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Characterization of machinability and environmental impact of cryogenic turning of Ti-6Al-4V

A. Damir[a], A. Sadek[a]*, H. Attia[a,b]

[a] *Structures, Materials and Manufacturing Lab (SMM), National Research Council of Canada, 5145 Avenue Decelles, Montreal, Quebec, H3T2B2, Canada*
[b] *Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada*

* Corresponding author. Tel.: +1-514-283-9280; fax: +1-283-9662. *E-mail address:* ahmad.sadek@nrc.ca

Abstract

Titanium alloys are widely used in aerospace applications due to their physical and mechanical properties. However, their poor machinability remains the main challenge to improve the productivity and the surface quality. Cryogenic machining recently gained interest as a clean and economical cooling technique. It becomes a promising candidate for applications that involve aggressive metal removal, especially for hard-to-cut material. This research provides insight into the cryogenic machining performance compared to flood machining in terms of its effect on tool life, surface quality, cutting forces and environmental impact. For such analysis, turning tests of Ti-6Al-4V using cryogenic and flood technologies were conducted at different cutting conditions. Life cycle analysis was conducted using the Eco-indicator method to compare the environmental impact of each technology. The cryogenic technology significantly improved the process environmental performance in addition to enhancing the tool life and surface quality compared to flood, hence improved the process productivity.

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Keywords: Life Cycle analysis; Cryogenic Machining; Environmental impact; Titanium alloy

1. Introduction

Titanium alloys are widely used in many industrial sectors, especially aerospace and medical applications. They are known for their high strength-to-weight ratio and toughness, as well as, the ability to retain their mechanical properties at high temperatures [1]. However, these excellent properties create challenges when machining titanium alloys. Their low thermal conductivity leads to localized high temperatures in the cutting zone, which leads to severe tool wear and short tool life [2, 3]. This negatively affects the machining performance and productivity of such alloys, which are considered as hard-to-cut materials [4].

Recently, cryogenic machining has gained importance as an emerging clean and environmentally safe cooling technology for machining hard-to-cut materials [5]. It leads to lower cutting temperature due to its cooling capacity and enhances the chemical stability of the tool and the workpiece [6]. This improves the tool performance and thereby, increases the productivity in machining of titanium alloys and hard-to-cut materials. Liquid nitrogen (LN2) is most commonly used in cryogenics due to its widespread availability worldwide [7].

Research work has focused on the application of cryogenic machining for different materials, such as nickel alloys [8], steel [9], and mainly, titanium alloys [10]. It has been reported that the application of cryogenic reduced the cutting temperature and led to a reduction in the tool wear as compared to dry cutting and flood coolant [11-14]. However, the application of cryogenic still remains a challenge due to the evaporation risks during delivery and no clear understanding of its environmental impact, as compared to flood coolant. The main objective of this paper is to characterize the machining performance, as well as, the environmental impact of cryogenic in turning of titanium

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alloy, as compared to flood coolant. Turning tests were performed to evaluate the machinability of each process. Life cycle analysis was conducted using the Eco-indicator method to quantify the environmental impact of each process.

2. Turning of titanium alloy

2.1. Machining Setup

Turning tests were performed to evaluate the machining performance of cryogenic cooling technology as compared to flood coolant in machining of Ti-6Al-4V. The machining tests were performed on a 6-axis Beohringer NG200, CNC turning center. The machining performance was evaluated in terms of cutting forces, surface quality and tool wear. Table 1 shows the test matrix of the tested parameters. The machining performance of the tested cooling techniques was evaluated at three speeds (100, 120, and 150 m/min) with two levels of feed and three radial depth of cut. The turning tests were performed using a CNGP 120408 Sandvik CVD coated insert. ICEFLY-200 cryogenic machining system was used to supply the liquid nitrogen (LiN) to the cutting zone at a flow rate of 1 ml/min using an external nozzle. Vacuum jacketed hose was used to ensure the insulation of LiN to avoid any evaporation prior to the cryogenic delivery, which can affect the jet efficiency. Cutting forces were measured using a three-component Kistler dynamometer, type 9121. A portable Taylor Hobson surtronic 3+, with 0.8 mm cut off and 0.02 mm resolution was used to measure the roughness of the machined surfaces. Tool wear was measured using a Winslow 560 tool analyzer. All the experimental tests were performed at the Aerospace Manufacturing, Structures, Materials and Manufacturing (SMM) Laboratory, National research Council Canada.

Table 1. Test matrix for turning tests

Tested parameters	Column A (*t*)
Cooling method	Cryogenic (1 l/min) and flood (6 l/min)
Cutting speed (V)	100, 120 and 150 m/min
Feed (f)	0.1 and 0.2 mm/rev
Radial depth of cut (RDOC)	0.3, 0.6 and 1 mm

Fig. 1 shows (a) the set up used in the machining tests, and (b) a close up showing the cryogenic jet delivered externally to the cutting edge. Thermovision A20 infrared (IR) camera was used to measure the temperature field near the cutting zone during cryogenic machining tests. Temperature measurements during flood machining could not be measured at the cutting area while flooded with the cutting coolant.

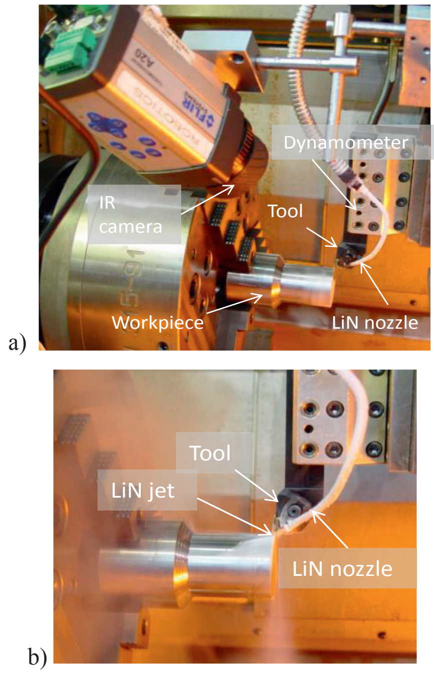

Fig. 1. a) Turning Setup; b) cryogenic application

2.2. Results and discussions

2.2.1. Cutting forces

The effect of cooling technique on the cutting forces was evaluated as shown in Fig. 2. Cryogenic machining showed lower forces (main cutting, axial, feed) as compared to flood coolant in low speed and feed (100 m/min and 0.1 mm/rev).

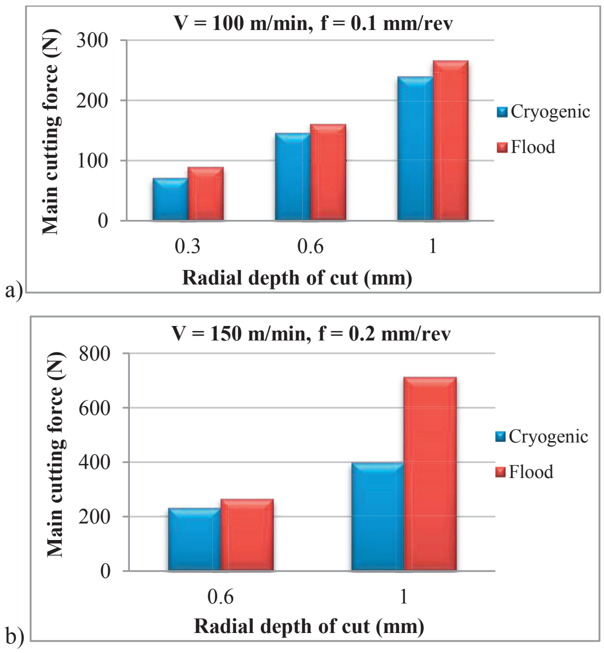

Fig. 2. Main cutting force for cryogenic and flood coolant at a) 100 m/min and 0.1 mm/rev and b) 150 m/min and 0.2 mm/rev

This was demonstrated by a decrease of 10% to 15% in the main cutting force and 30 to 40% decrease in axial and feed force as compared to flood coolant. On the other hand, cryogenic machining showed to be more effective at higher cutting conditions (150 m/min and 0.2 mm/rev). This was demonstrated by the lower forces (main cutting, axial, feed) as compared to flood coolant for high feed and speed, especially at higher depth of cut (1mm) as shown in Fig. 2b. A decrease of 44% in the main cutting force and 85% decrease in axial and thrust force were achieved with cryogenic. Additionally, the application of cryogenic cooling led to a decrease of 13% in the main cutting force, and 35% in axial and thrust force for 0.6 mm depth of cut.

Excessive wear was observed in flood coolant for heavy cuts as compared to cryogenic. This was demonstrated in the sudden increase in the force levels in feed and thrust force with flood coolant associated with the tool wear progression at high depth of cut (1 mm) at high speed and feed as shown in Fig. 3. This can be attributed to the elevated temperature which can lead to thermal damage to the insert. On the other hand, smooth and lower constant force levels were observed with cryogenic machining of titanium at the same cutting conditions. This highlights the cooling capability of LiN, especially at high MRR, which directly affect the tool performance and hence, improve the productivity.

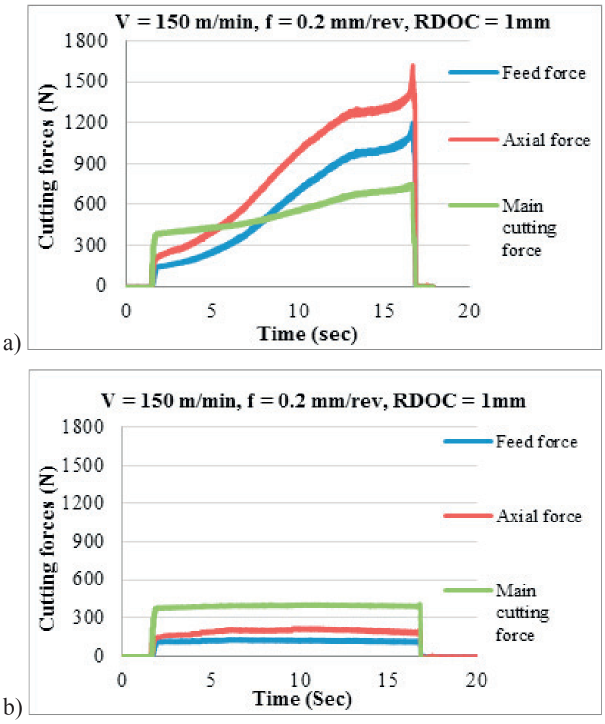

Fig. 3. Measured forces for a) flood coolant and b) Cryogenic machining for heavy cutting conditions (150 m/min, 0.2 mm/rev, 1 mm RDOC)

2.2.2. Surface roughness

Fig. 4 shows the effect of cooling technique on the surface quality of the machined surface at different speed and RDOC. It was observed that at low speed and low feed, both the cryogenic machining and flood coolant showed comparable results. However, at higher speeds and feeds, cryogenic machining showed better surface finish as compared to flood. This was translated in a decrease of up to 19% was observed when using LiN as compared to flood, especially in heavy cutting conditions (High MRR of high speed, feed and RDOC). This can be attributed to the high capacity of cryogenic technology for cooling and heat extraction, as compared to flood. This capacity was effective at higher MRR due to the associated high temperature generated during cutting with heavy conditions (150 m/min, 0.2 mm/rev and 1 mm RDOC).

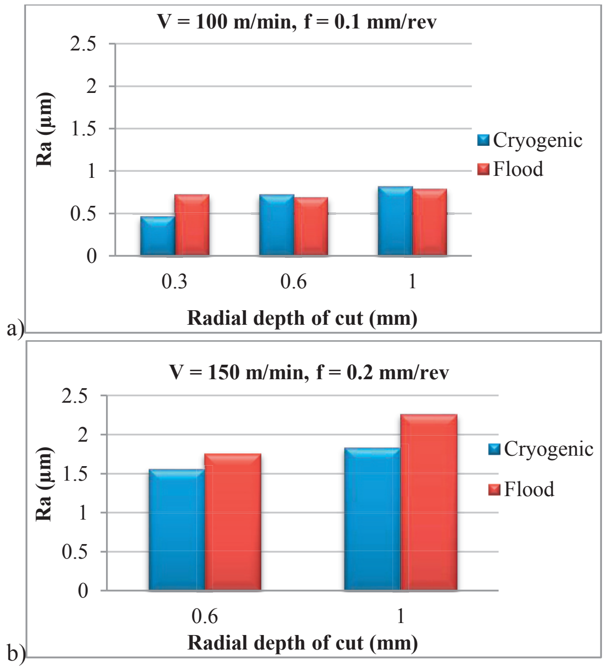

Fig. 4. Surface roughness measurement a) for 100 m/min and 0.1 mm/rev and b) for 150 m/min and 0.2 mm/rev

2.2.3. Tool wear

The effect of the cooling technique on the tool performance, in terms of tool wear, was evaluated for turning of Titanium alloy. Fig. 5 and Fig. 6 show the microscopic images of the flank and the rake of the insert used in turning at 150 m/min, 0.2 mm/rev, 1 mm RDOC, with cryogenic and flood coolant, respectively. It can be observed that excessive tool wear and damage resulted in turning using flood coolant, as compared to cryogenic machining. This was demonstrated by the excessive flank wear, as well as, the wear on the rake face accompanied by discoloration as a result of the elevated temperature associated with flood coolant at harsh cutting conditions. This empathizes the effectiveness of cryogenic in reducing the cutting temperature due to its cooling capacity, which improves the tool performance and hence, the productivity.

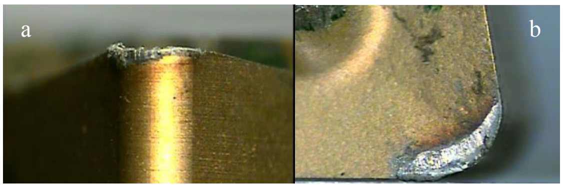

Fig. 5. Microscopic image a) Flank, b) Rake, for cryogenic machining at 150 m/min, 0.2 mm/rev and 1 mm RDOC

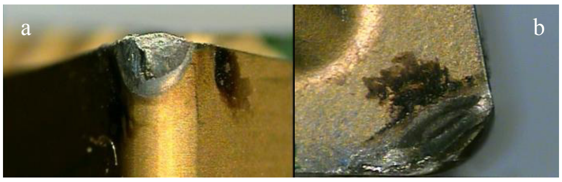

Fig. 6. Microscopic image a) Flank, b) Rake, for flood coolant at 150 m/min, 0.2 mm/rev and 1 mm RDOC

3. Environmental impact of cryogenic and flood in turning of titanium alloy

This section evaluates the environmental performance of the cryogenic and flood in turning. The cost analysis was out of the scope of this study as the cost of LiN can vary drastically depending on whether the supplied LiN is considered a prime product or a by-product of other industries. The single score indicator of the cryogenic and flood modes was computed to compare their environmental impact using the Eco-indicator 99 method for process life cycle analysis (LCA). Fig. 7 shows the stages of the LCA performed in this research. Consumed energy and materials used in the process are the main inputs to the LCA model, which outputs desired products, waste materials and emissions. The environmental performance of the process or product under study can be significantly improve by selecting the appropriate waste treatment methods (e.g. material recycling and/or parts reuse) and waste scenarios. The waste treatment process can also be associated with emissions from the power consumption or chemical reactions that form during waste transformation. The LCA model determines the impact of the emissions on three main environmental categories, namely, human health, ecosystem quality and natural resources. A final dimensionless single score is calculated based on the normalized and weighted impacts of the processes, activities and materials on such environmental categories. A higher single score value of a product or activity indicates a higher impact on the environment compared to alternatives with lower single score value. The Eco-indicator 99 method uses the European continental system as the reference for the LCA model parameters (e.g. land area, area fraction of water and number of inhabitants). In this research, the reference system and the emissions of different activities and their environmental impact were extracted from the database in the Eco-indicator 99_Annex Report [15].

Table 2 shows the main LCA model inputs to the process for the flood and cryogenic turning processes. All the inputs indicated in Table 2 were based on the functional units of 1 hour of turning of Ti6Al4V. This corresponds to removing 4.78 kg of Ti6Al4V at cutting conditions (speed = 150 m/min, feedrate = 0.2 mm/rev, rd = 0.6 mm). The LCA model boundaries included the activities of flood oil production from inorganic oils as well as the liquefaction of nitrogen and air separation processes. The machining power indicated in Table 2 for each lubrication mode was calculated based on the resultant cutting forces measured during the cutting tests performed in this research work. The model inputs included the average power of flood lubricant pumping as well as the transportation of the flood oil and LiN. Transportation activities were defined in units of t.km, which reflect the product of the distance travelled by the vehicle in 'km' and the mass of the transported material in 'metric tons'.

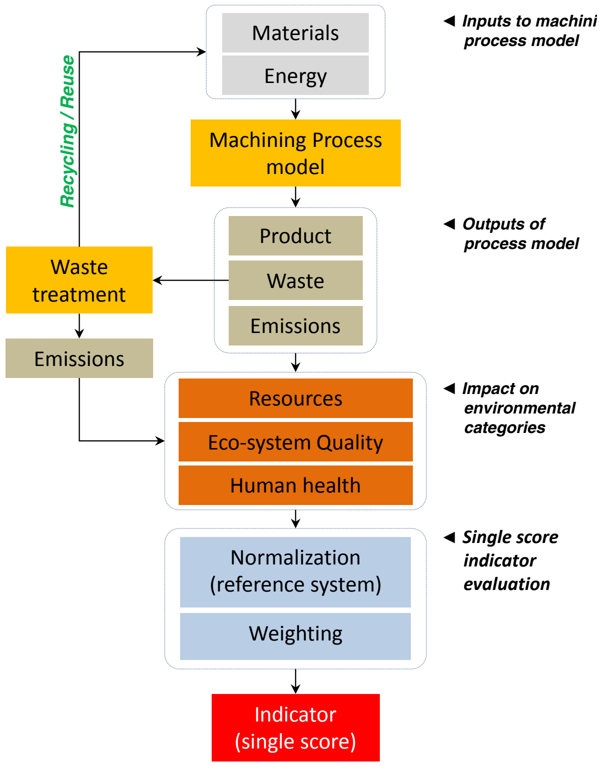

Fig. 7. Single score indicator evaluation method

For flood machining, the machine tool tank full capacity of cutting fluid was 3000 kg 5% of which is oil and 95% water. For the 1 hour machining process considered in this model, the flow rate of 6 l/min required 337 kg of cutting fluid of a 938 kg/m^3 density. Therefore, the effective amount of oil used in the process, based on the 5% oil ratio, was 16.9 kg. The electrical energy required to produce this type of oil is 11.6 kWh/kg [16]. Producing this amount of oil requires a total electric energy of 196.6 kWh. The electrical energy required for the liquefaction of LiN is 0.21 kWh per 1 kg [17].

For cryogenic machining, the input material was 10 kg of air to produce 5.4 kg of LiN. The transportation required was 0.10 t.km using a 1 ton capacity truck for 100 km from the supplier to the manufacturing facility. The environmental impacts of the extraction and production processes of the Ti6Al4V workpiece stock, the removed chip and the solid carbide tool were excluded from the LCA model boundaries since they have a common effect in all lubricant types.

The waste treatment of the flood lubricant after 6 months of use included the transportation of the mass of the full lubricant tank (3000 kg) to the waste oil treatment facility, where the oil and water emulsion could be separated. The waste scenario for the separated used oil was 50% recycling and 50% landfilling, and water treatment was applied to the waste water. The effect of flushing the flood oil traces suspended on the surface of the recycled formed chips was neglected compared to the effect of the amount of waste emulsion from the emptied machine tank. Fig. 8 (a and b) show a schematic of the functional units and boundaries for the flood and cryogenic machining models, respectively.

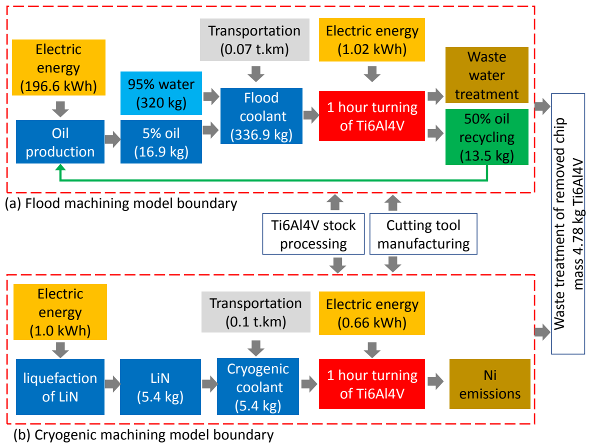

Fig. 8. Model boundaries of (a) flood and (b) cryogenic turning of Ti6Al4V

Table 2. LCA model inputs to flood and cryogenic machining processes

Type	Activity	Process inputs		
		Item	amount	unit
Flood	Flood oil production and transportation (100 km)	Oil	16.9	kg
		Water	320.8	kg
		Cargo van	0.07	t.km
		Electricity	196.55	kWh
	Machining	Electricity	0.82	kWh
	Pumping	Electricity	2	kWh
Cryogenic	LiN Production and transportation (100 km)	Air	10	kg
		1 Ton truck	0.1	t.km
	Ni liquefaction	Electricity	1	kWh
	Machining	Electricity	0.66	kWh

Table 3 shows the computed single scores in milli-point (mPt) for the activities and processes considered in the comparative LCA of the cryogenic and flood modes. The flood machining showed a higher impact on environment as indicated by its significantly higher total single score (3.94 mPt) compared to that of cryogenic machining (0.0673 mPt). The table shows that the flood oil production process has the highest score compared to other activities and processes associated with flood machining, which is mainly due to the high power consumption of the oil production process. The waste treatment of the flood oil contributed to increasing the total score of the process mainly due to the emissions of the water treatment process and the required transportation of the used lubricant. The negative score of the produced recycled oil indicates the improvement of the environmental performance of the process because of oil recycling, which reduces the amount of newly produced oil required for the same process. Other means of reducing the impact of the lubricant in machining processes can also include applying potential lubrication methods using vegetable oil based lubricants and minimum quantity lubrication.

Table 3. Single score indicator of flood and cryogenic machining process

Activity	Flood (mPt)	Cryogenic (mPt)
Lubricant production	5.22E+00	2.80E-02
Machining of Ti-alloy	6.20E-02	3.93E-02
Lubricant waste treatment	1.26E+00	0.00E+00
Recycled Lubricant (product)	-2.61E+00	0.00E+00
Total single score	3.94E+00	6.73E-02

4. Conclusion

The performance of Cryogenic machining (LiN) in turning of Titanium alloy was evaluated as compared conventional flood coolant. Cryogenic cooling showed better machining performance as compared to flood coolant in terms of cutting forces, tool wear and surface quality. It was shows that cryogenic machining can lead to a decrease in the main cutting forces by 15% for low speeds and feeds, and 44% in heavy cutting conditions as compared to flood coolant. Better surface finish was obtained, especially in harsh cuts with up to 19% decrease in surface roughness. Additionally, improved tool life, expressed by lower tool wear, was achieved with cryogenic coolant as compared to flood, which chowed excessive tool wear, especially in high speed, feed and RDOC conditions. This can be attributed to the superior cooling capacity of cryogenic that leads to lower cutting temperature, and hence, better tool performance. The life cycle analysis of the flood and cryogenic machining processes showed that the cryogenic machining had a significantly lower total single score compared to flood machining. This highlights the potential of cryogenic machining as a sustainable alternative to flood machining that can significantly improve the environmental and machining performance of the process.

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References

[1] Ibrahim Sadik M, Isakson S, Malakizadi A, Nyborg L. Influence of coolant flow rate on tool life and wear development in cryogenic and wet milling of Ti-6Al-4V. Proc CIRP 2016; 46.p. 91-94.
[2] Ezugwu EO, Bonney J, Yamane Y. An overview of the machinability of aeroengine alloys. J Mat Proc Tech 2003;133:233–53.

[3] Shokrani, A, Dhokia V, Munoz-Escalona P, Newman S.T. State-of-the-art cryogenic machining and processing. Int J Comp Integ Manuf 2013. 26(7): p.616-648.

[4] Yildiz Y, Nalbant M. A review of cryogenic cooling in machining processes. Int J Mach Tools Manuf 2008;48:947-964.

[5] Hong S.Y, Ding Y. Cooling approaches and cutting temperatures in cryogenic machining of Ti-6Al-4V. Int J Mach Tools Manuf 2001;41:1417-1437.

[6] Hong S.Y, Markus I, Jeong W. New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. Int J Mach Tools Manuf 2001;41:2245-2260.

[7] Jawahir I.S, Attia H, et al. Cryogenic manufacturing processes. CIRP annals 2016;65:713-736.

[8] Pusavec F, Deshpande A, Yang S, M'Saoubi R, Kopac J, Dillon OW, et al. Sustainable machining of high temperature Nickel alloy – Inconel 718: part 1 – predictive performance models. J Clean Prod 2014;81:255–269.

[9] Dhar NR, Kamruzzaman M. Cutting temperature, tool wear, surface roughness and dimensional deviation in turning AISI-4037 steel under cryogenic condition. Int J Mach Tools Manuf 2007 Apr;47(5):754–759.

[10] Sun, Y, Huang B, Puleo D.A, Jawahir I.S. Enhanced Machinability of Ti-5553 Alloy from Cryogenic Machining: Comparison with MQL and Flood-cooled Machining and Modelling. Proc CIRP 2015;31: p. 477-482.

[11] Bermingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS. New observations on tool life, cutting forces and chip morphology in cryogenic machining Ti-6Al-4V. Int J Mach Tools Manuf 2011 June;51(6):500–511.

[12] Sun, S, Brandt M, Palanisamy S, Dargush M.S. Effect of cryogenic compressed air on the evolution of cutting force and tool wear during machining of Ti-6Al-4V alloy. J Mat Proc Tech 2015;221: p. 243-254.

[13] Bordin, A, Bruschi S, Ghiotti A, Bariani P.F. Analysis of tool wear in cryogenic machining of additive manufactured Ti6Al4V alloy. J Wear, 2015;328-329: p. 89-99.

[14] Sun, S., Brandt M, and Dargusch M.S. Machining Ti-6Al-4V alloy with cryogenic compressed air cooling. Int J Mach Tools Manuf 2010;50(11): p. 933-942.

[15] Goedkoop M, Spriensma R. The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment - Methodology Annex. Product ecology consultants;2001.

[16] Li C, Tang Y, Cui L, and Li P. A quantitative approach to analyze carbon emissions of CNC-based machining systems. J Intell Manuf 2013;26(5): 911-922.

[17] Shen S, Wolsky A.M. Energy and materials flows in the production of liquid and gaseous oxygen, Office of Scientific and Technical Information (OSTI);1980.