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Cryogenic Machining through the Spindle and Tool for Improved Machining Process Performance and Sustainability: Pt. II, Sustainability Performance Study

Tao Lu[a,*], Ravikumar Kudaravalli[a] and George Georgiou[a]

[a]5ME Tech Center, 6990 Murthum Ave., Warren, MI, 48092, USA

Abstract

Cryogenic machining is considered a sustainable alternative to machining with flood cooling application. This paper describes a case study about the production of a titanium alloy part which involves multiple milling processes. It draws comparisons between conventional flood cooling and cryogenic machining. Factors such as productivity and cost, and total life-cycle sustainability performance such as energy consumption and emissions are evaluated. It is shown that cryogenic machining results in a comprehensive advantage in most of these aspects. The paper provides an example of how to assess the manufacturing sustainability performance gains through a technology improvement. It also points out potential directions to consider when optimizing the process for optimal sustainability performance.

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Keywords: Cryogenic machining; Machining coolant; Sustainable machining; Sustainability assessment; Cryogenic cooling; Environmental friendly

1. Introduction

Cryogenic machining, which uses liquid nitrogen as the cooling media, is considered a sustainable alternative to conventional flood cooling application used in the machining process. Though the benefits of cryogenic machining

* Corresponding author. Tel.: +1-586-473-5074; fax: +1-586-983-2575.
E-mail address: tao.lu@5me.com

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in various aspects have been studied in previous research, the lack of a real-world implementation generates uncertainties in its application. In this paper, a case study is presented to illustrate the impact of cryogenic machining applied in typical aerospace product manufacturing. More importantly, it illustrates the systematic approach to carefully review the overall sustainability advantages of the technology for the manufacturer.

2. Background and Previous Work

Sustainable manufacturing processes take into account performance in economic, environmental and societal aspects, which are known as the triple bottom line. The machining process is an important part of the manufacturing process thus it is expected to have a huge impact by improving the sustainability performance [1].

The application of coolant is typically considered as a critical element in achieving a sustainable machining process. This is due to the significant influence in economic, environmental and societal burdens from the application of conventional flood cooling. The metal working fluid, also called coolant, is used for both lubrication and cooling of the cutting process. Some other effects include chip evacuation, corrosion protection and machine tool protection [2]. In conventional application, coolants are usually applied in large volume to fully immerse the cutting zone and the surrounding area. To further enhance its effect, high pressure high flow rate technology has been developed and is widely used in the machining of difficult-to-machine materials [3].

The cost impact from coolant application is not limited to the purchase of the fresh fluid, either water-based or petroleum-based. Rather, it is the combined cost of coolant itself, utility maintenance, associated product treatment like cleaning and drying, and maybe most importantly the post-treatment of used coolant [4]. The environmental impacts due to the coolant application are most concerned with the resource consumption, emission and waste treatment [5]. And the societal impacts involve the health threat due to direct coolant contact and inhaling atomized coolant droplets [6]. During the evaluation of these potential impacts, all factors throughout the manufacturing, use and post-treatment stages, which compose the whole life-cycle of the coolant, need to be considered [7].

3. Cryogenic Machining Case Study

A case study is presented in this document to illustrate the performance of the proposed cryogenic machining solution as illustrated in Lu et al. [8], in both conventional aspects and in sustainability aspect.

3.1. Scope and system boundary

The main purpose is to illustrate the potentially different performance of the innovative cryogenic machining solution against conventional flood cooling method. In the process, different approaches are applied to evaluate sustainability performances.

As the cryogenic machining solution presented is a direct substitute of conventional machining with coolant, it is considered reasonable to limit the system boundary to the workstation level. For a target machine tool and its dedicated accessories, the input and output are carefully reviewed for an evaluation of their performance in various aspects. The study aims at revealing the sources of performance differences, and guides other process optimization.

To be specific, the energy consumption, emission and waste output is analyzed. Then the environmental impact is evaluated based on the energy consumption and corresponding greenhouse gas (GHG) emission, waste stream generation and water resource consumption. Based on the normalized production output and the consumptions of various resources for both coolant applications, the overall manufacturing cost for one part made is calculated. The resources considered include labor, material, energy, cutting tools, coolant and maintenance for both machine tool and accessories.

3.2. Processes, machine tool and setup info

The investigation is based on a series of milling processes of a Ti-6Al-4V blank to produce a frame structure. It is a typical example of the time-consuming machining process commonly seen in aerospace product manufacturing. The part is very machining intensive in that 95% of the blank mass needs to be removed.

The processes are designed that both coolant solutions will use the similar amount of tooling pieces, so that the total tool change pattern and setup procedure will be very similar. However, due to different machining performance, cutting with cryogenic machining will be carried out at a generally higher material removal rate (MRR). From the technical point of view, the current process design is based on similar number of tools consumed per product produced. Information about the tools involved and corresponding feed rates are given in Table 1 below. Note that the overall diameter and flute numbers are kept the same for each tool type, though the internal and external features are different as outlined in Lu et al. [8]. In this case, the actual feed rate, which is decided by both the spindle speed (cutting speed) and the uncut chip thickness per flute, represents the material removal rate difference between two coolant solutions. The tool paths can be complicated for some tools and the exact parameters would vary for different tools at different locations.

Table 1: Cutting tool consumption and feed rate

Tool Type	Number of Flutes	Role	Number of Tools Used per Part: Flood/Cryogenic	Feed, mm/min (Flood Cooling)	Feed, mm/min (Cryogenic)
Ø152.4mm Indexable Face Mill	7	Rough	2/2 (sets of 7 inserts)	101.6	203.2
Ø25.4mm Solid Carbide End Mill	5	Rough/Finish	11/11	106.68/177.8	177.8/381
Ø19.05mm Solid Carbide End Mill	4	Rough/Finish	10/8	127/ 203.2	388.62/388.62
Ø12.7mm Solid Carbide End Mill	5	Finish (Corner)	3/4	228.6	228.6
Ø12.7mm Solid Carbide End Mill	5	Finish	3/2	381	381

Cryogenic machining enables machining at approximately twice the material removal rate of conventional flood cooling process, which enables the same manufacturing plant to bear twice the production capacity without excessive investment in land, infrastructures, utilities and staffing.

The tests and evaluation is based on a Cincinnati 800XT horizontal machining center (HMC) equipped with both conventional flood cooling and a through the tool cryogenic machining system. Accounting on an annual basis is carried out based on 250 working days per year with two 8-hour shifts per day. Maintenance is done during off-shift time.

One difference in the process is that the through the tool cryogenic machining application requires pre-cooling the delivery line at the start of the shift and the cutting tools between each tool change and that will slightly increase the coolant related machine time over-head. This has been accounted for in the machining time tracking and corresponding resources allocation.

3.3. Accounting the energy and material streams

The coolant life cycle is tracked in this study as a cradle to grave scenario. The cutting fluid used in flood cooling application in this study is CIMTECH® 320 full synthetic metalworking fluid, which is used as a 7% volume ratio solution with water. The machine uses a 3785.4-liter tank, which takes 265 liters of the raw fluid per tank. In this application, the whole tank of coolant has a life span of 45 days, then it should be replaced with freshly made coolant. There are inspection and maintenance carried out every 6 days to maintain fluid concentration level. The corresponding labor is accounted for but the minor amount of materials and resources used in the maintenance work are ignored. The cryogenic coolant, liquid nitrogen, naturally vaporizes into the air and forms a one-time-use only scenario. A small portion of the liquid nitrogen vaporizes to build the required pressure for the fluid to flow through the delivery system. So, aside from a low power monitoring and control system, the entire cryogenic system requires little energy and needs no other consumables or resources.

Cutting tools are consumed as one time use only thus no regrinding is accounted for. The cutting tools are purchased, used and then turned into carbide solid waste for recycling. The workpiece blank is a 54.4kg Ti-6Al-4V block, while the final product weighs 2.7kg. All the material loss is turned into chips and sent for recycling.

Within the energy stream tracking, the cutting energy is estimated according to the spindle motor rating and the in-cut load indicator. The coolant system energy consumption is based on the power rating of the coolant system components, mostly the coolant pumps, and subjectively assigned a load factor of 80%. Total coolant application time equals the cycle time of the machining process. The idle power usage is a rough estimation based on empirical data [9]. The machine requires a nominal 850L/min compressed air flow at 552kPa, which is provided by a 20kW air compressor working at an allocated 20% load factor. The energy flow for the air compressor is tracked but the consumables such as the air filter and lubricant for the air compressor is neglected. Energy is in the form of electricity.

3.4. Power consumption analysis

The run time and energy consumption break down is summarized in Table 2 below. The idle stage covers the machine setup, NC program input, part clamping, tool and part alignment, manual part finish and machine cleaning. Maintenance refers to the off-shift labor investment, especially on coolant delivery system, based on the manufacturer's internal empirical data. But the power, consumables and resources consumption in this stage have not been tracked.

Table 2: Run time break down and power consumption summary

Component	Usage Time per Part, hours, Flood Cooling/Cryogenic	Power and Energy Usage under Flood Cooling	Power and Energy Usage under Cryogenic Machining
In Cut Spindle	44.7/22.0	4.0kW, 178.8kWh	7.4kW, 162.8kWh
Coolant Application	45.3/23.5	7.7kW, 348.8kWh	0.2kW, 4.7kWh
Idle Stage	1.5	5.0kW, 234.0kWh	5.0kW, 125.0kWh
Supporting Air Compressor	Cycle Time	4.0kW, 187.2kWh	4.0kW, 100.0kWh
Maintenance	26.7/8.0	-	-
Total	Cycle Time: 46.8/25 hours	948.8kWh	392.5kWh (58.6% reduction)
Total (with embedded energy in LN)	0.640kWh/kg	948.8kWh	732.9kWh (22.8% reduction)

The following Figure 1 summarizes the energy composition of the conventional flood cooling, cryogenic machining and the cryogenic machining including the liquid nitrogen embedded energy. The embedded energy in the consumed liquid nitrogen is both outside the scope of the manufacturing stage assessment, and outside the system boundary of the workstation. For general interest, the data is provided here as a reference about the life cycle behavior. It is found that the energy allocation towards liquid nitrogen is tricky in the sense that liquid nitrogen could be a co-product/bi-product of liquid oxygen manufacturing. Modern data on practical air liquefaction plants is rarely published and the authors hereby used the data from an early publication stating 0.640kWh/kg for liquid nitrogen [10]. At the density of 0.807kg/L, the 656 liters of liquid nitrogen consumed would have 340.4kWh of energy embedded. According to this data, when we include the embedded energy of the consumed liquid nitrogen and disregard the embedded energy in conventional coolant, the total energy consumption of conventional flood cooling and cryogenic machining are 948.8kWh and 732.9kWh, respectively. So, even when accounting for the embedded energy of the liquid nitrogen, the cryogenic machining process has lower energy requirements than a conventional coolant process. Life cycle analysis on the conventional coolant is not carried out here. It can be extended by accounting for the content of the cutting fluid and tracking the corresponding embedded energy throughout its life-cycle.

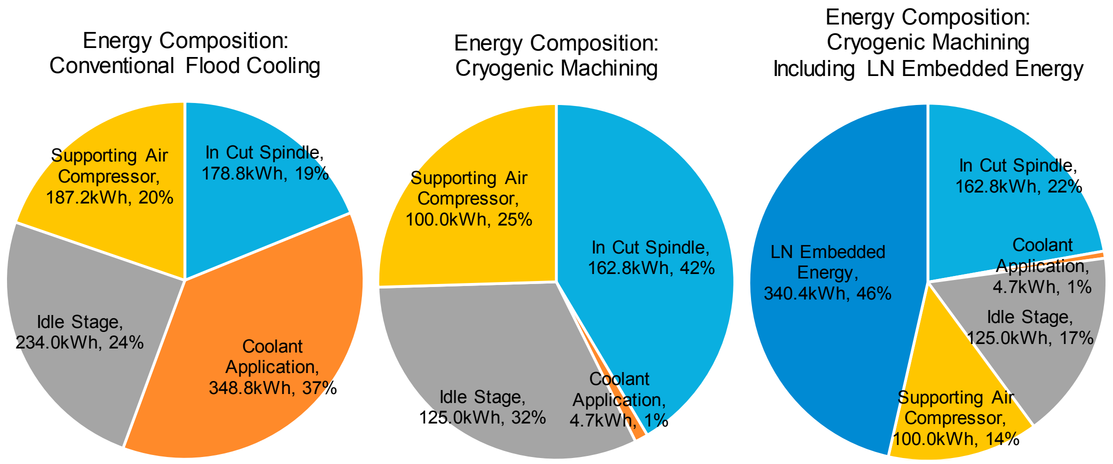

Figure 1: Energy composition comparison

3.5. Environmental impact analysis

In this environmental impact analysis, we track the greenhouse gas (GHG) emission, waste streams in both solid form and liquid form, and water consumption. Note that only those emission and waste streams at the facility are tracked according to the scope and previously described system boundary. These input and output streams are summarized in Table 3 below.

Table 3: Environmental impact summary

Element	Conventional Flood Cooling Process	Cryogenic Machining Process
Equivalent CO_2 Emission, kg	564.7	233.6
Titanium alloy chips, kg	51.7	51.7
Carbide scrap, kg	14.2	13.4
Liquid Waste, L	398.6	-
Water Consumption, L	370.7	-

The GHG emission here is a direct translation of energy consumption in the form of electricity according to the local supply source content on the local electric grid. The target manufacturing plant is in the state of Texas, USA, which has an annual CO_2 equivalent total output emission rate of 0.5952kg/kWh [11]. Hereby we assume that the plant's electricity source can be represented by the state average sources of supply. By converting the values summarized in Section 3.4, GHG emission amounts are 564.7kg per part and 233.6kg per part for the conventional flood cooling process and cryogenic machining process, respectively.

Solid waste streams are highly similar between the two types of processes. The scrap rate is not involved in this study. Thus, a same amount of material is processed, giving the same amount of generated machining chips. The total mass of chips generated is 51.7kg per part. However, it should be noted that the chips generated from conventional flood cooling have a certain amount of coolant attached to them. Most of the coolant are either drained or vaporized into the air with residues contaminating the chips. This will create difficulties in recycling the chips, while chips from cryogenic machining do not have such a problem. This advantage will not be effective until the corresponding recycling processes takes advantage of these cleaner chips. The process parameters are optimized to have very similar tool life, thus the total generation of carbide scrap in the form of used tools is similar, which are 14.2kg and 13.4kg for the conventional flood cooling process and the cryogenic machining process, respectively.

The liquid waste is generated in conventional flood cooling process only. The liquid nitrogen evaporates into the air and leaves no residue thus does not form any liquid waste. Based on the material information in Section 3.3, the total coolant consumption for one part is 398.6 liters. Within this amount, there is 27.9 liters of raw cutting fluid and 370.7 liters of water. Note that not all coolant would end up as used coolant for disposal. Vaporization, coolant mist generation through atomization and chip/part carrying away will consume part of the coolant. But in this study, these streams are not accounted for and all the fresh coolant fed into the system is assumed turning into used coolant. In this case, the used coolant is categorized as chemical contaminated waste water without specific highly hazardous material. Certified recyclers will charge the manufacturer to take away, treat and dispose used coolant.

3.6. Cost analysis

In the cost analysis, the cost for the labor, material, cutting tool, coolant and machine tool capital is captured. Labor cost is accounted for at an hourly rate of $150. Note that the labor hour values stated here include the off-shift setup and preparation, part manual processing and coolant system maintenance.

All values are rounded to one United States Dollar. The cost break down is summarized in Table 4 below.

Table 4: Cost break down summary for manufacturing one piece of part

Element	Allocation Notes	Amount Used for Flood Cooling Process	Cost for Flood Cooling, $	Amount Used for Cryogenic Machining	Cost for Cryogenic Machining, $
Labor	$150/labor hour	81.6 hours	$12,240	39.0 hours	$5,850
Material	$2610 per part	-	$2,610	-	$2,610
Cutting Tool	Various by type	29 pieces	$5,544	27 pieces	$7,205
Coolant	Various by type	398.6L	$214	656L	$52
Coolant Disposal	$1.29/L local contract rate	398.6L	$514	-	-
Energy	$0.0816/kWh	948.8kWh	$77	392.5kWh	$32
Capital	Based on 15-years machine life span	1282 parts made	$289	2493 parts made	$199
Material Recycling	Used cutting tools and machining chips		-$346		-$336
Total	-	-	$21,142	-	$15,612 (-26.2%)

Material cost involves the raw blank price and labor hours invested in the initial processing. It represents the pre-machining status value of the workpiece blank.

Cutting tools are based on the quoted prices for the tools involved. The through the tool cryogenic machining tools have a relatively more complicated internal structure thus are more expensive to make. The current value is based on a 30% premium over conventional tools with similar features. Experimental prototype tools could be more expensive.

The cost of using conventional coolant is divided into two parts, namely the coolant cost and the coolant disposal cost. The prior one considers the raw cutting fluid and the water to dilute its concentration. The purchasing cost for the 370.7 liters of water is $0.40 based on a local large scale industrial water supply rate which is a minor part and is included in the coolant cost. The later one includes the disposal cost for the whole amount of used coolant and it applies to the conventional flood cooling process only. Here the disposal price includes not only the treatment cost and transportation, but also the tax and regulated environmental protection fees. It is obvious that the post-use stage of conventional coolant bears most the true overall coolant cost, when excluding the related labor hours. When the post-use stage cost is considered, the overall coolant consumable cost is even higher with the conventional flood cooling process than with cryogenic machining. The difference would be further enlarged by including coolant system maintenance cost.

Energy in the form of electricity is counted at the local commercial electricity price in the state of Texas, USA.

Capital cost is based on a 15-years of machine tool life span assumption for both the machine tool and the coolant delivery system. Then the allocated hourly cost is combined with the cycle time of the two types of processes to give the overall capital cost.

Ti-6Al-4V aerospace grade scrap is accounted for being sold in chip form at the price of \$3.25/kg. The cleanness level of the chips is not accounted for in these price quotes. Tungsten carbide scrap, on the other hand, is taken at \$12.54/kg.

4. Summary

A brief review on the background of cryogenic machining is presented. It reveals the potential benefits and critical design considerations of the technology, especially in the sustainability aspect. The fundamental mechanism of cryogenic machining is also reviewed to emphasize the scientific basis for its engineering implementation.

A detailed case study is presented here, evaluating the economic and environmental impacts of the cryogenic machining implementation for the manufacturer. Contrary to the typical method starting with cost calculation, we would suggest carefully sorting out the input and output streams of the manufacturing facility under discussion first. Then these material streams' life-cycle behavior should be reviewed to highlight all stages that may occur outside the system boundary but directly associated with the manufacturer's activity. This is critical in developing sustainability thinking. The influence from the technical elements to the manufacturing process should be reviewed throughout their life-cycle stages. The corresponding evaluation should not be limited by the scope of any specific departments of the manufacturer. By presenting the cost evaluation as the last step, the paper strives to change the common belief among industrial partners and manufacturers that sustainable manufacturing is a constraint or burden to current manufacturing processes. Just the opposite, it is believed that sustainable manufacturing thinking encourages a comprehensive scope based on triple bottom line and total life-cycle evaluation, and fundamentally it is aimed at seeking comprehensive benefits in manufacturing activities, including economic benefits.

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