Machining characteristics based life cycle assessment in eco-benign turning of pure titanium alloy

Munish Kumar Gupta[1], Qinghua Song[1,2*], Zhanqiang Liu[1,2], Catalin Iulian Pruncu[3], Mozammel Mia[4], Gurraj Singh[5], Jose Adolfo Lozano[6], Diego Carou[6], Aqib Mashood Khan[7], Muhammad Jamil[7], Danil Yu Pimenov[8]

[1]Key Laboratory of High Efficiency and Clean Mechanical Manufacture, Ministry of Education, School of Mechanical Engineering, Shandong University, Jinan, P.R. China, email: munishguptanit@gmail.com. https://orcid.org/0000-0002-0777-1559

[2]National Demonstration Center for Experimental Mechanical Engineering Education, Shandong University, Jinan, P.R. China, email: ssinghua@sdu.edu.cn; melius@sdu.edu.cn.

[3]Mechanical Engineering, Imperial College London, Exhibition Rd., SW7 2AZ London, UK, email: c.pruncu@imperial.ac.uk

[4]Department of Mechanical Engineering, Imperial College London, SW7 2AZ, London, United Kingdom, email: m.mia19@imperial.ac.uk , https://orcid.org/0000-0002-8351-1871

[5]Industrial and Production Engineering Department, NIT Jalandhar, Punjab, India, email: singh_gurraj@yahoo.co.in

[6]Department of Mechanical and Mining Engineering, University of Jaen, EPS de Jaen, Campus Las Lagunillas, 23071, Jaen, Spain, email: joselomi@hotmail.com, diecapor@gmail.com

[7]College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China, email: dr.aqib@nuaa.edu.cn, engr.jamil@nuaa.edu.cn

[8]Department of Automated Mechanical Engineering, South Ural State University, Lenin Prosp. 76, Chelyabinsk 454080, Russia, email: danil_u@rambler.ru

*Corresponding author: Qinghua Song, ssinghua@sdu.edu.cn, Tel/Fax: +86-(0)531-88392539

Abstract: Minimum quantity lubrication (MQL) is considered as an eco-benign, greener, and socio-economic alternative to dry cutting. Nevertheless, its effectiveness is limited to mild cutting materials owing to less generation of heat during machining. In order to address this challenge regarding hard-to-cut materials, energy requirement, and material flow, Ranque-Hilsch Vortex Tube assisted Minimum Quantity Cutting Fluids (RHVT-MQCF) has been practiced in the turning of pure titanium and compared its effectiveness with conventional MQL cooling techniques. The turning experiments were performed on pure titanium alloy by varying the cutting speed (250-300 m/min), feed rate (0.05-0.13 mm/rev), and depth of cut (0.3-0.5 mm), respectively. In addition, a statistical modeling technique and desirability function approach was used to analyze and optimize the sustainable indicators for the machining process associated with the cutting force, power consumption, specific cutting energy, chips morphology, material removal rate, and surface quality (i.e. surface roughness). Regarding sustainability performance, Life Cycle Assessment (LCA) model was applied using Simapro 8.3 software connected to EPS 2000 and ReCiPe Endpoint v1.12 databases. Findings have depicted the high performance of RHVT-MQCF conditions regarding machining characteristics compared to MQL under same conditions. In-depth analysis has shown that RHVT-MQCF is a sustainable and useful alternative to the manufacturing sector.

Keywords: Sustainability; Life cycle assessment; Machining; Difficult-to-cut metal; Titanium.

Abbreviations

a_e: Depth of cut

E_p: Energy consumed per product

E_y: Energy consumed per year

F: Feed rate

F_c: Main cutting force

MQL: Minimum quantity lubrication

M.R.R.: Material removal rate

P: Power consumption

RHVT-MQCF: Ranque-Hilsch vortex tube assisted minimum quantity cutting fluids

Rz: Surfaces roughness values i.e., maximum peak to valley

SCE: Specific cutting energy

TBL: Triple bottom line

v_c: Cutting speed

1. Introduction

Over the past years, the demand for sustainable and green products in the manufacturing sector is growing day by day (Campitelli et al., 2019). Such burgeoning in demands stimulates the novel internal and external policies that drive the companies towards sustainable manufacturing initiatives. 'Sustainability' is a comprehensive approach that relates the environment, economic and social behavior having direct impact on the market (Najiha et al., 2016) . In other words, 'Sustainability' follows the concept of triple-bottom-line (TBL) in which the social, economic, or/and environment aspects have been considered as roots for the development of any product or process (Hourneaux Jr et al., 2018). In the manufacturing sector, especially in machining, the Product Sustainability Index (ProdSI) criteria is used to evaluate the sustainability assessment of the manufactured component (Yip and To, 2018). This evaluating criterion is very useful to integrate the socio-economic aspects of sustainability, i.e., economic, environment and social dimensions in the manufacturing sector (Hegab et al., 2018; Pervaiz et al., 2018). Moreover, there is a dire need to develop and design such environmental-friendly systems that can combine the academic knowledge and technical skills to save energy and resources when machining by a continuum process assessment (Priarone et al., 2018).

Among numerous potential characteristics of titanium alloy, it has same strength as steel and only half as heavy. It could overcome the demand of iron and aluminum; therefore, nowadays the metallurgists classified it as one of the three most important metals (Machai and Biermann, 2011; Pervaiz et al., 2019). Owing to its excellent physio-chemical properties, it is one of the most suitable materials for aerospace, biocompatible to the human body, and corrosion resistance (Bortagaray et al., 2016; Boyer, 2010). Nonetheless, these materials are difficult-to-machine due to some bete noire properties (i.e. high chemical reactivity, poor thermal conductivity, low modulus of elasticity) accelerating tool wear, lower production rate and surface quality during machining (Faga et al., 2017; Jamil et al., 2019). In order to improve the machining characteristics of titanium and its alloys, the modern applications of eco-benign cutting strategies such as dry machining, MQL conditions, cryogenic cooling, nitrogen cooling, air cooling, high-pressure cooling, etc. are reported as the sustainable and green alternatives (Gupta et al., 2019; Mia et al., 2018a). In MQL system, the small quantity of cutting fluid along with the compressed air is directly targeted to the tool-chip interface zone (Maruda et al., 2017, 2016). This mechanism of cooling allows for obtaining higher material removal, tool life, surface quality and low temperature than dry cutting for the machining of mild-cutting materials (Mia et al., 2018b, 2018c). The elevated temperture under machining of hard-to-cut materials is due to provision of insufficient lubrication spray at ambient tempature air (Gajrani et al., 2019). Nevertheless, additional cooling by mixing cold air with minute cutting oil can limit the heat genration by lubri-cooling effect at the tool-chip interface (Krolczyk et al., 2019, 2017; Sen et al., 2019). Hence, there is a need to develop such efficient cooling system that can help to improve the cooling-lubricating efficiency of available MQL system. Recently, the integeration of Ranque-Hilsch vortex tube (RHVT) with MQL technique has gained much attention to the researchers and academicians around the globe. In RHVT assisted cooling method, the more heat is dissipated from the cutting zone as compared with the conventional MQL system (Liu and Kevin Chou, 2007). The main reason is that the air before entered into cutting zone is splitted into two parts i.e., cold and hot air without any usage of external enegy in RHVT cooling system. RHVT cooling system includes some basic designing parts such as generator, spin chamber, conical valve and cold end that helps to increase its efficiency as compared with the conventional MQL system (Liu and Kevin Chou, 2007). For instance, initally the compressed air at high speed is passed through the generator followed by the spin chamber. After that, the conical valve blocked the central air at the hot terminal inside the vortex tube and as a result the cold air is supplied to the cold end of the vortex tube. This cold air is producing more cooling effect at the cutting zone, and consequently, the genertaion of temperature is less as compared with conventional MQL system. Besides, the performance of RHVT cooling condition is far better and it is also considered as the economical alternative because the efficiency of MQL system has been improved without any usage of external energy. In the literature, the enormous research efforts were focused on MQL cooling conditions, but the work reported on vortex tube integrated with the MQL system is very limited. For instance, (Liu and Kevin Chou, 2007) implemented the RHVT cooling condition in machining of hypereutectic Al-Si alloys. In another similar study, (Boswell and Chandratilleke, 2009) also conducted experiments using vortex tube for metal cutting operations. (Sanchez et al., 2012) performed experimental tests on steel by simulating the turning process. (Ha et al., 2012) conducted exhaustive research by using a vortex tube for the metal cutting industry. (Salaam et al., 2013) performed experimentation for comparing the performance of dry cutting and RHVT air cutting while turning mild steel. (Taha et al., 2014) used the RHVT technique at variable feed and cutting depth in comparison to dry ambient air cutting. (Sharma et al., 2016) also provided a review work related to potential application of MQL using conventional and nanofluid based cutting fluids. In this work, the benefits of MQL cooling over other methods have been discussed. Some other work related to the RHVT and MQL cooling is prescribed in Table 1.

Table 1: Literature review related to the various cooling conditions

Authors	**Work/ Tool material**	**Cooling conditions**	**Investigations**	**Remarks**
		RHVT cooling techniques		
(Liu and Kevin Chou, 2007)	Hypereutectic Al-Si alloys/ Tungsten carbide inserts	Dry, Vortex tube 1 (outlet air of 5–15 °C at flow rate of $1.32*10^{-2}$ m^3/s) and Vortex tube 2 (outlet air of -25 to -15 °C at a flow rate of $9.43*10^{-4}$ m^3/s)	Cutting temperature and tool wear	Vortex tube 2 conditions help to reduce the temp and tool wear
(Boswell and Chandratilleke, 2009)	-	Dry machining and air cooling with vortex tube	Cutting temperature and tool life	Vortex tube shows better results
(Sanchez et al., 2012)	SAE EV-8/ coated cemented carbide	Flood cooling, MQL and pulverization	Tool life, surface roughness, cutting tool temperature, cutting force, chip morphology, microstructure	MQL shows good results as compared with other methods
(Ha et al., 2012)	-	MQL and RHVT	Working principles and types of RHVT	-
(Salaam et al., 2013)	Mild steel/ coated carbide	Dry and RHVT	Surface Roughness and Power Consumption	RHVT reduces the temperature but dry machining produces the

				good surface finish
(Taha et al., 2014)	Mild steel/ coated	Dry and RHVT	Surface Roughness and Carbon Footprint	RHVT reduces the temperature but dry machining produces the good surface finish and less carbon footprints
(Pinar et al., 2016)	Al 5083-H36/ Uncoated cemented carbide flat end mill	Classical cooling system of machine tool and vortex tube cooling strategies	Surface roughness and tool wear	Vortex tube shows better results
(Saberi et al., 2016)	CK45 soft steel/ Aluminum oxide	Dry, flood, RHVT-MQCF	Surface roughness and grinding temperature	RHVT-MQCF is better to improve the machining performance
		MQL and other cooling methods		
(Sarikaya and Güllü, 2014)	AISI 1050 steel/ Coated carbide	Dry, wet and MQL	Surface roughness	MQL is better
(Sarikaya and Güllü, 2015)	Haynes 25/ Uncoated carbide insert	MQL parameters	Tool wear, surface roughness	-
(Sarıkaya et al., 2016)	Haynes 25/ Uncoated carbide insert	Dry, wet and MQL	Tool wear, surface roughness	MQL is better
(Yıldırım et al., 2019)	Inconel 625/	Dry, MQL, Nano-MQL	Tool wear, roughness and temperature	Nano-MQl shows better results

In the light of current state-of-art review, it has been interestingly noted that the applications of MQL and RHVT-MQCF conditions are considered suitable cooling conditions and, besides, they significantly improve the machining performance of different materials like steel, inconel and titanium etc. Many authors have made very great efforts to improve the machining characteristics, but to the best of our knowledge, the holistic understanding of sustainability assessment (using LCA and other models) of pure titanium alloy under MQL and RHVT-MQCF conditions has not been reported yet. Therefore, this work firstly deals with the sustainability aspects of pure titanium alloy under MQL and RHVT-MQCF conditions using one of the well-known industrial tool i.e., LCA.

LCA is an environmentally benign manufacturing (EBM) tool responsible to generate the sustainability characteristic of any specific manufacturing process from sustainable and environment point of view. In other words, EBM is considered a competitive measure between the industrial companies and the environmental regulations (Gutowski et al., 2005). EBM is also dictated by the three main factors i.e., manufacturing and supply chain, manufacturing processes and the manufactured product. The environmentally friendly approach is used directly for Environmentally Benign Pretreatments/treatment that permits to create effective systems with reduced negative features on the environment (Dhandapani and Sharma, 2014). Some specific global trends were observed in the literature in regard to Eco Manufacturing. (Dornfeld, 2014) proposed a smart solution based on "eco-route maps"– that considers a strategy comparable to one, for a night of preparation, before taking a road trip. Moreover, the introduction of environmental indices associated to the traditional manufacturing measures (i.e. production rate, quality parameters and energy utilization) allows developing robust process modeling and planning decisions leading to facilitate waste management/reductions. When decision-making is designed for environmentally-conscious manufacturing, the specific elements (i.e. design of parts for machining, process planning and selection of operating parameters) linked to the priority of environmental factors have been included. There is enormous potential to obtain sustainable manufacturing of titanium and its alloys by reducing the amount of effort and cost. Therefore, identification of driving factors and patterns mechanism leading to process failure is paramount important to improve the machining time and use the resources in a sustainable manner (Pramanik and Basak, 2018). On the light of the above discussion, the objectives of this paper are: (1) Experimentation of pure titanium alloy under MQL and RHVT-MQCF conditions (2) Statistical modelling (3) In-depth analysis (4) Optimization of process parameters and (5) Sustainability assessment using LCA tool.

2. Materials and Methods

The details of the experiments are presented in (Singh and Sharma, 2017). From there, we have adopted the results of cutting forces and power consumption. Here, for better understanding of readers, the key experimental details are highlighted. The workpiece material used is commercially available pure titanium alloy in the form of round bars having dimension of 150 mm length and 50 mm diameter. The major reason for the selection of this material is its widespread application in medical equipment, aerospace parts, nuclear reactor, marine sector, etc. Table 2 presents the chemical composition of the investigated material.

Table 2: Chemical composition of material.

	C	Fe	H	O	N	Ti
Titanium (Grade-2)	0.1 % max	0.3 %	0.015 %	0.25 %	0.03 %	99.2 %

The cutting inserts used are uncoated carbide inserts having technical specification of 0.8 mm nose radius and 7° relief angle. The complete details are presented in Table 3. The benefits of these inserts are their cost effectiveness and good machining compatibility against pure titanium and its derived alloys.

Table 3: Technical details of machine, workpiece, cutting insert and cooling conditions

Type	**Details**
Material	Titanium (Grade-2) alloy, 150 mm length and 50 mm diameter
Machine tool	Batliboi made Sprint 20TC, 11 kW spindle motor, Speed range 30–4000 rpm
Cutting tool	Uncoated Carbide, ISO Designation: CCMT 09 T3 08, 7° relief angle
Cutting fluid	Commercially available cutting fluid
Flow rate	30 ml/hr
Air pressure	6 bar

The cutting speed, feed rate and depth of cut are continuous factors while the two cooling conditions are categorical factors. The range of continuous parameters are purely based upon pilot experiments, literature review and tool manufacturer recommendations. The experiments are performed as per the design of experiment Box-Behnken technique. The lathe tool dynamometer made by TeLC DKM2010, coupled with power consumption meter, is connected to an online recorder to acquire the details of the main cutting forces and power consumption. The major benefit of this device is that the cutting power is directly calculated along with the cutting forces. Then, the two responses i.e., productivity in terms of material removal rate (M.R.R., mm^3/min) and specific cutting energy (SCE, kN/mm^2) are calculated with Eq. (1) and (2) (Mia and Dhar, 2017).

$$M.R.R. = 1000 \text{ x } v_c \times f \times a_p \tag{1}$$

$$SCE = \frac{F_c}{f \text{ x } a_e} \tag{2}$$

where, v_c denotes the cutting speed in m/min, f represents the feed rate in mm/rev, a_p is the depth of cut in mm and F_c represents the main cutting force in N.

The surfaces roughness parameter i.e., maximum peak to valley (*Rz*, Eq. 3), after each cut is evaluated using Mitutoyo make SJ 301 model surface roughness tester. The parameters selected for roughness are according to ISO standards i.e., sampling length 2.5 mm, cut-off length 0.8 mm, gauss filter, diamond tip (5 µm diameter) and 40 mm skid radius, respectively. Note that a fresh insert and three readings were taken for each cut of turning operation.

$$Rz = \frac{1}{s}\sum_{i=1}^{s} Rt_i \tag{3}$$

where, *s* represents the length number of samples, and Rt_i is the *Rt* for the i^{th} sample length. The turning tests are performed under two eco-benign environments i.e., MQCF and RHVT-MQCF cooling conditions. In MQCF system, the two sets of nozzles (NOGAMINI MQCF made, imported from Israel) is used to deliver the minimum quantity of cutting fluid. The nozzle system constitutes one inlet air pipe, cutting fluid pipe, knob for controlling the fluid quantity, etc. Furthermore, the separate attachment i.e., the Ranque-Hilsch vortex tube (Essen engineers 002H, made) is integrated with these sets of nozzles for RHVT-MQCF conditions. Some specific parameters are kept fixed as showed in Table 3. Figure 1 presents the complete working methodology of the present paper.

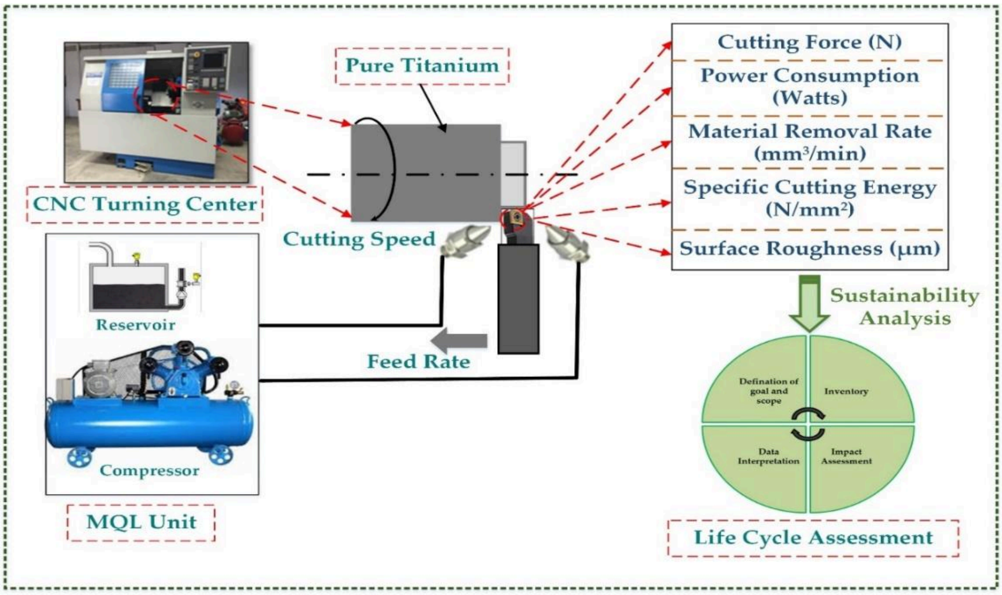

Figure 1: Complete methodology of experimental work

3. Sustainability Model: Life Cycle Analysis

The industrial activities that cover the manufacturing processes are one of the major energy consumption area that converts the energy within greenhouse gas (GHG) emissions. They have negative consequences for resources preservation and environment, which contribute to the global warming. The GHG emissions are formed of carbon dioxide (CO_2), which act as main contamination gas in the world, and other specific gases (i.e. methane, nitrous oxide and chlorofluorocarbons) measured in units of CO_2 equivalents (CO_2-eq). Nowadays, many companies have created their own policies which focus on clean manufacturing production (Tanaka, 2011). These policies are designed to reduce environmental effects with potential to increase the resource efficiency when manufacturing gear parts. In the industrial environment, the focus should be oriented to major factors (e.g., equipment, materials and tools). Therefore, a novel approach that permits to introduce new materials and structured processes allows producing components with high performance of sustaining the global competition. Using the Simapro 8.3 computer program and two evaluation methodologies, the EPS 2000 and ReCiPe Endpoint v1.12, the environmental impacts of the 26 trials sample have been determined.

LCA offers an accessible sustainable methodology oriented on the holistic knowledge approach that is related to three aspects of global world i.e., social, environment and economic. In this work, the impact associated to the life cycle for a system submitted to two cooling conditions is evaluated and simulated using the LCA SimaPro 8.30 software. This analysis is possible to detect the effectiveness of cooling condition in terms of resources, environment, economics and machining performance. Further, the LCA model implemented is associated to ISO 14040 standards, defining the principles and framework, and to ISO 14044 that defines various steps for the analysis (as presented in Table 4). Similarly, Figure 2 shows the processes and methodologies involved in the LCA process as per the ISO 14040:2006. The complete detail of this analysis is presented in subsequent sections.

Table 4: ISO 14040, 14044 and 14047 standards (Source: AENOR)

Standard	Description	Edition
ISO 14040:2006	Environmental management. Life Cycle Assessment. Principles and framework.	2006
ISO 14044:2006	Environmental management. Life Cycle Assessment. Requirements and Guidelines.	2006
ISO/TR 14047:2012	Environmental management. Life Cycle Assessment. Illustrative examples on how to apply ISO 14044 to impact assessment situations.	2006
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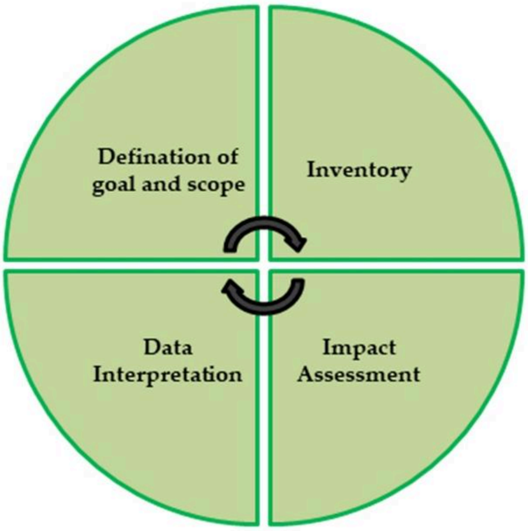


Figure 2: LCA framework (ISO 14040:2006)

3.1 Definition of objective, scope and system boundries

The LCA methodology permits identification of the environmental effects from the processes, products and systems studied. The LCA enables partial analysis for specific steps or a full cycle evaluation. In this work, the amount of energy consumed throughout the trial is determined. The following initial hypotheses conditions have been defined in order to increase the speed of processing and reduce potential limitations, such as:

- It is considered three input parameters with three levels i.e., cutting speed, feed rate, depth of cut and two cooling conditions as first objective.
- Electricity consumption corresponds to the production mix of the European system of energy generation.
- Productivity, energy consumption, forces, and surface quality characteristics are considered as sustainable indicators. The complete system boundary conditions used in this experimental work is depicted in Figure 3.

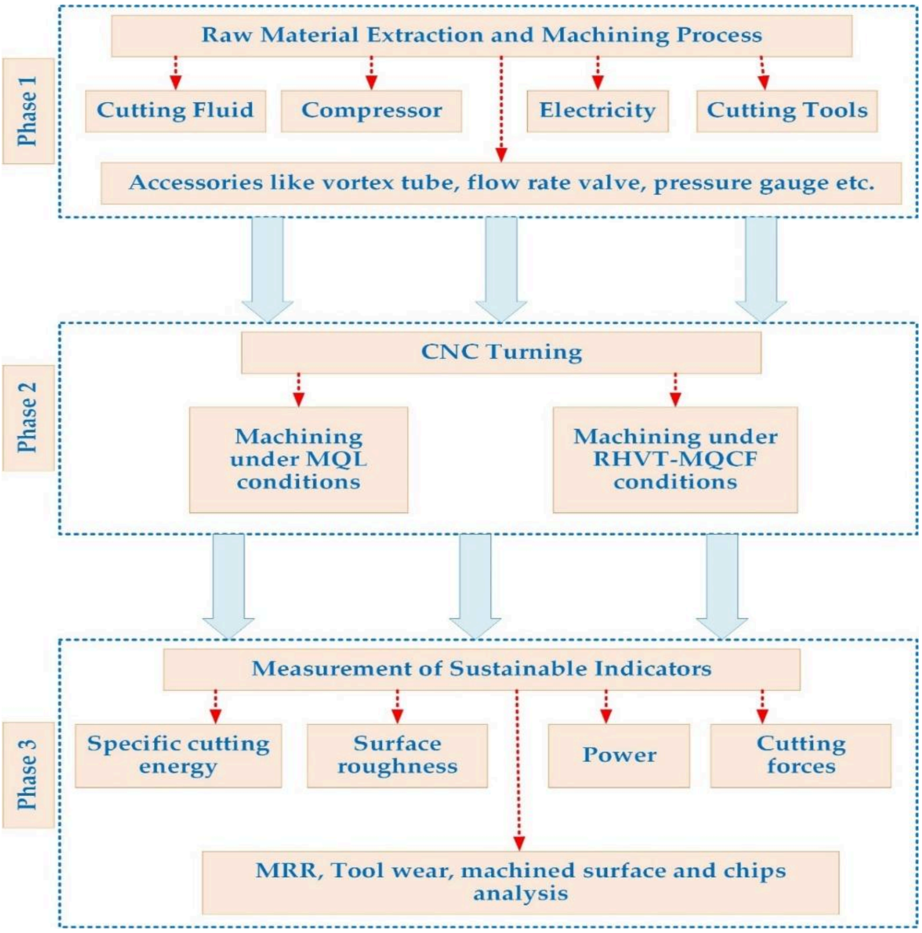


Figure 3: System boundaries of pure titanium alloy machining process using MQCF and RHVT-MQCF conditions

- The cleaning process for different devices is not considered in the analysis as they have negligible contribution.

- Fixed parameters are tool geometry, tool material, lubrication properties, coolant flow, air flow, humidity.
- Transport of material has not been considered. Because it has a reduced percent contribution and is performed in the laboratory.
- In the end, the effect of used CNC machine in the LCA is considered insignificant, as it is used from last couple of years.

3.2 Inventory

For carrying out the LCA, an analysis for raw material inventory and energy consumed within each of the experiments is needed. Table 5 shows the overview of the input and output conditions used in turning of pure titanium alloy. This data is gathered from the experience of the machine operatore and CNC machine manufacturer's. Moreover, some assumptions after experiments are considered in this work. Note that the assumptions are not specified by the simapro sofwtare and database of ecological systems, they are assumed based upon the experience of machine tool operator. The details of assumptions are given below:

- Scrap: after experiments, we postulated that the scraps produced are mostly reusable and recyclable.
- Cutting tool: Uncoated carbide inserts are used because of economical cost. A new fresh insert has been used for each turning condition and the effect of tool conditions are not assumed in this work.
- Environmental concerns such as humidity, pressure etc.

Table 5: Overview of the input and output conditions used in turning of pure titanium alloy

Basic data used for machining			
Process	**Functional Unit**	**Description**	**Input-output flow**
Machining Process	Refer Table 3	Refer Table 3	Input: workpiece material, tools, compressed air, electricity, cutting fluids etc. Output: Machining surface, chips, forces etc.

Cutting fluid	1 litre	Commercially available oil Technical Specifications: Bright and Clear, 68.16 Viscosity (CP) (at 20°C), 0.1432 thermal conductivity (W/m-K)	Input: Compressed air, electricity, saturated fat, monounsaturated fat, polyunsaturated fat, trans fat Output: MQCF-oil
Cutting tool	1 Pcs	Material is removed with cutting tool Technical Specifications: Un-coated carbides (CCMT 09 T3 08), 7° relief angle	Input: Compressed air, electricity, titanium. MQCF oil Output: Uncoated carbide tool, used oil etc.

3.3 Impact Assessment

The LCA permits to evaluate the environmental impacts at any step of product life cycle, service or process, considering that some phases may affect others. In this way, it is possible to obtain the necessary information that allows us to carry out actions that reduce the negative impacts to the environment. In this work, the impact of two indicators i.e., EPS 2000 method and ReCiPe Endpoint (E) v1.12 is well discussed. The EPS-2000 method incorporates for evaluation of major challenges such as human health, ecosystem production capacity, abiotic stock resource and biodiversity. Similarly, three analyses such as human health, ecosystems and resources are considered for ReCiPe Endpoint (E) v1.12 analyses. These indicators are considered because they are prominent factors that directly deal from perspectives of sustainability. Further, to carry out the LCA, the ISO 14040 standard that defines the principles and framework, and the ISO 14044 that establishes the requirement and guidelines are used. Moreover, the ISO 14047 is also used as a tool for improving the understanding on how to carry out LCA. In Table 4, the details of these standards are listed.

3.4 Interpretation

Once, the data of the inventory of all the relevant components are obtained, they are introduced in the Simapro program to identify the environmental impact by means of two methods. These methods are the EPS 2000 and ReCiPe Endpoint v.1.12. 26. The titanium material samples are considered as inventory production to validate the study outcome.

4. Results and Discussion

4.1 Statistical modelling

The response values are first checked for the normality of the data. Figure 4 presents the empirical cumulative distribution functions for the cutting force, power, respectively, the material removal rate, amount of cutting energy and the surface roughness. The data are plotted for the 26 experiments, which are conducted under both the MQCF and RHVT-MQCF conditions. The trend obtained from the investigated data follows the Normal Distribution. However, the values of standard deviation, which seem high in respect to the corresponding outputs mean, are due to the variation of the application of different cooling-lubrication modes that reduce some of the response's values at quite low level.

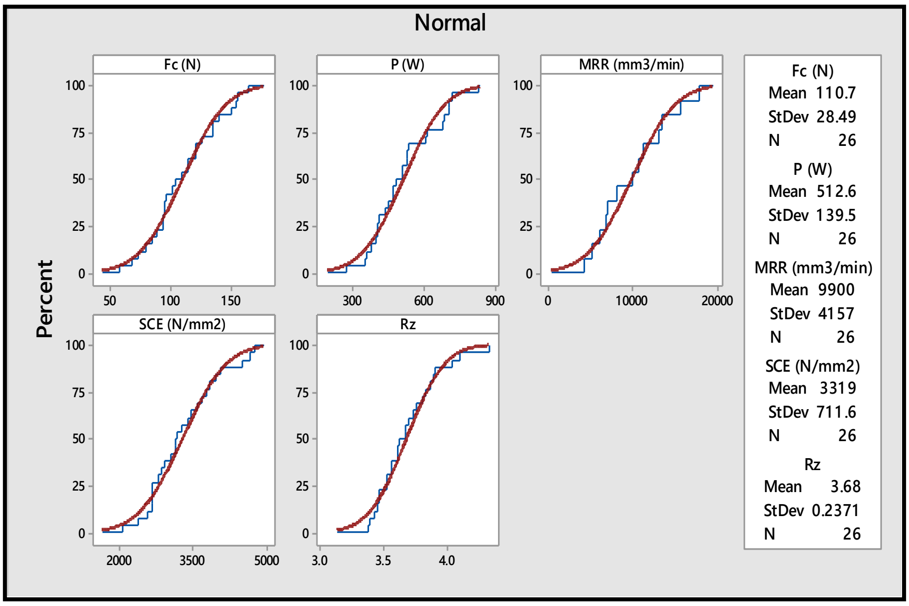
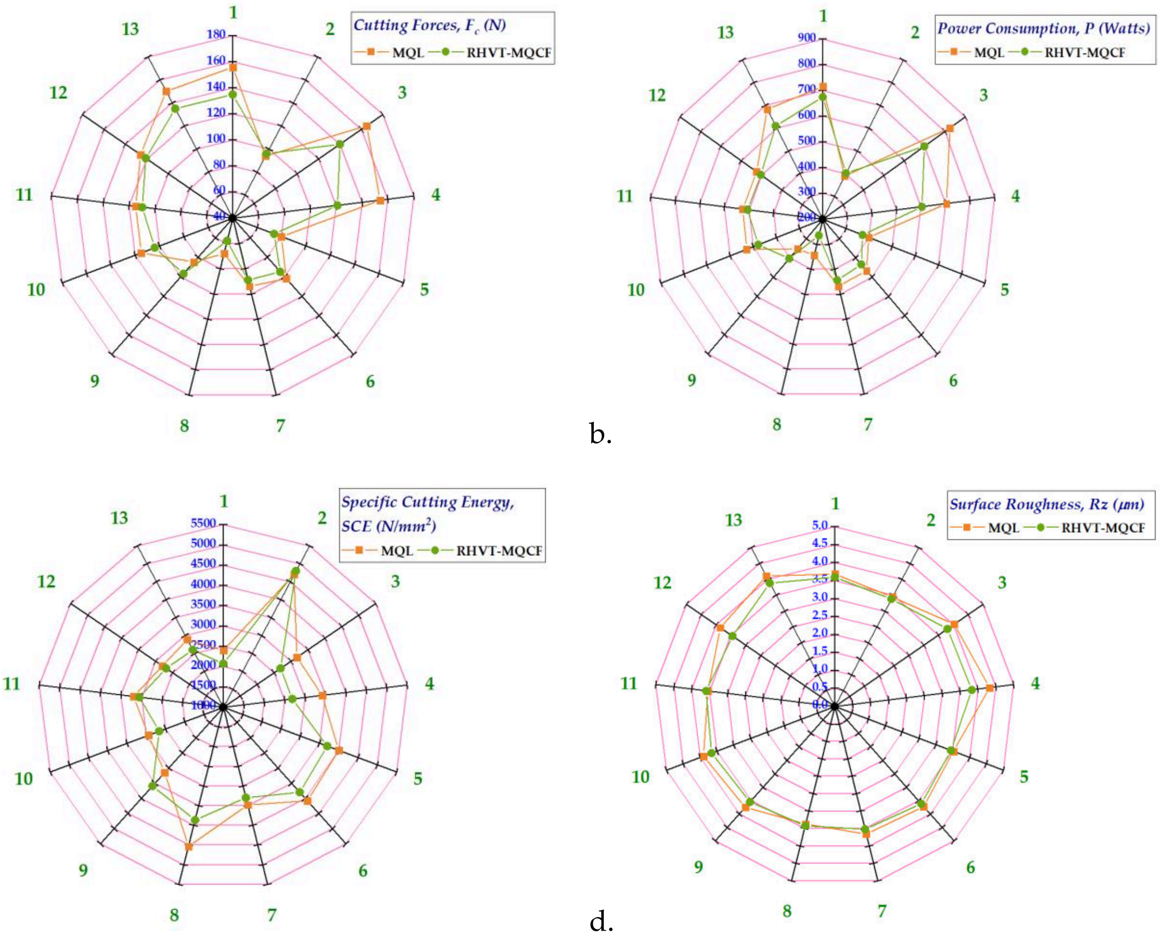


Figure 4: Empirical Cumulative Distribution Function for normal distribution

4.2 Influence of cooling conditions on machining characteristics

Figure 5 depicts the comparison between MQCF and RHVT-MQCF cooling techniques for the studied output values. The plots show that RHVT-MQCF helps in further reduction of the output values compared to the MQCF technique. This is because the heat mechanisms concept of MQCF cooling is totally different from RHVT-MQCF cooling. In RHVT-MQCF conditions, the more chilled air is used along with the cutting fluid and this chilled air provides the good cooling effect at cutting zone. As a result, the low values of responses are observed in the case of RHVT-MQCF conditions. Figure 5 also justified this statement. Moreover, in RHVT-MQCF conditions, Ranque–Hirsch vortex tube is used to enhance the process performance of MQCF system. For instance, due to the vortex action, the velocity of fluid is reduced with the increase of degree of reaction from inlet to outlet. This change in phenomena results in low pressure as well as temperature values at exit of the nozzle. The efficiency of the RHVT-MQCF technique over the MQCF condition is highlighted in Figure 5(a), which is demonstrated by the decreasing of the cutting forces requirement when machining pure titanium alloy. The reduction is higher at lower range of cutting speeds, while it reduces abruptly at higher ranges of cutting speeds. This can be seen in the experiments number 1, 5, 12, 13 where the speed levels are on the lower side in the range of 250 m/min. It can also be observed that for experiments 2, 4, 6, 7, the trends of results are nearly similar for both MQL as well as RHVT-MQCF strategies. The explanation for such observations can be given on the basis on an abrupt increase in cutting temperature at higher cutting speeds (Mia et al., 2019). Since, the use of vortex tube reduces the mist temperature by 20-40 ^{o}Celsius, at lower cutting speeds the reduction in mist temperature overpower the cutting temperature generated due to cutting effect. Therefore, it is possible to achieve a lower friction at the contact of workpiece vs cutting tool. When the cutting speed exceeds 300 m/min, the cutting temperature surpasses the cooling effect of the cold mist generated with the assistance of vortex tube. This abrupt raise in temperature further neutralizes the vortex cooling effect and thus the RHVT-MQCF starts behaving in a similar way as the MQCF technique. The power consumption (Figure 5(b)) and the specific cutting energy (Figure 5(c)) follow similar pattern as the cutting forces. Since, the force increases under specific circumstances, the power consumption and cutting energy also increase. The elevated temperature increases the frictional forces as well; which help to supports the reason for the increase in power and energy consumption. When considering surface roughness, the results as in Figure 5(d) clearly show that the use of RHVT-MQCF cooling strategy reduces the surface roughness values further by an average reduction of 6 % (approximately). Moreover, the rough, tearing, burnt surface and cavities are observed under MQCF conditions, as depicts in Figures 6 and 7. The reason for such phenomena can be supported by the fact that the vortex tube reduces the cutting temperature at the cutting zone. It also tends to decrease the stickiness of the material. Due to a decline in stickiness of the material, the cutting insert may shear the material away in a much cleaner way with the application of less force and friction (refer Figure 8).



a.

b.

c.

d.

Figure 5: Comparison of (a) cutting forces (b) power consumption (c) specific cutting energy (d) surface roughness for MQCF and RHVT-MQCF conditions

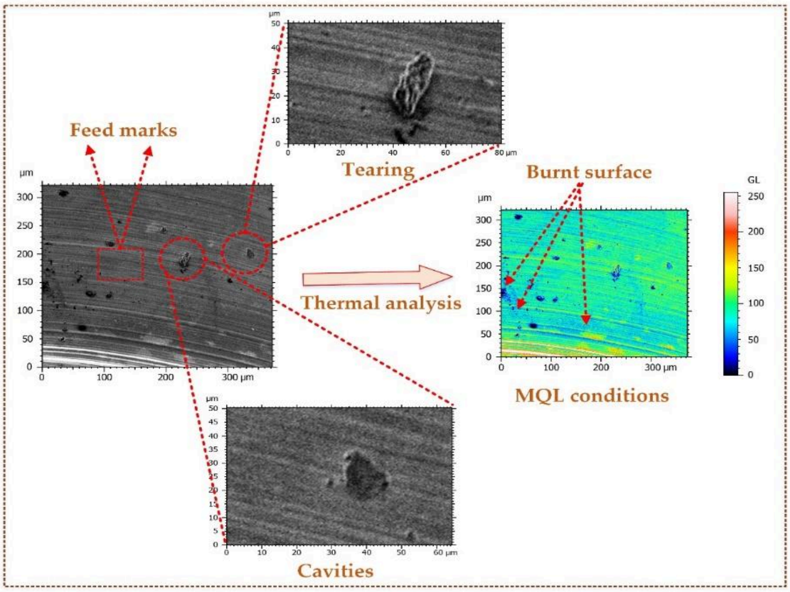


Figure 6: Machined surface images under MQCF conditions at cutting speed: 300 m/min, feed rate: 0.13 mm/rev & depth of cut: 0.4 mm

Thus, the surface roughness is reduced. Since, MRR, which is driven by the cutting speed, feed rate and cutting depth, is not influenced by the cooling conditions, it is not plotted here. In the end, the chip analysis has been performed for better understanding of process mechanisms. Here, the workpiece material is a pure titanium. So, it's obvious that the chips produced are not in a proper manner. For instance, the chips produced during dry and wet turnings of titanium alloys are asymmetrical, uneven and irregular saw-teethed, as shown in Figure 9. The similar concept was observed by Gupta et al., (2016), simulating turning process of titanium alloys using dry and wet conditions. From the current study of chips, it has been noticed that using the small washer allows to form acceptable chips under MQCF as well as RHVT-MQCF conditions. However, there is some minor colour difference in the chips because of the generation of high temperature at tool chip interface.

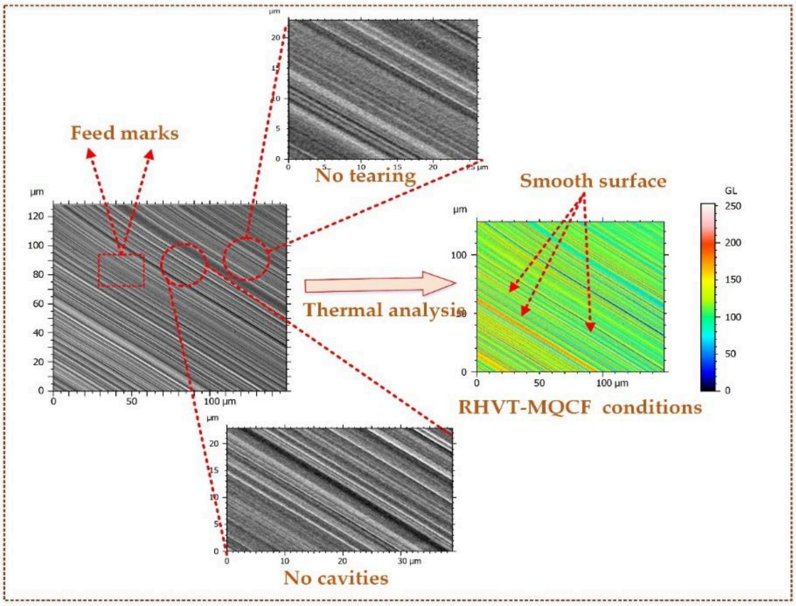


Figure 7: Machined surface images under RHVT-MQCF conditions cutting speed: 300 m/min, feed rate: 0.13 mm/rev & depth of cut: 0.4 mm

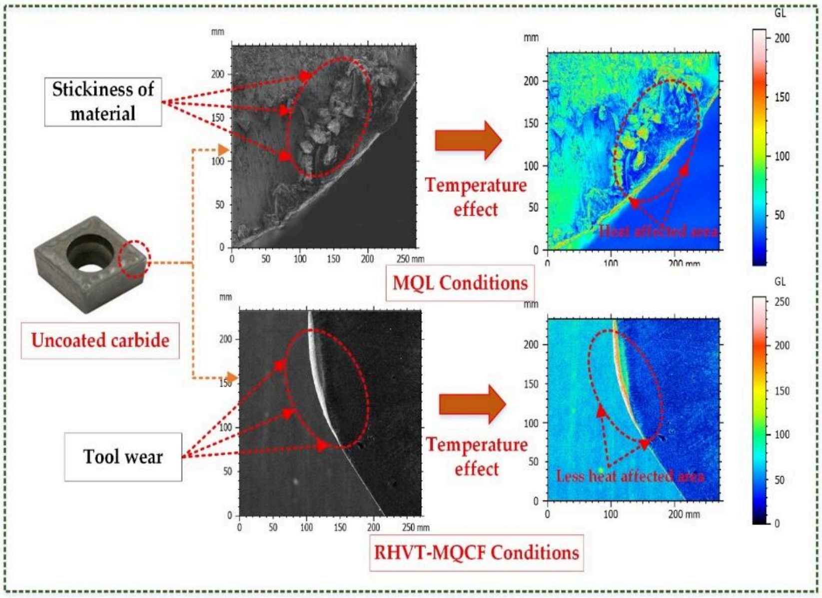


Figure 8: Tool wear mechanism under MQCF and RFVT-MQCF conditions at cutting speed: 300 m/min, feed rate: 0.13 mm/rev & depth of cut: 0.4 mm

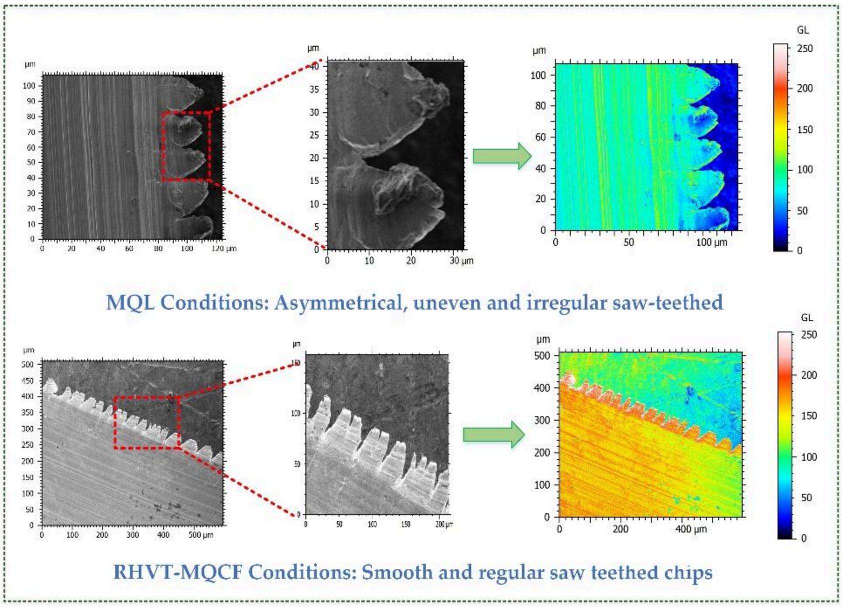


Figure 9: Chip analysis under MQCF and RFVT-MQCF conditions at Cutting speed: 275 m/min, feed rate: 0.13 mm/rev & depth of cut: 0.5 mm under RHVT-MQCF conditions

4.3 Desirability approach for optimization of process parameters

In this work, four sustainable indicators i.e., power consumption, material removal rate, specific cutting energy and surface roughness are considered for optimization process. Because the cutting force and power consumption have direct link with each other and therefore, as per the theme of this paper, the power consumption is optimized along with the other sustainable indicators. It is universal fact that to achieve the highest sustainability, these indicators should be minimized or maximized in relationship to input conditions (i.e. cutting speed, feed rate, depth of cut and cooling conditions). With this regard, the multi-response optimization of process parameters has been carried out with the well-known desirability function approach. In this method, the lower-is-best characteristics, are used to find the individual desirability values for power consumption, specific cutting energy, surface roughness while the highest-is-best characteristics are used only for the MRR. Then, the optimum solution is achieved from a combination of these parameters which have the highest desirability. Table 6 shows the results from the desirability approach. The results indicate that the cutting speed ~ 260 m/min, feed rate ~ 0.12 mm/rev, depth of cut ~ 0.50 mm and RHVT-MQCF conditions are the optimum parameters for turning pure titanium alloy. For the validation of optimal results, another set of turning experiments is performed (refer Table 7). It has been observed that the predicted optimum results are very close to the experimental values. Hence, the developed optimization model is good for prediction of responses under specific conditions.

Table 6: Optimized values obtained through desirability approach

Cutting Speed (m/min)	Feed Rate (mm/rev)	Depth of Cut (mm)	Cooling Conditions	P (W)	MRR (mm^3/min)	SCE (N/mm^2)	Rz (µm)	Desirability
259.61	0.12	0.50	RHVT-MQCF	610.9	15468	2149.5	3.59	0.696769
258.19	0.12	0.50	RHVT-MQCF	607.9	15344	2158.3	3.57	0.696529
258.58	0.12	0.50	RHVT-MQCF	617.4	15732	2117.3	3.56	0.696482
257.20	0.12	0.50	RHVT-MQCF	617.5	15738	2112.0	3.60	0.696104
263.58	0.12	0.50	RHVT-MQCF	622.0	15882	2123.3	3.59	0.694825

Table 7: Confirmatory experiments at optimal conditions

				Experimental values			
Cutting Speed	Feed Rate	Depth of Cut	Cooling Conditions	P (Watts)	MRR (mm^3/min)	SCE (N/mm^2)	Rz (µm)
260	0.12	0.50	RHVT-MQCF	620.32	15600	2140.3	3.56
258.19	0.12	0.50	RHVT-MQCF	618.4	15600	2135.2	3.54
258.58	0.12	0.50	RHVT-MQCF	614.85	15600	2135.7	3.55.

4.4 Sustainability assessment using LCA

The assessment of manufacturing processes from sustainable point of view is very crucial because of the strict environmental and social concerns. Therefore, the development of sustainable models for manufacturing processes is referred as one of the crucial stages to understand its impact on environment and on other aspects. With this regard, the one of the well-known assessment analysis i.e., LCA is developed based on the results achieved from machining of pure titanium alloy using the MQCF and RHVT-MQCF conditions. Initially, the Energy Consumed Per Product (E_P, Joule) and Energy Consumed Per Year (E_y, kWh) are calculated using the Eq. (4) and after that the comparison is made between MQCF and RHVT-MQCF conditions.

$$E_p = \frac{F_c * V_c * Machining\ Time}{60} \tag{4}$$

$$Machining\ Time = \frac{60 * Machining\ Length}{Spindle\ Speed\ in\ RPM * Feed\ rate} \tag{5}$$

where, F_c denotes the cutting force in N, V_c denotes the cutting speed in m/min, the machining time is determined from Eq. 5 and both the machining length and diameter are kept fixed at 50 mm, respectively. Then, the E_y is calculated by considering the conditions i.e., 20% down time, 8 hrs per day, 22 days per month with 20% no work beacuse of maintence.

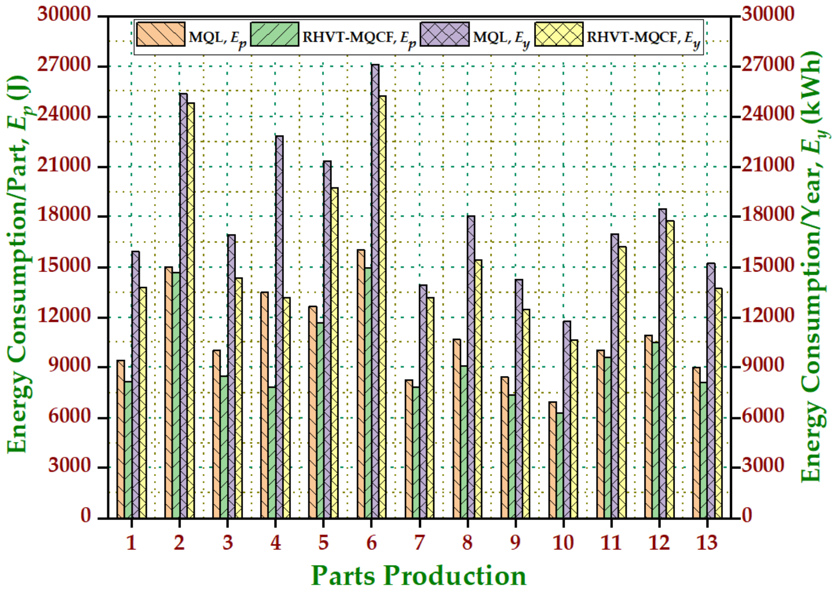


Figure 10: Comparison of energy consumptions per part and yearly energy consumption under MQCF and RHVT-MQCF conditions

The above analysis states that the energy consumed in RHVT-MQCF conditions is less (around 5 to 20%) as compared with MQCF conditions, as exhibit in Figure 10. The main phenomena behind MQCF consuming more energy is that the high cutting forces have been produced during turning of pure titanium alloy. In Figure 10, energy consumed per year for both MQCF and RHVT-MQCF assited turning process is also evaluted. During the calculation, 20% down times is also considered for both machining process. Results showed that RHVT-MQCF has capacity to reduce 2.084% to 42.20% energy onsumption annually. Presumably, the LCA is develpoed to evaluate the machining of 1 kg of pure titanium alloy. The energy consumption is determined by considering that 1 kg of material is removed after 12 turning tests. In MQCF conditions, it has been observed that the average 10878 Joule energy is required for 1 kg of pure titanium alloy, whereas 9839 Joule energy is used in RHVT-MQCF conditions. The reasons of this phenomena are already deliberated in the above sections. Moreover, these energy consumption data are used to perform the LCA analysis and the complete details are furnished below:

4.4.1 Impacts evaluation through EPS 2000 Method and ReCiPe midpoint v1.12 Method

The objective of our study is to validate the suitable condition linked to EPS 2000 Method and ReCiPe midpoint v1.12 Method. The EPS 2000 (Environmental Priority Strategies) method that is focused on sustainable product development, has been firstly used. This method allows to evaluate the damage produced within four main impact categories and 13 midpoint categories, respectively. Table 8 gives the details of their characteristics.

Table 8: Indicators of impacts according to EPS 2000 v2.08.

Impact category	**Category indicator**	**Measurement units**
Human health	DAILY**	People / year
Ecosystem Production capacity	FDP*	FDP / m^2 x year
Abiotic stock recourses	Exhaustion	Kg
Biodiversity	Damage to resources	MJ/Kg

** Fraction of potential disappearance of the ecosystem per m^2 and year.*

*** Disability-adjusted life year: Reduction of years of life per person / year*

This methodology permits to understand the energy consumption while generating decreasing of the non-energy resources (i.e. human health, ecosystem production capacity, abiotic stock resource and biodiversity, respectively). Figure 11 presents the values obtained from LCA analysis. It indicates that the greatest impact is produced on the climate change, depletion of fossil resources and human health. Therefore, the peak values are identified in the test numbers 2, 6, 16 and 23. It is interesting to observe how the impacts are fundamentally focused on two areas, that of human health and the abiotic stock resources, leaving out the ecosystem infrastructure processes and biodiversity. This methodology is based mainly on three aspects, human health, the ecosystems quality and resources reduction. When evaluating with these two methodologies, it allows us to perform an overview check and confirm that there are no significant discrepancies between them. From the obtained data shown in Figure 12, we can observe that they link the same samples, 2, 6, 16 and 23 that generate impact with higher peak values above. This methodology shows the greatest effect that occurs on human health, on the reduction of resources and on climate change, however the quality of ecosystems is not much affected. From the given results, it is deduced that the samples that contribute the greatest impacts are those that have the highest energy consumption. There is a direct relationship with the consumption of electrical energy and therefore with the emissions of CO_2 into the atmosphere.

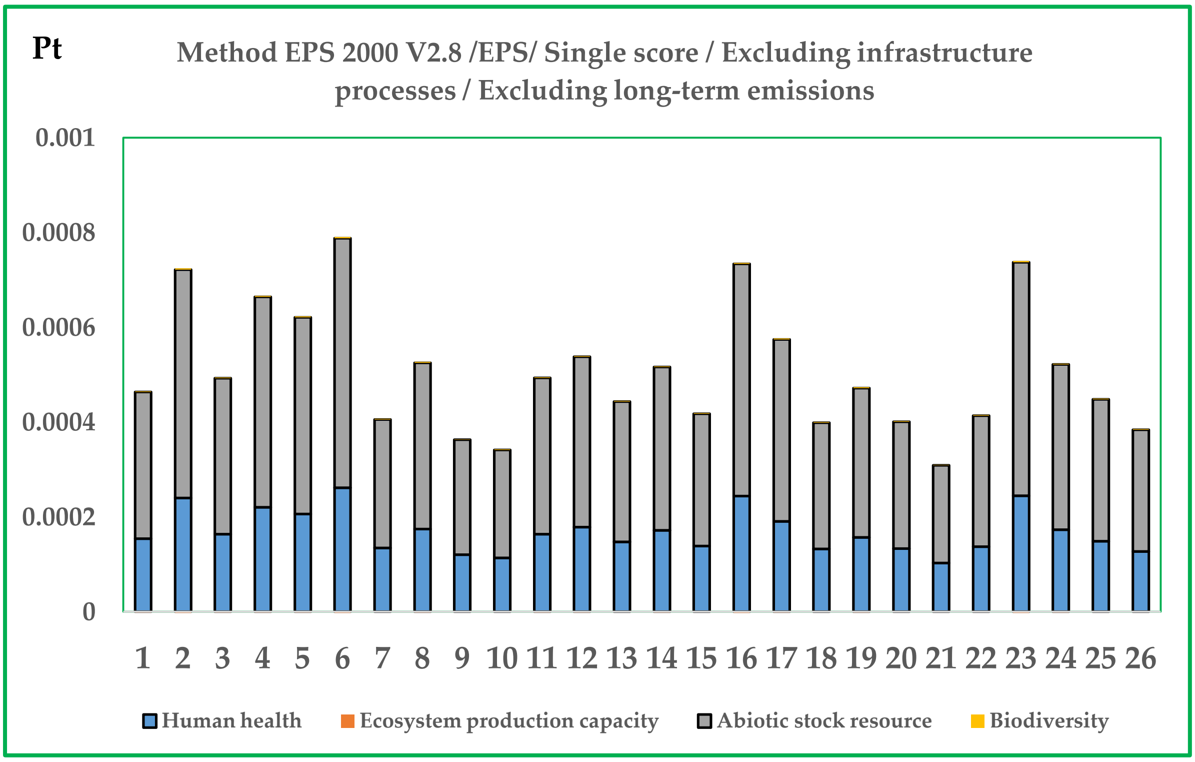


Figure 11: Single score indicators according to EPS 2000 method

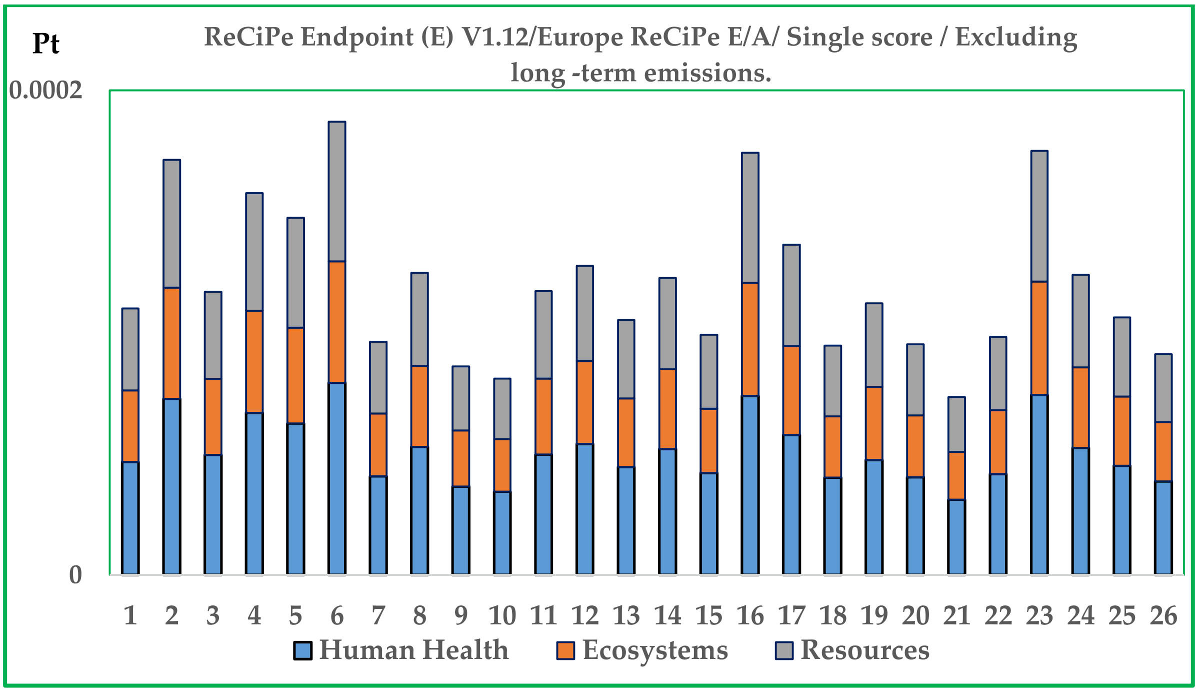


Figure 12: Single score indicators according to ReCiPe Endpoint (E) v1

The results prove the dominant role of energy as important factor on the CO_2-eq emissions. In fact, the increase of emissions because of a higher energy level is highlighted. When comparing the two methods, it has been indicated that no significant distortions occur, thus obtaining the values relative to the damage caused. The two characteristics, the energy and emissions, show that the determining factor in machining is the cutting speed and energy consumption.

By means form the analysis of two methodologies, Impact 2002+ and ReCiPe Midpoint v 1.12, similar results have been obtained, being detected the samples that generate greater impacts, as well as the elements that originate them. In this work, the carbon footprint is directly proportional to the consumed energy. The results have given us information about the amount and importance of various environmental aspects. The summary of critical factors influencing sustainability of the pure titanium alloy is described in Table 9. From the analysis of the results, it has been determined that the environmental impacts that are more determining occurred in the consumption of electricity, which is directly related to the emission of CO_2 into the atmosphere and human health. The values obtained in the impact aspects both in the capacity of the ecosystems and in the biodiversity are not significant, since they result in very small values in comparison with those of the other categories.

Table 9: Summary of critical factors influencing sustainability of the pure titanium alloy

Sector	***Recommendations***
Economic Concerns	In RHVT-MQCF conditions, one extra vortex tube is used along with the MQCF conditions. However, it increases the one-time overall cost, but the effect of this vortex tube is in very positive manner and the overall machining cost is reduced up to certain extent with the application of it.
Energy Consumption	When we concern about the energy consumption, it is worthy to state that the application of MQCF and RHVT-MQCF conditions saves the energy as compared with dry and wet conditions. On the other hand, the RHVT-MQCF conditions produce the more energy effective results as compared with MQCF conditions.
Environmental Concerns	It is obvious that the turning of highly used modern material i.e., titanium alloy consumes large amount of cutting fluids and its effect on environment is quite harmful. Therefore, the experiments are performed under two environment friendly cooling conditions namely MQCF and RHVT-MQCF.
Social Concerns	During the machining of difficult-to-machine materials like titanium alloy, the heat generation is very much high. Sometimes, the heat in the form of sparking is observed in machining of titanium alloys. Therefore, the dealing with this type of situation is very difficult for machine operator or programmer. Moreover, this heat generation produces so much harmful fumes which directly causes the inherent diseases such as asthma, acute lower respiratory diseases, dyspnoea, neurotoxicity and lung cancer to the operator. So, the application of environment friendly cooling conditions as well as cutting fluids is the promising solution for this type of problem.
Machining Performance	The machining performance in terms of cutting forces, surface roughness, material removal rate etc. is improved with the vortex tube. Therefore, it is recommended that the RHVT-MQCF conditions are more suitable for improving the machining as well as sustainability characteristics during turning of titanium alloys.

5. Conclusions

This paper presents the implementation of LCA on two novel cooling strategies during turning of pure titanium alloy. The results from environmental point of view i.e., the impact of machining parameters and cooling conditions on sustainability, ecology, cost, energy, and machining characteristics have been analyzed. Finally, the parameters have been optimized using desirability approach. The complete conclusions drawn from the study are discussed below:

- The results of machining characteristics integrated with LCA conclude that the human health, biodiversity, ecosystems and resources are the prominent sustainable indicators that highly affect the environment. However, the use of RHVT-MQCF condition reduces these effects as compared with the normal MQCF condition.
- The energy consumption in RHVT-MQCF condition is less (around 5 to 20%) as compared to MQCF conditions. This is mainly due to the generation of high cutting forces and high-power consumption compared to RHVT-MQCF condition.
- In terms of cost and health of operator, the RHVT-MQCF conditions exhibit good results. For instance, the vortex tube in RHVT-MQCF increases the one-time cost of machining process, but the overall machining performance hinders the economic cost by producing a better-quality result.
- The better machining characteristics (i.e., cutting forces, power consumption, lower surface roughness, specific cutting energy) are achieved using the RHVT-MQCF conditions in respect to MQCF. The main reason for this phenomenon is that the higher amount of temperature is generated during MQCF conditions. Besides, smoother surfaces and regular chips are observed under RHVT-MQCF conditions.
- In the end, the optimization results determined through the desirability approach show that the cutting speed ~ 260 m/min, feed rate ~ 0.12 mm/rev, depth of cut ~ 0.50 mm and RHVT-MQCF condition are the ideal conditions during turning of pure titanium alloy.

Regarding the future research, the new avenues can be implemented to bridge the gap between green and sustainable manufacturing. For instance, the LCA models can be used in other machining operations like drilling, grinding, milling etc. by implementing different cooling conditions like cryogenic, high pressure coolant, compressed air, respectively. Furthermore, the various analytical models that permit to reduce the energy, power consumption, economical machining can be used as an outlook for different manufacturing processes.

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