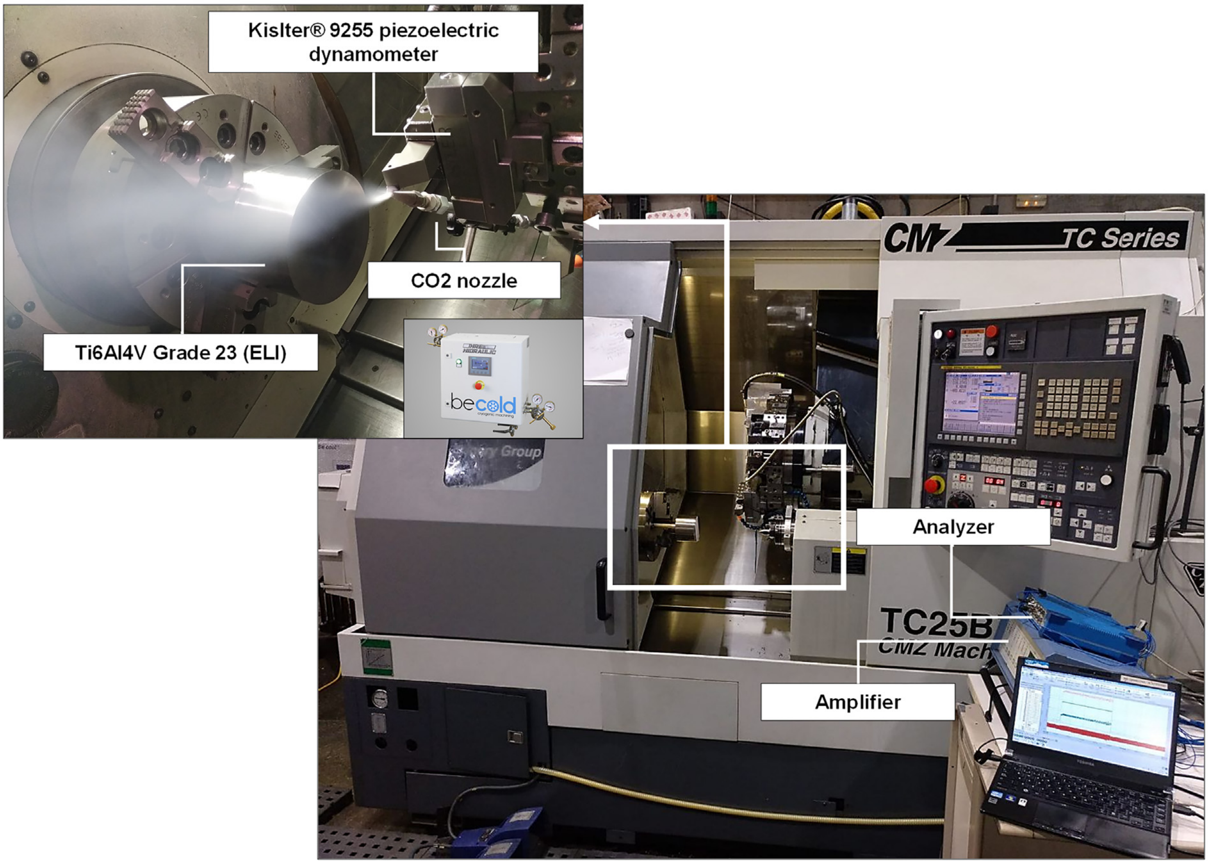

Fig. 1. Experimental setup.

carry out machining. The alloy tested was Ti-6Al-4V ELI alloy having an initial 100 mm diameter and 120 mm length, that is, a Ti-based alloy used in the medical industry. This alloy is characterized by presenting a higher tensile and yield strength; slight chemical differences in comparison with Ti-6Al-4V grade 5 used in the aeronautics sector. Table 1 presents the chemical composition of Ti-6Al-4V ELI.

In this turning tests, three different cutting fluid strategies viz., flood, MQL, and cryogenic coolant of LCO$_2$ were employed at the cutting zone. Fig. 1 shows the experimental setup carried out. The BeCold® was employed to provide LCO$_2$ at 15 bar at −78.5 °C on the cutting tool as shown in Fig. 1. Canola, a biodegradable oil was used with a flow rate of 100 ml/h at 6 bar pressure to provide MQL at the cutting zone. Finally, oil emulsion used in the flood turning test was an emulsion of water and Houghton made synthetic oil with a 10% concentration in water. In all three techniques indicated above, the external nozzles were employed aiming the cutting fluids on the rake face of insert. The cutting speed (v_c), feed (f), and depth of cut (a_p) were selected as 75 m/min, 0.035 mm/rev and 1 mm respectively for all cutting techniques. During these tests, cutting forces were measured with a Kistler® 9255. Besides, several stops were carried out to measure flank tool wear with a PCE-200 optical microscope and surface roughness in terms of R_a and R_z with a Taylor Hobson® made Surtronic Duo 112-3115 contact type roughness tester. The turning tests were stopped in case of 20 min of cutting time or the flank wear (V_b) exceeds 0.2 mm. This tool-life criterion was taken from the biomedical manufacturing sector. Table 2 provides the summary of cutting conditions followed in this study.

3. Results and discussion

This section describes the comparison of results obtained for machinability indicators viz., cutting force, tool wear and surface roughness in terms of R_a and R_z when MQL, flood, and LCO$_2$ were used as cutting conditions for turning Ti-6Al-4V ELI.

Table 2
Summary of cutting conditions employed.

Particular	Details		
Workpiece	Ti-6Al-4V bar having 100 mm diameter and 120 mm length		
Cutting tool	TiAlN coated VNMG110404 FN WC inserts		
Cutting parameters	v_c	f	a_p
	75 m/min	0.035 mm/rev	1 mm
Cutting conditions	*Flood*	*MQL*	*Cryogenic LCO$_2$*
	Fluid: - 10% Emulsion of Houghton made synthetic oil in water	*Fluid:* - Canola based vegetable oil	*Pressure:* - 15 bar
	Flow rate: - 6 kg/min	*Flow rate:* - 0.0015 kg/min	*Temperature:* - -78.5 °C
	Coolant motor rating: - 1.1 kW	*Air pressure:* - 6 bar	*Nozzle diameter:* - 1.5 mm
		Nozzle diameter: - 3 mm	*Flow rate:* - 0.42 kg/min
		Air-compressor rating: - 1.8 kW	

3.1. Cutting force

Fig. 2 presents the comparison of cutting force evolved for turning Ti-6Al-4V ELI with a succession of machining time for three cutting techniques.

From Fig. 2, it was evident that a higher cutting force was observed using MQL techniques as compared to flood and cryogenic machining using LCO_2. A lower machining time indicated in MQL reveals that the tool wear criterion was reached before 20 min of cutting time. The higher cutting force observed in the MQL technique is due to its incapability of extracting a larger heat generating in the cutting zone. In the case of MQL technique, the heat-absorbing capacity is highly dependent on air which has a poor thermal conductivity raising a higher cutting zone temperature. It leads to a rapid tool wear increasing the cutting force. A similar kind of observation indicating a higher specific cutting force was found in the case of turning aluminum alloy (AA1050) compared to flood machining [33]. Approximately, 60% higher cutting force was observed for flood machining in comparison with LCO_2 considering the whole machining time. Comparatively a higher value of cutting force observed for LCO_2 at the final stage of tool life can be used to predict the uncontrolled tool failure. The lower cutting force observed in the case of LCO_2 is due to a better penetrability of it in the cutting zone reducing friction and requirement of cutting force. Besides, a lower tool-chip contact length was observed for LCO_2 promoting discontinuous chips as compared to flood machining. This type of chips reduces the cutting force by lowering friction between tool-chips [34].

3.2. Tool wear

Fig. 3 presents the variation in tool wear with change in cutting time for three cutting fluid strategies viz., flood, MQL, and LCO_2.

From Fig. 3, it is evident that the higher and sudden tool wear was observed for MQL machining in comparison with steady and lower tool wear seen in the case of flood and LCO_2 coolant. The tool life ends in 5 min for MQL machining resulting 75% reduction of it as compared to flood and LCO_2 coolants which maintained tool wear within tool life criterion after 20 min of cutting time. It is due to the incapability of the MQL technique to escape the heat from cutting zone which leads to a raise in cutting zone temperature. There is a serious issue with carbide tools once the temperature raises. Though the carbide tool loses its hardness at 1100 °C, a 50% reduction in hardness is observed at around 800 °C. It leads to the initiation of cutting edge's plastic deformation by weakening the Co binder phase and results in permanent loss of its geometry in terms of sharpness [35]. Fig. 4 depicts the comparison of MQL, flood and cryogenic machining using LCO_2 based on their tool-life in minutes. Fig. 5 presents the tool wear images captured with an optical microscope after the completion of turning tests performed using MQL, flood, and LCO_2 as coolants.

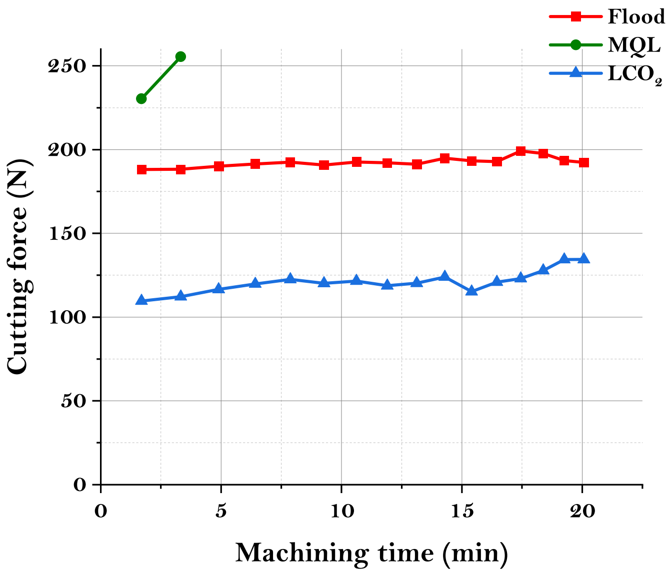

Fig. 2. Comparison of cutting force with a succession of machining time for three cutting techniques viz., flood, MQL, and LCO_2.

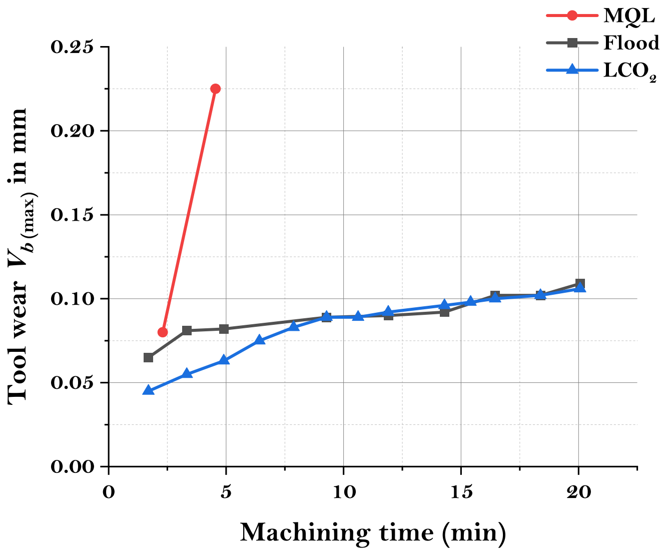

Fig. 3. Variation in tool wear with change in machining time using cutting fluid strategies as flood, MQL, and cryogenic coolant using LCO_2.

This higher tool wear in terms of abrasion and adhesion shown in the case of MQL machining is due to the dominancy of thermal load over mechanical to cause wear mechanisms. In particular, Ti-based alloys, cutting temperature control is mandatory to avoid chemical reaction in which Ti presents in workpiece and cobalt binder phase available on the tool after peeling of coating welds by diffusion effect and causes abrasion and adhesion wear. A similar kind of abrasion wear was also identified due to back and forth rolling action of workpiece material and broken fragments of a tool when low thermally conductive material viz., 15-5 PHSS was cut using MQL machining [36]. In the contrary, at lower cutting speed (50 m/min), a longer tool life was reported in the case of turning Ti-6Al-4V using MQL compared with flood machining [37]. However, the flood coolant capable of removing excessive heat generated at the cutting zone resulted in a negligible tool wear in terms of peeling of the coating. It is due to the continuous flow of chips over the primary cutting edge resulting in rubbing action over it and the coating was peeled off. Slight adhesion wear in terms of built-up edge observed over the cutting edge used for LCO_2 is due to lack of lubrication which does not prevent the friction between chip and tool effectively.

3.3. Analysis of R_a and R_z

The R_a presents an average roughness profile height within considered sampling length. It includes all surface profiles and not sensitive to abrupt changes observed in surface profile. In contrast to R_a, R_z one of the industry-relevant surface roughness parameters presents the maximum height of roughness profile and has a direct indicator of the highest height of roughness profile i.e., the maximum distance between peak-valley within sampling length [38]. In this regard, Fig. 6 presents the variation in R_a and R_z with change in cutting time for three cutting techniques.

From Fig. 6, clear evidence between tool wear and surface roughness parameters viz., R_a and R_z can be seen. Higher values of R_a and R_z observed for MQL machining are due to higher wear which results in a

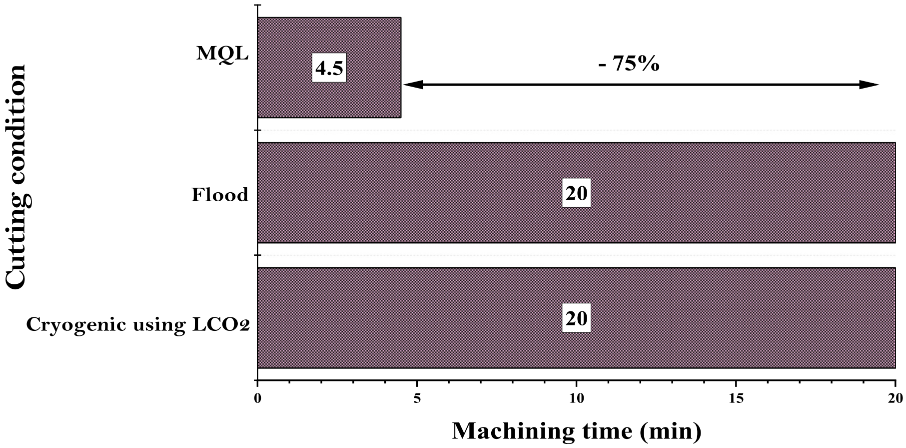

Fig. 4. Comparison of MQL, flood and cryogenic machining using LCO_2 based on their tool life.

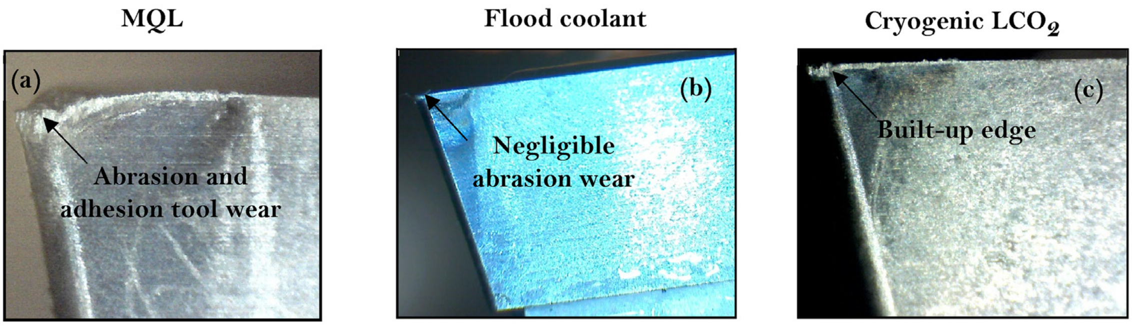

Fig. 5. Tool wear images of worn cutting edge after the end of turning tests performed using (a) MQL (b) Flood coolant, and (c) LCO_2 coolant.

loss of sharpness and cutting geometry. Finally, it increases chatter marks on machined surfaces and consequently higher values of R_a and R_z were observed. The MQL mainly depends on controlling heat generation through friction reduction while flood and cryogenic coolants absorbs the heat generated effectively. This difference plays a vital role to promote tool wear and hence surface roughness for machining low thermally conductive material like Ti-6Al-4V [39]. Comparable values of R_a were observed for flood coolant and LCO_2 except at the final stage of machining wherein 65% lower values of R_a were found in the case of flood coolant in comparison with LCO_2. The same comparison yields 35% lower values of R_z in case of flood coolant in comparison with LCO_2. The lower values of R_a and R_z observed for flood coolant are due to a combination of coolant and lubricant provided by emulsion. Besides, the built-up edge observed at the cutting edge used for LCO_2 also increases surface roughness.

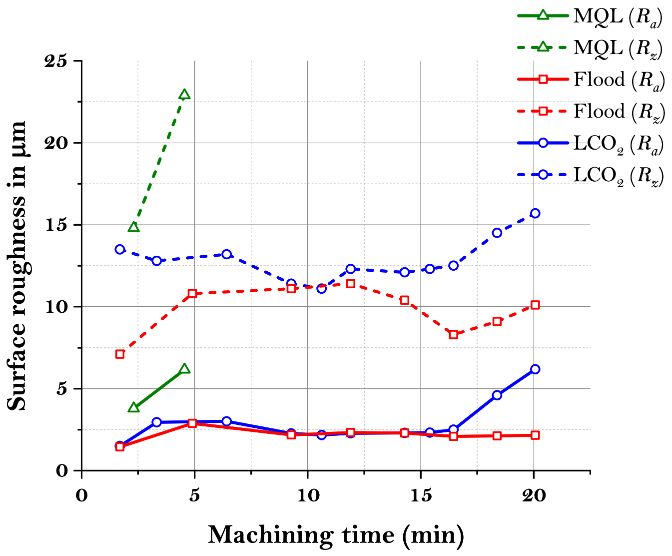

Fig. 6. Variation in R_a and R_z with change in machining time for three cutting techniques.

4. Life Cycle Assessment (LCA)

This study aims to compare the environmental impacts associated with the turning of Ti-6Al-4V ELI using three cutting techniques viz., flood, MQL, and LCO2 as a cryogenic coolant. The LCA analysis was performed on SimaPro 9.1.0 software using the ReCiPe 2016 (H) LCIA methodology.

LCA analysis was performed using the guidelines mentioned in ISO 14010:2006 and ISO 14044:2006 [40]. Fig. 7 presents the various stages and methodology followed for the LCA analysis.

4.1. Definition of goal and scope

This study focuses to compare three cutting conditions viz., flood, MQL, and cryogenic machining using LCO_2 based on their impacts on ecology for turning Ti-6Al-4V ELI. This study also wants to identify the hotspot having a higher ecological impact due to cutting fluid strategy so the required corrective actions can be taken. This LCA analysis follows the "Gate-to-Gate" approach excluding the other life cycle stages of a

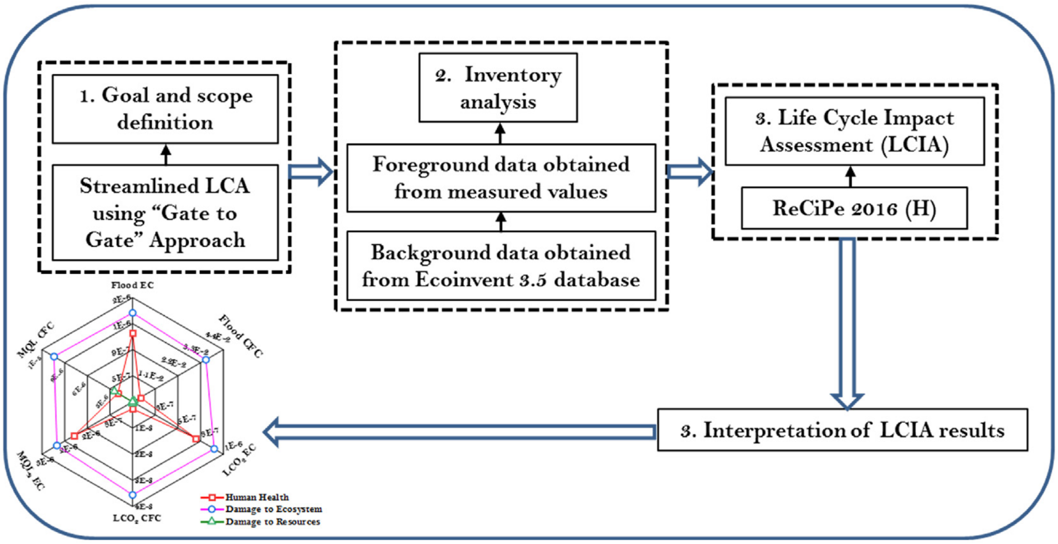

Fig. 7. LCA methodology followed in this study.

process like transportation and energy consumption to extract raw material, processing of raw material, usage of Ti-6Al-4V ELI bar, and disposal of material once its life ends. Here, streamlined LCA was applied considering the impacts generated due to cutting process only. So, it nullifies the LCA analysis of machine tools, workplace, and components used to carry out cutting processes as their impacts on ecology are either independent of cutting techniques or negligible [41]. Fig. 8 describes the system boundaries of considered elements mentioning the relation between their input-output flows in the turning process. The processes for which the data was obtained from the workplace and Ecoinvent 3.5 were identified as foreground and background processes respectively. Functional Unit (FU) is treated as an important indicator especially when the alternative techniques are aimed to compare based on their ecological impacts. With this view, the cutting time of 1 min was considered as a FU for this study. Machining time as FU is more industry-relevant in comparison with the amount of material removal considered in the Ecoinvent database [42]. Due to the unavailability of inventory data and make this analysis simpler, the LCA analysis followed in this study is based on the following assumptions.

- The leakage of emulsion due to sticking on chips was treated as 7.6% weight of chips. This value was obtained by measuring machined

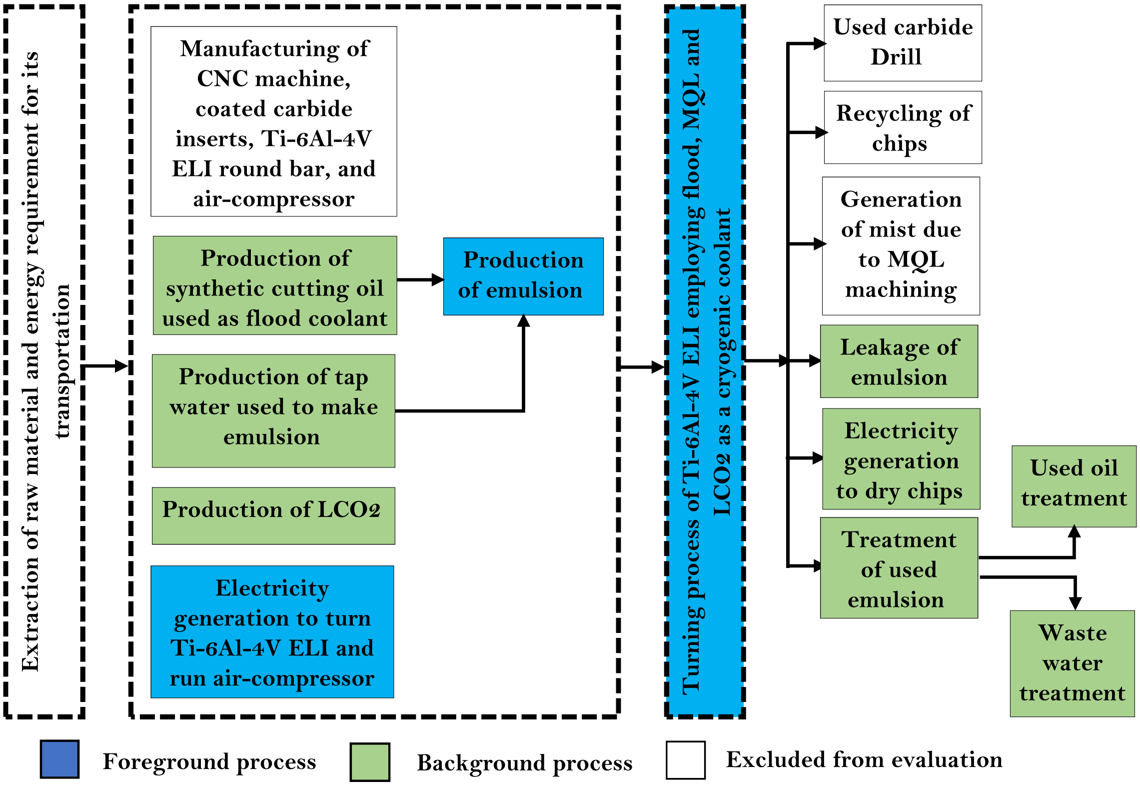

Fig. 8. System boundaries considered in this study.

Table 3
Depiction of inventory used in this study for one FU.

Particular	Flood	MQL	LCO_2
Workpiece	As mentioned in Table 1		
Cutting tool	As mentioned in Table 1		
Consumption of coolant (kg)	5.96	1.52 E-03	0.42
Average electrical energy required for cutting (kWh)	4.89E-03	7.84E-03	3.04E-03
Electrical energy used to run coolant pump (kWh)	3.05E-04	NA	NA
Electrical energy used to run air-compressor (kWh)	NA	5.0 E-04	NA

Table 4
LCI data source considered in this study.

Element	Database
Production of synthetic cutting oil	Raimondi et al. [45]
Generation of electricity	ELCD 3.2 Green Delta V2.18: electricity consumption mix at consumer
Production of Canola oil	Bart et al. [47]
Production of LCO_2	Ecoinvent database 3.5: CO_2 production, LCO_2
Additives	Raimondi et al. [45]
Leakage of emulsion	Campitelli et al. [42]
Tap water	Ecoinvent database 3.5: Market for tap water
Used oil	Campitelli et al. [42]
Electricity for centrifugal pump	Pereira et al. [31]
Wastewater treatment	Campitelli et al. [42]

chips before and after being washed. As emulsion leakages in the form of evaporation, adhesion on machine parts and dust were excluded. The energy required to run cyclone was considered as 0.5 kW to filter and exhaust the smog generated due to MQL machining [31].

- The energy consumed by the air-compressor to raise the air pressure to 6 bar is neglected due to the common compressor was used available at the workshop. So, it has an insignificant contribution to ecology.
- The environmental impact generated due to the insert consumption during the tests was left out of the boundaries. This is due to the tool wear obtained per FU was similar in case of flood and cryogenic machining analyzed. This exclusion, from a quantitative point of view, lowers the accuracy of obtained LCA results, especially when a significantly lower tool-life was observed for MQL machining as compared to flood and cryogenic machining using LCO_2. However, previous results of LCA suggest that the impact of tool wear is not so significant in comparison with coolant consumption, which may be obviated from a qualitative point of view [42].
- In this LCA analysis, the CO_2 used is a recycled gas, that is, it is liquified from a primary process where it would be spilled into the atmosphere as waste. Therefore, the environmental footprint is not carried out by the machining process itself but the primary process [43].
- The melting of chips required to recycle them was excluded because the LCA is focused on the machining process. Besides, the mist generated during MQL machining was excluded due to the used flowrate is negligible.

4.2. Life Cycle Inventory (LCI)

In this section, the quantification of input-output flows considered between the elements of the boundary system was made. The total energy consumed during the cutting process using three cutting techniques each was measured using Eq. (1) [44]. Eq. (2) calculates the total energy required to carry out the turning operation.

$$E_{cutting} = \frac{F_c \times v_c \times t_c}{60} \tag{1}$$

$$E_{total} = E_{cutting} + E_{pump} + E_{air\ compressor} \tag{2}$$

In Eq. (1), $E_{cutting}$, F_c, v_c and t_c denote the cutting energy (J), cutting force (N), cutting velocity (m/min), and cutting time (s) respectively. The total energy required to carry out the turning operation was calculated based on Eq. (2). Then, the value of total energy was converted as per one FU by dividing the total cutting time. The value of LCI for poly-α olefins obtained by Raimondi et al. [45] was referred for emulsion having a 10% concentration of synthetic cutting oil in water. The LCI data used by Campitelli et al. [42] was referred to make emulsion and treatment of waste emulsion. However, the real consumption of emulsion based on 5.96 kg was measured in view of leakage, coolant life, and re-circulation [46], and its long-term effect was considered to calculate its impact values. For calculating the impact due to Canola oil used in MQL machining, the data available at Ecoinvent 3.5 were used. Table 3 presents the description of inventory used in this study for one FU and a detailed summary regarding LCI data considered in this study was mentioned in Table 4.

Table 5
LCIA results of one FU for three cutting strategies.

Turning Ti-6Al-4V ELI	Flood			MQL			LCO_2		
Impact category	EC	CFC	Total	EC	CFC	Total	EC	CFC	Total
OFH	1.02E-07	2.40E-03	2.40E-03	1.66E-07	1.08E-05	1.09E-05	5.97E-08	3.20E-04	3.20E-04
FEu	1.09E-10	1.46E-04	1.46E-04	1.77E-10	−2.36E-06	−2.35E-06	6.34E-11	2.43E-05	2.43E-05
FRS	0.00E+00	7.42E-01	7.42E-01	0.00E+00	5.03E-04	5.03E-04	0.00E+00	6.20E-02	6.20E-02
ME	4.72E-07	2.24E-02	2.24E-02	7.67E-07	9.05E-06	9.82E-06	2.75E-07	7.39E-04	7.39E-04
TA	8.99E-06	2.48E-03	2.49E-03	1.46E-05	4.45E-05	5.91E-05	5.24E-06	7.44E-04	7.50E-04
FPMF	2.92E-06	8.55E-04	8.58E-04	4.75E-06	4.22E-06	8.97E-06	1.70E-06	2.65E-04	2.67E-04
GW	2.31E-03	9.40E-01	9.42E-01	3.75E-03	−1.30E-03	2.46E-03	1.35E-03	3.48E-01	3.49E-01
WC	2.34E-05	1.72E-02	1.72E-02	3.81E-05	2.77E-04	3.15E-04	1.37E-05	2.44E-03	2.45E-03
MEu	3.80E-09	1.01E-05	1.01E-05	6.18E-09	9.83E-06	9.84E-06	2.22E-09	1.59E-05	1.59E-05
SOD	5.25E-10	1.32E-07	1.33E-07	8.54E-10	6.42E-08	6.51E-08	3.06E-10	7.84E-08	7.87E-08
HCT	4.26E-07	2.81E-04	2.81E-04	6.94E-07	3.01E-06	3.71E-06	2.49E-07	3.44E-05	3.46E-05
LU	6.97E-07	1.22E-02	1.22E-02	1.13E-06	7.52E-03	7.53E-03	4.06E-07	7.29E-03	7.29E-03
MRS	2.80E-06	1.65E-03	1.65E-03	4.56E-06	8.03E-06	1.26E-05	1.63E-06	1.08E-03	1.08E-03
IR	6.22E-05	3.14E-02	3.14E-02	1.01E-04	2.78E-06	1.04E-04	3.63E-05	3.08E-03	3.11E-03
FE	1.05E-07	1.56E-02	1.56E-02	1.70E-07	−6.71E-06	−6.54E-06	6.10E-08	3.72E-04	3.72E-04
TE	4.06E-04	1.34E+00	1.34E+00	6.61E-04	8.47E-03	9.13E-03	2.37E-04	2.50E+00	2.50E+00
OFT	1.65E-07	2.87E-03	2.87E-03	2.68E-07	1.09E-05	1.12E-05	9.61E-08	3.26E-04	3.26E-04
HNCT	1.93E-05	4.83E-01	4.83E-01	3.13E-05	4.59E-03	4.62E-03	1.12E-05	2.22E-02	2.22E-02

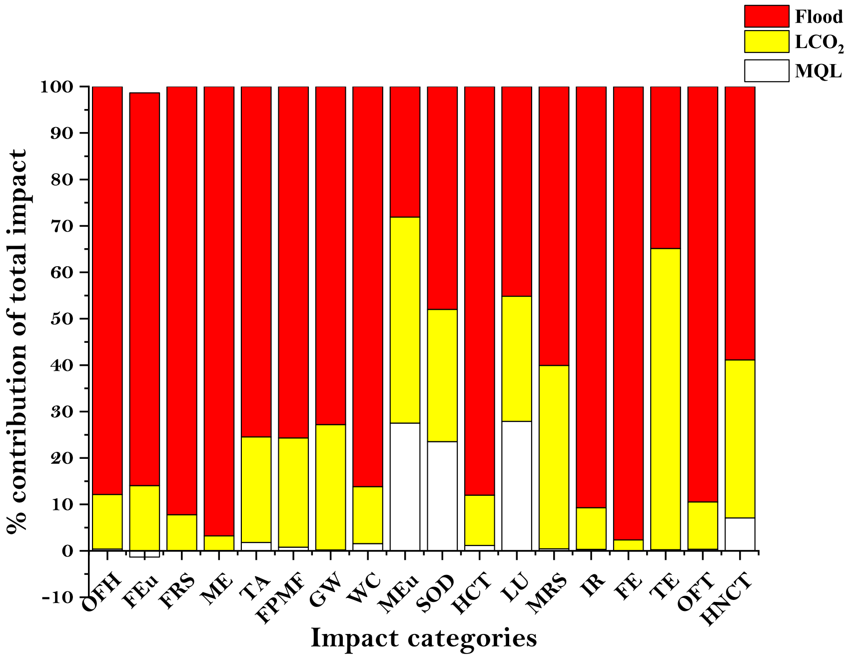

Fig. 9. Comparison of the flood, MQL, and cryogenic machining based on absolute values of ReCiPe 2016 (H) midpoint's 18 categories.

4.3. Life Cycle Impact Assessment (LCIA)

The impact categories of two widely used LCIA methods viz., Eco indicator 99 and CML 2002 are clubbed in the ReCiPe method which includes the midpoint as well as endpoint impact categories [48]. The values of impact categories in the form of midpoint and endpoint can be clubbed into a single score. This score can be directly utilized to compare different competitive alternatives and identify their overall impact on ecology irrespective of their individual impacts. In this study, ReCiPe 2016 (H) was used to identify the values of 18 midpoint categories as they were found more accurate than endpoint categories [49]. Besides, these categories were grouped in the damage categories viz., human health, environment, and natural resources after performing normalization of them using World 2010 (H) method. Table 5 provides the values of ReCePi 2016 (H)'s midpoint impact categories for the turning process of Ti-6Al-4V ELI using three different cutting techniques considering one FU. Here, the values of impact generated due to electricity consumption (EC) and cutting fluid consumption (CFC) were denoted separately to identify their significance.

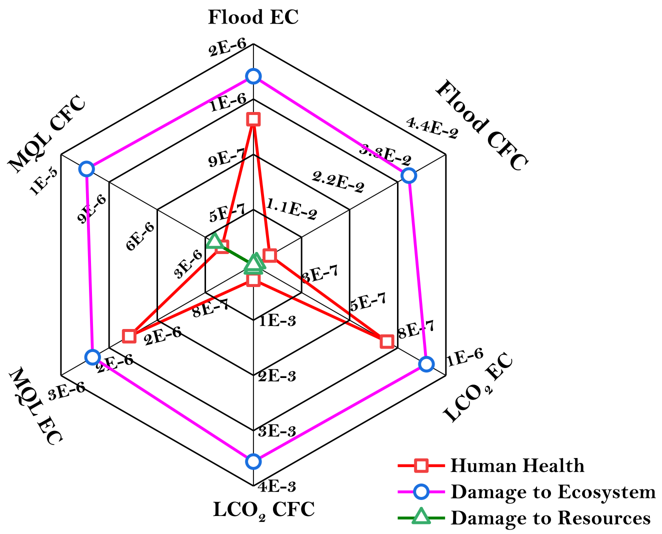

Fig. 10. Comparison of the flood, MQL, and cryogenic machining using LCO_2 based on the values of damage categories due to EC and CFC.

4.4. Life cycle results interpretation

Fig. 9 presents the percentage contribution of total impacts generated due to each cutting strategy in a cumulative form. From Fig. 9 and Table 5, it is evident that overall, lower impacts were generated for MQL machining as compared to other coolants. The values of 18 impact categories for MQL machining ranges between −1.4% to 28% of total impacts considering three cutting techniques. As the same comparison yields for 28%–98% and 2%–65% for flood and cryogenic machining using LCO_2 respectively. Here, it is also required to note that the values of GW, FE, and FEu due to consumption of Canola oil are negative. Its negative value of GW is attributed to the absorption of CO_2 by Canola from the atmosphere during photosynthesis process. However, the total impact value for GW was found positive for MQL machining when the impact generated due to EC has been added. This indicates that CFC has an insignificant impact on GW for MQL machining. Besides, the negative values of FE and FEu obtained for consumption of Canola oil indicate that the trees play a vital role to bring rain which is the main source of freshwater.

From Fig. 9, it can be also conferred that the flood machining is appeared as the "hotspot" due to a higher negative impact on ecology as compared to other cutting conditions. Except, MEu, SOD, LU, and TE, it alone has a greater than 50% of total impacts. Individually, flood machining has a lower negative impact in only categories viz., MEu, and TE when compared with LCO_2. The higher values obtained for the above categories for LCO_2 are attributed to the emission of monoethanolamine used for the process [50]. However, the higher impacts shown for the emulsion-based coolant are due to synthetic cutting oil used. As per the supplementary data provided by Raimondi et al. [45], approximately 34 kg of synthetic cutting oil is extracted from 1000 kg of crude oil. So, the higher impacts can be expected though

90% of water is used along with consideration of recirculation effect for the life of flood coolant.

To make a more relevant comparison which is directly co-related to the ecology and human being, normalized values of ReCiPe 2016 (H) midpoint impact categories are grouped into damage categories viz., human health, ecosystem, and natural resources. Fig. 10 presents the comparison of these damage categories for three different cutting conditions due to coolant and electrical energy consumption EC and CFC. From Fig. 10, it can be conferred that the flood coolant has a higher impact for three damage categories due to CFC. As the higher values of damage categories were observed due to the EC for MQL machining. Besides, a separate air-compressor required to run, a higher value of tool wear necessitating a raised energy is responsible for higher values of damage categories due to EC for MQL machining.

5. Conclusions

In this novel study, flood, MQL, and cryogenic machining using LCO_2 were compared based on machinability indicators viz., cutting force, tool wear, and surface roughness; and LCA results. ReCiPe 2016 (H) LCIA method was employed to measure its midpoint impact categories and hence to compare cutting fluid strategies based on environmental impact generated. Based on the obtained results, the following conclusive remarks can be made.

- The higher cutting force was observed for MQL machining which was followed by flood and cryogenic machining using LCO_2 in decreasing order respectively. Approximately, 60% higher cutting force was observed for flood machining in comparison with LCO_2. The pressurized jet of LCO_2 enabled a better perviousness at difficult to reach cutting area which reduced the friction at tool/workpiece interface.
- Around 75% lower tool life (less than 5 min) was observed for MQL machining in comparison with flood and cryogenic machining using LCO_2 for which less than 0.11 mm tool wear was observed even after machining time of 20 min. A lower tool-life observed for MQL machining is due to its heat extracting incapability resulting in higher tool wear.
- At the initial stage of turning test, lower tool wear was found for machining using LCO_2 but as it approached the machining time of 20 min the tool wear increased in case of LCO_2 while nearly steady tool wear was found for flood machining. The exceptional capability of LCO_2 to extract the heat due to its lower boiling temperature (−78.5 °C) controlled the tool wear effectively.
- The flood machining emerged as a “hotspot” having a higher than 50% of total impacts on ecology for all categories except MEu, SOD, LU, and TE. By considering the 18 midpoint impact categories of ReCiPe 2016 (H), their contribution ranges from −1.4 - 28%, 2 -65%, 28 - 98% and for MQL, cryogenic machining using LCO_2 and flood respectively. The lower impacts generated due to MQL was credited to the minimal amount of cutting oil used during machining. The higher impacts shown by flood machining were justified by the usage of synthetic cutting oil which consumes approximately 1000 kg of raw crude oil to make 34 kg of it.
- The results of damage categories for EC were found lower in comparison with CFC for all three cutting conditions. It shows that the cutting fluid strategy is more sensitive to impacts on ecology than electricity consumption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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