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Sustainability Assessment: Cryogenic Machining of Inconel 718

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This paper disseminates the foreground of sustainable cryogenic machining technology that has a high potential to cut production costs and improve competitiveness by reducing resource consumption and creating less waste. The sustainability issues on a shop floor level are pointed out via a life cycle assessment, concluding that the future of sustainable production is going to entail the use of cryogenic machining to reduce environmental burdens and health risks, while increasing machining performance and profitability. In addition, machining evaluation is covered by an experimental study undertaken to understand the likely impacts of the use of cryogenic technology on production costs. The case study refers to the machining of high-temperature Ni-alloy (Inconel 718). It is shown that tooling costs greatly contribute to the total production cost and that cryogenic machining offers a clean and a cost-effective route to improve sustainability performance in comparison to conventional machining.

Keywords: machining, sustainability, cryogenics, LCA, cost evaluation

0 INTRODUCTION

This paper presents a case study that highlights the importance of sustainable cryogenic machining in achieving sustainable development objectives. Global environmental problems caused by the consumption of natural resources and the production/life of technical products have led to increased political pressure and stronger regulations applied to both, the producers and users of such products [1] and [2]. The adoption of sustainable development in the production offers the industry a cost effective route [3] to [5] to improve economic, environmental, and social performance [6].

Sustainable development initiatives are established on a political level within the UN, the OECD, the EU, and national levels. These initiatives are well positioned and promoted on the production macro level [7], but there is a lack of implementation practices on the shop floor dealing with machining. With the implementation of sustainability principles on the shop floor level, users have the potential to save money and improve their environmental and social performance even if their production stays in the same range or decreases, as shown in the machining evaluation included in this paper. In this way conducted evaluation of sustainability in cryogenic machining is more than a method for supporting technology design and an instrument for supporting decision-making. It is also a tool for supporting technology policy and for encouraging its adoption and application in the industry.

The ambitions of implementing cryogenic machining to the practice aims at transitioning towards sustainable production on the machining technology/shop floor level and include the following research and application issues:

- Design and development of sustainable cryogenic technologies (machining processes and fluid delivery systems) that can be accommodated over different machining operations.
- Optimization of cryogenic fluid delivery system with a controlled pressure, mass flow and flow phase (liquid or vapor).
- Optimization of nozzles for selectively dispensing liquid phase cryogenic fluid.
- Evaluation of cryogenic machining in various industrial case studies.
- Identification of research/application demands and future industrial opportunities.

1 CRYOGENIC MACHINING

It is known that oil-based cooling lubricating fluids (CLFs) are one of the most

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unsustainable elements of machining processes. Most CLFs are formulated from mineral oils, which are extracted from crude oil, primarily for economic reasons. Although alternative, naturally derived CLFs are available (vegetable oils), there has been limited use of these CLFs. This is partly due to higher costs and partly due to a reduced performance [8].

In cryogenic machining a cryogenic CLF (non-oil-based) is delivered to the cutting region of the cutting tool, shown in Fig. 1, which is exposed to the highest temperature during the machining process, or to the part in order to change the material characteristics and improve machining performance.

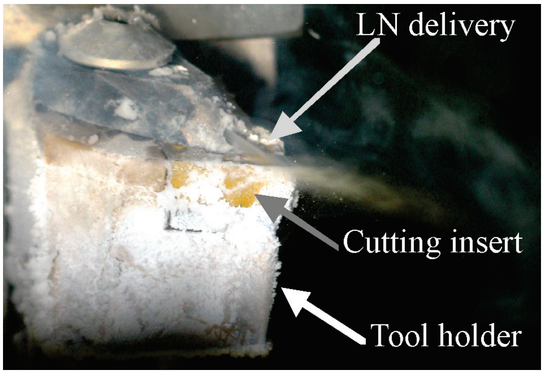

Fig. 1. *Cryogenic liquid nitrogen delivery*

The CLF is nitrogen fluid, which is liquefied by cooling to -196 °C (liquid nitrogen – LN). Nitrogen is a safe, non-combustible, and non-corrosive gas. The LN in cryogenic machining systems quickly evaporates and returns to the atmosphere, leaving no residue to contaminate the part, chips, machine tool, or operator, thus eliminating disposal costs. Additionally, cryogenic machining could help to machine parts faster, with higher quality, increased machining performance, and a reduced overall cost [9]. Some potential benefits of cryogenic machining are:

- Considerably reduced friction coefficient on the tool-chip interface [10].
- LN applied locally to the cutting edge is superior to emulsion in lowering the cutting temperature [11].
- Increased tool-life due to lower abrasion and chemical wear [12].
- Increased material removal rate with no increase in tool-wear and with reduced cutting tool changeover cost, resulting in higher productivity [13].
- Improved machined part surface quality with the absence of mechanical and chemical degradation of the machined surface [14].

Most cryogenic CLF applications have been examined in the machining of heat resistant super-alloys. However, some studies also included machining of low/high carbon steel and bearing steel [15]. One of those high-temperature alloys are Nickel-based alloys that are normally machined with WC-Co grades, with cutting speeds of about 50 m/min. With the introduction of sialon materials, it is possible to increase the cutting speed by a factor of 5, and more recently even higher cutting speeds are possible with silicon carbide whisker-reinforced aluminia tools. The other alternatives are ceramic cutting tools that show lower chemical affinity with Ni materials. Unfortunately, the accumulation of cutting heat on the cutting edges of ceramic tools causes many problems and sometime leads to early tool failure [16]. Additionally, their fracture toughness is much lower than that of the other widely used tool materials such as carbides. This is the reason that the geometry of the ceramic tools is mostly neutral or even negative (negative rake angle), while carbide cutting tools are available also with very sharp cutting edges and highly positive rake angles. Both properties lead to the reduction in temperature and significant lower cutting forces. While in this work the goal was oriented towards finishing process, the carbide cutting tools are used and analyzed.

In the machining of high-temperature alloys, conventional oil-based CLFs are not always effective enough in terms of decreasing the high cutting temperature, increasing tool-life, reducing machining costs and improving environmental/social sustainability. The problem is that conventional CLFs do not access the tool-part and tool-chip interfaces, which are under high contact pressure, as they vaporize at a high temperature generated close to the cutting tool edge. Taking this into account, it becomes clear that technologies employing conventional CLFs are ineffective and unsustainable when machining materials with high shear strength and low thermal conductivity. In this case, the avoidance of conventional CLFs, would yield an enormous gain from the sustainability point of view [17].

2 LIFE CYCLE ASSESSMENT (LCA)

In order to evaluate sustainability of a product, system, or process, the impact resulting from each stage of its life cycle has to be considered [18]. Although cryogenic machining offers to reduce the negative impacts of conventional CLFs usage on the environment, the additional sustainability characteristics of this technology have yet to be analyzed. Therefore, a quantitative assessment of the CLF's production and use is evaluated with additional qualitative measures associated with health, safety and performance.

These assessments consider machining (turning or milling) over a one-year production period. At this stage, it is assumed that the production and the quality of machining do not vary depending on the CLF type. In other words, LCA was performed strictly for the production and delivery of the CLF into the cutting zone, while machining performance was assumed to be the same. This assumption is limited to CLF environmental and health influence comparisons.

2.1 CLF Quantitative Characterization (Production and Use)

Looking at the machining system schemes, shown in Fig. 2, it can be seen that in conventional machining, the CLFs (emulsions) are composed of lubricant oil (petroleum-based) and a lubricant carrier (water). Additionally, water serves also as a coolant. In the case of cryogenic machining, the lubricant and carrier are provided by LN, which is known to be stable, while oil-based emulsions are not and thereof need to contain emulsifiers for their stabilization. With regard to oil-based CLF production, most of the CLFs are used as emulsions containing mineral oil and surfactants based on petroleum. Producing these components requires a distillation and processing of crude oil, which creates several by-products. The components considered in this case are a semi-synthetic CLF system containing oil, two surfactants, and water. Consideration of surfactants is important since they play a dominant role in the overall environmental emissions of water/oil surfactant systems [19].

On the other hand, LN can be used as a CLF, which is a liquefied atmospheric gas produced industrially in large quantities by fractional distillation of air. The input into the process is

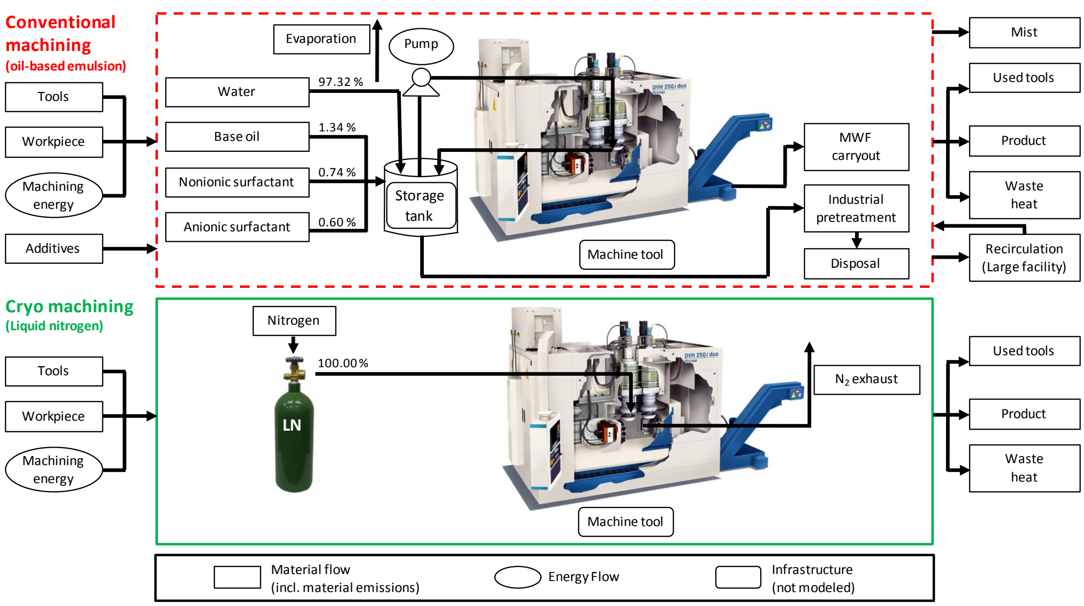

Fig. 2. *Comparison of cryogenic with conventional machining system*

electrical energy (approximately 0.5 kWh/kg) and cooling water (50 l/kg at 15 °C), while the output is LN and the remaining components of the air as a waste. The data for LN production were given by the LN supplier (SIAD – Istrabenz Plini). It must be pointed out that there is no other waste, such as CO_2, SO_2, etc., when producing LN. However, LN production is an energy-intensive process that can be directed towards sustainable development by powering the cooler in LN production with renewably generated electricity or through direct mechanical work from hydro or wind turbines.

Firstly, considering the LCA, the CLF compositions must be known. Typical oil-based CLFs are composed of water, oil, surfactants, and approximately ten other specific chemicals. In general, CLFs are sold as concentrates with 10 to 30% mineral oil (semi-synthetic fluids) and are diluted 10 to 20 times with water, thus forming the CLF as an emulsion. In the LCA of environmental impact of CLF production, the considered factors were related to:

- water use,
- solid waste production,
- land use,
- energy use,
- global warming potential (GWP),
- acidification.

The specific data included in the LCA are given in [20].

Knowing the CLF composition and CLF component production environmental impact, the remaining missing data are the CLF usage amounts (conventional machining), CLF consumption rate (cryogenic machining), and machining system usage in a fixed time period. In the following analyses, for ease of comparability, a one-year production period is considered.

A major difference between oil-based systems and cryogenic-based systems is that oil-based CLF systems recirculate CLFs, while cryogenic fluid is delivered only once due to immediate evaporation upon delivery. Therefore, the concept of consumption takes on different meanings in these systems. In cryogenic fluid delivery, the consumption rate is determined by the mass flow rate of LN through the nozzle. In contrast, in conventional flooding systems the consumption rate is determined by the volume of emulsion per machine tool and the disposal interval.

A comparison of material production impacts broken down by components, given in [20], suggests that surfactants dominate the emissions for three of the six impact categories: energy use, acidification, and solid waste. The need for surfactants in conventional machining means that this technology has a significant environmental impact. However, in the case of cryogenic machining, there is only the need for electrical energy to produce the CLF, and process cooling water, while it has no other impact on the environment. When comparing obtained data, it has been proved that the level of energy needed for the liquidation of nitrogen is lower than for mineral oil production, when comparing the same amount of the two items. However, in the case of cryogenic machining, the delivered LN evaporates and is not reusable in the process, as it is in conventional machining. Therefore, a higher portion of energy is needed for its production.

In addition to production, the CLFs have to be delivered to the cutting zone (by a pump or pressure) from a reservoir. The energy for this depends on the CLF delivery rate. For this reason, the emissions and energy consumption for the delivery are given explicitly as a function of volumetric/mass flow rates and/or pressure. The production of the CLF delivery equipment is not taken into consideration since the impacts are relatively small compared to the use phase and the equipment has a working life of several years [21]. The conditions used to estimate the power consumption from the delivery phase are the following:

- Conventional machining: pump is used with a power of 500 W, providing 0.2 MPa pressure and a volume flow rate in the range of 0 to 8 l/min. Actual energy consumption is related to the CLF volume flow rate.
- Cryogenic machining: LN reservoir is pressurized and therefore pressure itself forces the CLF to the cutting zone. For this, no additional energy is needed.

In conventional machining, energy use is strongly influenced by the annual amount of CLF consumption. The electrical consumption of the delivery pump is small and therefore much less than CLF production energy (822 MJ). In cryogenic machining, energy use deriving from the LN production (136,858 MJ) is the dominating factor. A detailed analysis of energy consumption related to CLF production and use is given in [20].

Environmental impacts considered in the LCA are summarized in Fig. 3. The observing functional unit is case dependent. For ease of comparability and based on the case study, the following parameters were chosen:

- Conventional machining: 1000 l/year of oil-based CLF usage, 2112 h/year machining hours, and 60 l/min emulsion delivery rate.
- Cryogenic machining: 2112 h/year machining hours and 0.6 kg/min LN delivery rate.

The presented comparative life cycle burdens reveal that in cryogenic machining, burdens such as GWP, acidification, water use, and solid waste are eliminated at the price of the increased energy use required for nitrogen extraction and liquidation. In short, in cryogenic machining there is a trade-off with regard to higher energy use and a cleaner machining process. As we know that the production of LN requires immense electrical energy consumption, it is possible to talk about cryogenic machining being a sustainable process only when using a renewable energy to produce the LN.

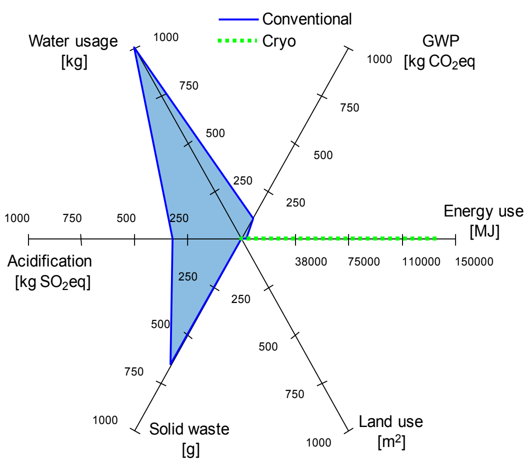

Fig. 3. *Life cycle burdens*

In conventional machining, the CLF has to be disposed of. It needs to be removed from the part and chips after the machining, and then collected and recycled. All this represents additional processes, costs, and environmental burdens. The usual procedure for oil-based CLF disposal consists of drying the emulsion and its subsequent combustion. In contrast to oils, emulsions do not have high energy values; therefore the combustion process must take into account the high potential for additional environmental burdens. Although combustion does recover some energy from the waste CLF, it additionally highly impacts GWP and acidification.

2.2 CLF Qualitative Characterization (Health, Safety and Performance)

With regard to health and safety of machine tool operators, the effort to find machining alternatives has been driven largely by a desire to make machining processes safer, healthier, and thus more sustainable in view of the society. Chronic inhalation of oil-based mists has been shown to be responsible for serious health risks [17]. Such emulsion mists can harbor bacteria, and contain surfactants, biocides, chlorinated fatty, chelating agents and defoamers, all of which are harmful to health. This is notable since surfactants and biocides have been found to impair lung functioning [22]. In addition to mists, oil-based CLFs can cause dermatitis and other skin irritations. They also tend to result in the accumulation of an oily sludge on and around the production plant over time. Spills can also be a rather regular workplace hazard.

None of those are present in evaporated LN. More importantly, it has been proven that machining mist can be eliminated in cryogenic machining. On the other hand, in cryogenic machining less likely but more serious safety issues are required, related to the extremely low temperature of the pipes delivering the LN, which can cause physical burns in the event of contact. In addition, concerns have been raised in relation to the inhalation of metallic aerosols resulting from cryogenic machining. It has been reported that the development of lung disease due to the presence of micro metallic particles (tungsten carbide, cobalt, titanium) is a rare event and is almost unrelated to the duration and extent of exposure [23].

With regard to machining performance the LCA assumed that both processes employ the same machining time, while having comparable machining performance. In practice this is usually not the case, therefore a detailed experimental case study that extends the LCA through a detailed machining evaluation, has been carried out.

3 MACHINING EVALUATION

The machining evaluation has been carried out to demonstrate that cryogenic machining offers a cost-effective route to improve sustainability performance in comparison to conventional machining of Inconel 718. To determine the applicability of cryogenic machining, costs need to be calculated.

In the calculation of costs, tool-life is a key factor, therefore machining experiments were performed. Experiments were conducted on turning of Inconel 718 bars with a diameter of 40 mm and length of 100 mm. Machining employed SANDVIK GC 1105 grade carbide tool inserts and the CNMG120408-23 ISO tool geometry designation. Tool-life was assessed according to the ISO 3685, regulating an average tool-life criteria, VB_{max} = 0.4 mm. Tool-wear was measured with an optical microscope. Conventional machining employed vegetable-based CLF (6.7% emulsion), with a flow rate of 6 l/min. The cryogenic machining was performed by applying LN under 1 MPa pressure and a flow rate of approximately 0.6 kg/min.

3.1 Hourly Rate of Machining System Usage

The machining system usage hourly rate calculations covering operation and labor are presented in Table 1. The calculations consider 80% operating machining system efficiency and do not include shop floor space/rental costs.

The main differences in costs are the higher initial costs in the case of cryogenic machining, due to the additional equipment needed for the CLF delivery system. The results show that when using additional equipment, machining system usage costs are higher, and therefore benefits have to be gained within the process itself. In addition to machining system usage costs, the labor cost has to be added. For operating more sophisticated equipment a higher skill level of labor is required. Summing machining system usage costs and labor cost determines the overall machining cost, C_{mh}, i.e. hourly rate. Machining costs for cryogenic machining are 17% higher in comparison to conventional machining.

Table 1. *Hourly rate of machining system usage*

Categories	Conv.	Cryo.
Machine tool costs [€] (a)	150000	150000
Tooling (3% of (a))[€] (b)	4500	4500
CLF delivery system [€] (c)	0	10000
Machining system costs [€]	157500	167500
Annual depreciation [€/year]	22500	23929
Maintenance (1.5 % of $_{(a)+(b)+(c)}$) [€]	2318	2468
Insurance (0.4 % of $_{(a)+(b)+(c)}$) [€]	618	658
System usage costs [€/h]	12.53	13.29
Direct labor [€/h] $_{(d)}$	12	15
Indirect labor (10 % of $_{(d)}$) [€]	1.20	1.50
Supervision (12 % of $_{(d)}$) [€]	1.44	1.80
Fringe benefit (33 % of $_{(d)}$) [€]	3.96	4.95
Cost of labor [€/h]	18.60	23.25
Machining costs, C_{mh} [€/h]	**31.13**	**36.54**

3.2 CLF Consumption and Costs

In order to determine the CLF contribution to the machining cost, the hourly rate has to be calculated. This calculation is given in Table 2.

Table 2. *CLF consumption and costs*

Categories	Conv.	Cryo.
CLF concentrate [€/l]	10	/
CLF disposal [€/l]	0.2	/
CLF amount [l]	450	/
CLF concentrate needed [l]	28.12	/
CLF concentrate costs [€]	281.25	/
CLF disposal [€]	90	/
CLF maintenance [€]	60	/
Overall CLF costs [€]	431.25	/
Duration life [h]	2640	/
Nonreturnable CLF [kg/min]	/	0.6
Nonreturnable CLF costs [€/kg]	/	0.21
CLF costs, C_{ch} [€/h]	**0.17**	**7.51**

From an environmental perspective, cryogenic machining is preferable due to the complete elimination of oil-based CLFs. For the conventional case, the amount of usage and its lifetime has to be determined in order to calculate its hourly rate. In this case, calculations for an annual period are made.

In cryogenic machining, where LN is used, the CLF is not reusable because it evaporates into the air immediately when it is delivered. Due to this, CLF represents a directly consumed item, which has a relatively high cost but does not need to be recycled. In calculating costs, the LN hourly rate (C_{ch} = 7.51 €/h) is significantly higher than for the CLFs in the conventional method (C_{ch} = 0.17 €/h).

3.3 Costs Associated with Waste

Another important sustainability measure that has to be considered refers to the waste produced during machining. Waste products are mostly connected to oil-based CLFs, as discussed above, worn cutting tools, and chips/swarf. In the presented study, the amount of swarf produced is assumed to be equal for both machining cases. This results in equal costs related to swarf compacting (including shredding if needed), which is required to ease transportation. However, conventional machining includes an additional cost for separation of CLF from the swarf. The CLF separation usually includes separation of unemulgated oils through skimming, separation of the hard particles by means of filtration, emulsion separation and treatment of the separated water.

3.4 Total Production Cost per Part

The total production cost per part is given in Table 3. The presented partial costs included in the total production cost are valid for machining with the following parameters:

- Cutting speed: v_c = 90 m/min.
- Feed: f = 0.25 mm/rev.
- Depth of cut: a_p = 1.2 mm.

In the total production cost, $c_{p,p}$, machining cost, $c_{m,p}$, represents the expenses of the machining system and labor needed for one part. During machining tool-wear occurs, therefore tool cost per part, $c_{t,p}$, is added, as well as CLF usage cost per part, $c_{CLF,p}$. The energy consumption cost, $c_{E,p}$, is divided into the cost when the machine tool is performing the actual machining and the cost when the machine tool is in a stand-by mode (e.g. when changing parts and cutting inserts). The additional costs include the cost for cleaning the CLF on the surface of a machined part, $c_{pcl,p}$, the cost for separating CLF from the swarf, and the cost for compacting swarf for ease of transportation, $c_{sp,p}$.

Table 3. *Production costs*

Categories	Conv.	Cryo.
Number of parts per tool life time	1	6
Tool changing time [s/part]	180	30
Machining cycle time [s/part]	243.5	93.5
Part production rate [part/h]	14.8	38.5
Machining cost, $c_{m,p}$ [€/part]	2.11	0.95
Tool cost, $c_{t,p}$ [€/part]	2.50	0.42
CLF cost, $c_{CLF,p}$ [€/part]	0.002	0.07
Down time [s/part]	210	66
Electrical usage [kWh/part]	0.076	0.055
Cost of electricity, $c_{E,p}$ [€/part]	0.009	0.007
Part cleaning cost, $c_{pcl,p}$ [€/part]	0.063	0
Swarf preparation cost, $c_{sp,p}$ [€/part]	0.015	0.004
Total production cost, $c_{p,p}$ [€/part]	**4.69**	**1.45**

From Table 3, it can be seen that the total production cost is greatly affected by tool-life, CLF cost, disposal, and waste management. Considering the tool-life in conventional machining, a huge improvement can be observed in cryogenic machining, as described in [24]. It has been shown that the conventional method yields the shortest tool-life for all cutting speeds in the tested range. If cryogenic machining is used, a significant increase in tool-life was achieved due to highly efficient cooling needed when machining high-temperate alloy (Inconel 718). If this condition is not satisfied, the temperature in the cutting zone rapidly rises, softening the cutting tool material and causing rapid tool-wear, as in the case of conventional machining.

Moving one step further, production time is not correlated only to the machining time, but also to the machining system down time due to changing the worn cutting tool insert. It has been confirmed in our previous experimental study that conventional machining yields the longest production time. By applying cryogenic machining production time can be decreased by up to 63%, depending on which cutting speed is used [24]. This reduction can be attributed to the tool changing time, which has a much higher contribution to total production cost in conventional machining. The actual cutting tool changing time is not longer, but the number of changes is higher, due to the increased rate of tool-wear in conventional machining.

By combining tool-life and production times, the total production cost per part can be determined for different cutting speeds, as presented in Fig. 4.

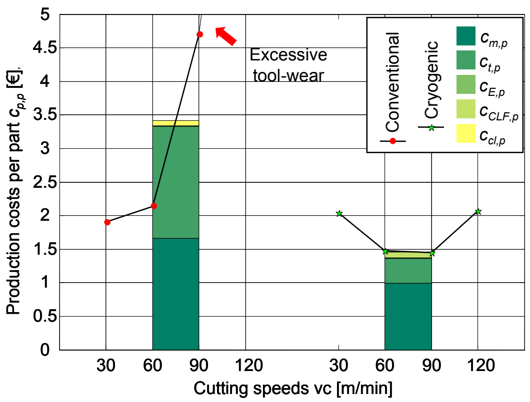

Fig. 4. *Production costs*

The total production costs for different cooling conditions are represented by stacked bars, indicating the individual contributions to the total of the production cost at the cutting speed of v_c = 75 m/min. The solid line represents the changing trends of the total production cost per part due to the cutting speed variation.

From the presented results, it is possible to assert that conventional machining is significantly more expensive than cryogenic machining. This trend is even more dominant if high cutting speeds are employed. What is interesting from these plots is that at lower cutting speeds conventional machining can be the cheapest. However, this production rate is not optimal. Therefore, cryogenic machining should be used when high efficiency and high productivity are required.

Regarding the contribution to the overall production cost, it can be seen that machining costs and costs arising from changing the cutting tool are the highest in conventional machining. Energy consumption costs are almost negligible in both cases, while coolant costs are almost negligible in conventional machining. The exception is cryogenic machining, where the price of the LN is much higher. While conventional machining has low CLF cost, the costs of cleaning are higher, while they are negligible in the case of cryogenic machining.

4 LCA UPGRADE - ADDING TOOL INSERT PRODUCTION ENERGY CONSUMPTION

Since two comparing processes (cryogenic and conventional machining) differ in cutting tool life and thus in the overall cost for consumed cutting inserts, also the environmental impacts associated with their production should be considered. In this way, the energy spent for their production is going to be determined and compared with the additional electrical energy spent in cryogenic machining for the production/extraction of nitrogen from the air.

In this work, carbide tools were used in experiments and have been analyzed in this work. In practice, the starting materials for the manufacture of carbide tools are hard refractory carbides (i.e. tungsten carbide) and metal binder (i.e. Cobalt), both in the form of powder. To achieve good toughness and hardness of WC–Co tool, fabrication of composite powder of nanometer size is preferred. For this process ball milling comminution method in carbide industry is used. The WC–Co composite powder will then go through three sequential procedures, i.e. pressing, sintering and machining to convert shape to the final product i.e. cutting tool. All those processes, especially the milling processes are energy intensive processes. Therefore, in this paper, life cycle inventory related to energy consumption, for producing cutting insert is evaluated based on the process data extracted from [25]. The boundary of energy consumption is limited to include ball milling, pressing, sintering and grinding processes. The energy/material consumption inventory for producing WC–Co cutting insert is listed in Table 4. Since the tool insert used in this paper has CNMG shape with a total weight of 9 g, the inventory data are scaled based on weight, except for the grinding time, which is scaled based on total area of surface requiring grinding.

Table 4. *Input inventory of WC–Co cutting insert manufacturing*

Categories	Quantity
Cutting tool weight [g]	9
Surface to grind [cm2]	5.3
Milling specific energy [kWh/g]	0.52
Milling energy consumption [kWh]	4.68
Pressing energy consumption [kWh]	0.008
Sintering energy consumption [kWh]	0.5
Grinding energy consumption [kWh]	0.34
Total energy consumption [kWh]	**5.53**
	=19.9MJ
* In addition to energy consumption there are also consumables like inert argon gas, water, grinding CLF, etc. that also affect life cycle impact. However, this is beyond the scope of this work.	

From the results in Table 4 it can be seen that 5.53 kWh of electrical energy is spent for the production of a cutting tool. This means that lowering the tool-wear or a prolongation of tool-life in machining production is going to result in lower energy consumption in production of cutting tools. Additionally, this can be used to justify the difference of cryogenic and conventional machining process overall energy consumption that was initially on the side of conventional machining on account of the liquid nitrogen production (extraction of air).

To correlate these results, the total energy consumption is calculated for conventional and cryogenic machining/production of product specified in section 3 at different batch sizes. The analysis includes:

- energy consumption for production of CLF,
- energy consumption for production of cutting tools,
- energy consumption for machining process.

The results, correlating the batch size, productivity via cutting speed and total energy consumption are shown in Fig. 4. It can be seen that the batch size does not significantly affect the total energy consumption process, while cutting speed is a significant parameter. With increasing cutting speed, the tool-wear is nonlinearly increasing, while the machining time (for the whole batch size) is nonlinearly shortening. The first results in lower energy consumption for cutting tool production, while the latter means lower energy consumption in using CLF and the energy spent for the machine tool usage (both were scaled from the annually calculations to the exact batch size production time). It is possible to see that at small cutting speeds, the LN extraction is the dominant energy consumption source, while at higher cutting speeds, cutting tools become dominant energy consumption sources (high tool-wear). The threshold, where cryogenic machining becomes more energy efficient than conventional machining in Inconel 718, is at approximately v_c = 90 m/min.

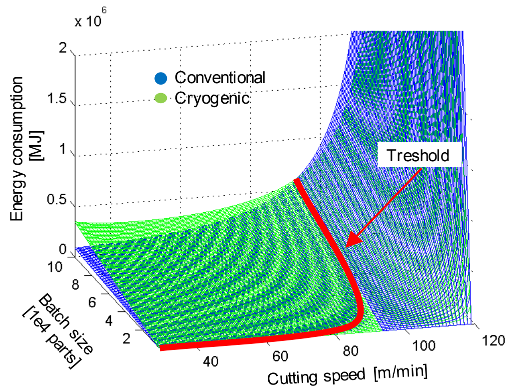

Fig. 5. *CLF, cutting tools production and machining process total energy consumption*

Based on these results it can be concluded tha cryogenic machining, even due to the fact that LN extraction is a very intensive process in terms of energy, can be more energy efficient that conventional machining on the account of the prolongation of tool-life and thus decreased cutting tool consumption.

5 CONCLUSIONS

Challenges in production with regard to the economy, society, and the environment in view of machining technology, are discussed in the first part of this paper. More specifically, LCA aims to convince the industry of the merits of sustainable machining technologies, taking into account the overall life cycle of the CLFs. In this respect, cryogenic machining is presented as a viable and sustainable machining technology in comparison to conventional machining. The LCA demonstrated that transitioning from oil-based CLFs to LN used in cryogenic machining is a move towards more sustainable machining, which results in a significant reduction in solid waste, water usage, global warming potential, acidification, and in an increased energy use for CLF production. However, it has been found that in addition to the nitrogen extraction, the production of cutting tools is also a very energy consuming process is also. Based on the comparative analysis and calculation of total production energy consumption, it has been proved that cryogenic machining can be more energy efficient than conventional machining. This goes on account of drastic reduction on cutting tools consumption.

In the second part of this paper an experimental machining study of Inconel 718 is discussed. The tool-wear was measured and used for the determination of tool-life. Once cutting tool-life was known, the cryogenic CLF was evaluated in terms of the total production cost per part, covering all sustainability measures. It has been shown that the elimination of conventional CLFs, the reduction of costs associated with waste and higher tool-life in cryogenic machining drastically reduces total production cost per part in comparison to conventional machining (by up to 30%). This confirms that even though the initial cost and effort involved with the cryogenic machining system is higher, it can obviously offer significant sustainability benefits through shorter production cycles and a lower cost needed to machine a part as well as enhanced productivity due to higher output.

An additional evaluation of Inconel 718 machining, not reported here, proved that cryogenic CLF increases machining reliability while maintaining dimensional tolerances and improving machined surface integrity. However, the reliability of the cryogenic CLF delivery system itself is not yet clear. For this, the industrial implementation of the system that reduces consumption rates (costs), environmental burdens, and health risks, while simultaneously increasing machining performance and profitability, is required.

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7 REFERENCES

[1] Ana, Q.L., Fub, Y.C., Xub, J.H. (2011). Experimental study on turning of TC9 titanium alloy with cold water mist jet cooling. *International Journal of Machine Tools & Manufacture*, vol. 51, p. 549-555.

[2] Adamczak, S., Čuš, F., Miko, E. (2009). A model of surface roughness constitution in the metal cutting process applying tools with defined stereometry. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 55, no. 1, p. 45-54.

[3] Zuperl, U., Cus, F. (2004). A determination of the characteristic technological and economic parameters during metal cutting. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 50, no. 5, p. 252-266.

[4] Zuperl, U., Cus, F., Gecevska, V. (2007). Optimization of the characteristic parameters in milling using the PSO evaluation technique. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 53, no. 6, p. 354-368.

[5] Cus, F., Zuperl, U., Kiker, E. (2007). A model-based system for the dynamic adjustment of cutting parameters during a milling process. *Strojniški vestnik - Journal of Mechanical Engineering*, vol. 53, no. 9, p. 524-540.

[6] Jovane, F., Westkamper, E., Williams, D. (2009). *The Manufuture Road*. Springer-Verlag, Berlin, Heidelberg.

[7] Jovane, F., Yoshikawa, H., Alting, L., Boer, C.R., Westkamper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M. (2008). The incoming global technological and industrial revolution towards competitive sustainable manufacturing. *CIRP Annals - Manufacturing Technology*, vol. 57, no. 2, p. 641-659.

[8] Herrmann, C., Hesselbach, J., Bock, R., Zein, A., Ohlschlager, G., Dettmer, T. (2007). Ecologically benign lubricants - evaluation from a life cycle perspective. *Clean Soil Air Water*, vol. 35, no. 5, p. 427-432.

[9] Yildiz, Y., Nalbant, M. (2008). A review of cryogenic cooling in machining processes. *International Journal of Machine Tools & Manufacture*, vol. 48, no. 9, p. 947-964.
[10] Hong, S.Y., Ding, Y., Jeong, W. (2001). Friction and cutting forces in cryogenic machining of Ti-6Al-4V. *International Journal of Machine Tools & Manufacture*, vol. 41, p. 2271-2285.
[11] Hong, S.Y., Ding, Y. (2001). Cooling Approaches and Cutting Temperatures in Cryogenic Machining of 6Al-4V. *International Journal of Machine Tools & Manufacture*, vol. 41, p. 1417-1437.
[12] DaSilva, F.J., Franco, S.D., Machado, A.R., Ezugwu, E.O., Souza, A.M.J. (2006). The performance of cryogenically treated HSS tools. *Wear*, vol. 261, p. 674-685.
[13] Pusavec, F., Kramar, D., Krajnik, P., Kopac, J. (2010). Transition to sustainable production - Part II: Evaluation of sustainable machining technologies. *Journal of Cleaner Production*, vol. 18, no. 12, p. 1211-1221.
[14] Pusavec, F., Deshpande, A., M'Saoubi, R., Kopac, J., Dillon, O.W.J., Jawahir, I.S. (2008). The modeling and optimization of machining of high temperature nickel alloy for improved machining performance and enhanced sustainability. *Proceedings of the 11th CIRP conference on Modeling of Machining Operations*, p. 21-28.
[15] Zhao, Z., Hong, S.Y. (1992). Cooling strategies for cryogenic machining from a materials viewpoint. *Journal of Materials Engineering and Performance*, vol. 1, no. 5, p. 669-678.
[16] Wang, Z.Y., Rajurkar, K.P., Fan, J., Lei, S., Shin, Y.C., Petrescu, G. (2003). Hybrid machining of inconel 718. *International Journal of Machine Tools & Manufacture*, vol. 43, no. 13, p. 1391-1396.
[17] Skerlos, S.J., Hayes, K.F., Clarens, A.F., Zhao, F. (2008). Current advances in sustainable metalworking fluids research. *International Journal of Sustainable Manufacturing*, vol. 1, no. 1-2, p. 180-202.
[18] Ostlin, J., Sundin, E., Bjorkman, M. (2009). Product life-cycle implications for remanufacturing strategies. *Journal of Cleaner Production*, vol. 17, no. 11, p. 999-1009.
[19] McManus, M.C., Hammond, P.H., Burrows, C.R. (2004). Life-cycle assessment of mineral and rapeseed oil in mobile hydraulic system. *Journal of Industrial Ecology*, vol. 4, no. 3-4, p. 163-177.
[20] Pusavec, F., Krajnik, P., Kopac, J. (2010). Transition to sustainable production – Part I: Application on machining technologies. *Journal of Cleaner Production*, vol. 18, no. 2, p. 174-184.
[21] Clarens, A.F., Zimmerman, J.B., Keoleian, G.A., Hayes, K.F., Skerlos, S.J. (2008). Comparison of life cycle emissions and energy consumption for environmentally adapted metalworking fluid system. *Environmental Science & Technology*, vol. 42, p. 8534-8540.
[22] Cohen, H., White, E.M. (2006). Metalworking fluid mist occupational exposure limits - discussion of alternative methods. *Journal of Occupational and Environmental Hygiene*, vol. 3, no. 9, p. 501-507.
[23] Ruediger, H.W. (2000). Hard metal particles and lung disease: coincidence or causality? *Respiration*, vol. 67, p. 137-138.
[24] Pusavec, F., Kramar, D., Kenda, J., Krajnik, P., Kopac, J. (2009). Experimental analysis of sustainability in machining of Inconel 718. *Proceedings of the 42nd CIRP Conference on Manufacturing Systems*, Grenoble, France.
[25] Zhao, F., Bernstein, W.Z., Naik, G., Cheng, G.J. (2010). Environmental assessment of laser assisted manufacturing: case studies on laser shock peening and laser assisted turning. *Journal of Cleaner Production*, vol. 18, p. 1311-1319.