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Using Metrics to Assess the Sustainability of Cryogenic Machining

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Abstract

Cryogenic machining is considered the most environmentally friendly alternative to the more prevalent flood-cooled, near-dry, and dry machining technologies. This article explores the use of a sustainability evaluation method for manufacturing processes, with a focus on cryogenic machining methods. Our investigation is predicated on Process Sustainability Index (Process) metrics. To To determine the best conditions for cryogenic machining, studies are conducted using a variety of machining parameters as adjustable variables, including cutting speed and coolant flow rate. From an eco-friendly production standpoint, process analysis helps choose the best cutting settings. During the assessment phase, the process's behaviour is taken into account under different process conditions, and its controllability and mechanism are analysed to improve sustainability.

1. Introduction

The evaluation of manufacturing processes' effects on the economy, the environment, and society must all be taken into account. Sustaining human life is emphasized as While maintaining or enhancing product and process quality, manufacturing must show decreased negative environmental effect, increased energy and resource efficiency, reduced waste generation, and enhanced operational safety and employee health [1, 2]. Early research by Wanigarathne et al. [2] identified the six interrelated factors shown in Figure 1 as crucial to the development of environmentally friendly production methods.

Figure 1: The six main components of eco-friendly production [2].

The production cost, energy use, and waste management are three of the six factors that may be modeled. Approaches that are analytical because of the certainty they provide. Due to their nondeterministic character, modeling the environmental effect, personnel health, and operator safety would need the adoption of methods like fuzzy logic. It takes a lot of work and case studies to validate with actual practices the results of quantitative modeling and analysis of all six parts and combining them to support decision making via optimization. Cryogenic machining techniques are the topic of this research, which details the implementation of a sustainability assessment approach for manufacturing processes. A Process Sustainability Index (ProcSI) analysis is employed as the basis for this study's approach. The physical behavior of the processes is evaluated using whole life cycle factors included into the metric set proposed in this article. In what follows, we'll have a quick look at the ProcSI procedure. In the tests, the cutting speed and coolant flow rate are two of the machining parameters that serve as the movable controls. From a green manufacturing perspective, the optimal cutting conditions may be determined with the use of the ProcSI analysis. Understanding the process mechanism requires taking into account how the process behaves under a range of settings.

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2. Previous Work

Feng et al. [3] provided a summary of the most useful measures and indicators for gauging industrial facilities' commitment to sustainability. Different research approaches may be broken down into technological level (from basic to advance) and scope of use (anything from a single product to an entire industry to a single nation to the whole planet). Error! Provides a classification of these many approaches. The referenced article could not be located.

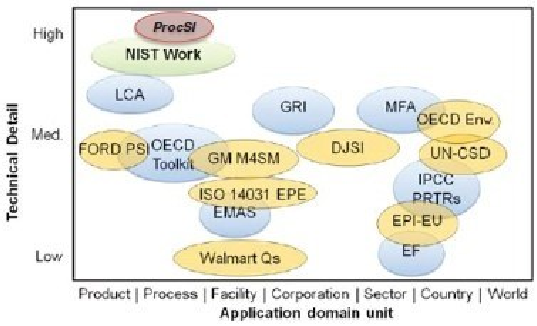

Figure 2: Groupings of well-known sustainability assessment approaches, modified from [3].

Despite a lot of work put into modeling and to evaluate the overall sustainability content of machining processes, no comprehensive technique has been undertaken to grasp the numerous component elements of process sustainability [4-5]. In order to maximize machining performance in near-dry conditions, Granados et al. [6] built on the work of Wanigarathne et al. [2] by providing a hybrid (deterministic and non-deterministic) model to assess machining process sustainability. This study demonstrates that by establishing and combining the different science-based models with acceptable optimization methodologies, sustainable manufacturing may be achieved, allowing for more consistent sustainability assessment. These first efforts provide a solid basis for quantifying the difficulty of process sustainability modeling [7]. But a more thorough investigation of sustainability factors is required, ideally using a metric-based system that can handle more precise and quantitative data.

Consequently, researchers come up with the idea for the Process Sustainability Index (ProcSI) system. As an example of a universal discrete product manufacturing process, machining serves as a case study in the development of the Process Sustainability Index (ProcSI) [8]. It's a tool for designing processes that helps manufacturers consider the effects of their actions on the environment. The following is a brief overview of the most important aspects that have been reviewed and revised in this most current study. Manufacturers may use the established scope and system boundaries to choose the most effective production methods and their associated parameters. Accordingly, the manufacturing plant's physical perimeter serves as the system boundary [8]. The whole suite of metrics is refined in light of established standards. The ProcSI technique employs a hierarchical framework with four levels to organize the flow of data. Clusters, then sub-clusters, and lastly individual measures make up the index's hierarchy. Normalization, weighting, and aggregation bring the measures up from the bottom. [7]. The ProcSI concept may be used at the operation, workstation, and plant levels to improve the overall organization of a manufacturing facility [8]. Cryogenic machining has the potential to outperform the current best sustainability performance of any machining process [9, 10], making it a viable alternative to the traditional flood cooling approach. However, the effects of various process parameters on the long-term viability of cryogenic machining have not been well investigated. Therefore, an investigation into the problem at the operational level would aid in developing a deeper comprehension of the use of cryogenic machining.

3. Experiments

The experimental setting used here is similar to that used in Pu's publication [11]. However, the two most important factors are cutting speed and coolant. Machining takes place on 3mm thick sheets of hard rolled AZ31B magnesium alloy. Haas TL2 CNC lathe with MTFNL2525M22 tool holder and uncoated carbide inserts, model TNMG432, Kennametal tool grade K420. With a fixed feed rate of 0.2 mm/rev, the chosen cutting speed range was from 50 meters per minute (m/min) to 500 m/min (m/min). This will result in a cutting time per work piece of anywhere between a few seconds and a few minutes. Each individual work piece requires between 27 seconds and 71 seconds of total operating time. Table 1 summarizes the machining parameters. In this case, we use a low-pressure liquid-nitrogen delivery system that was designed specifically for our application. A low pressure air compressor of 207kPa is used to provide mechanical energy for the system. Calibration of the flow rate at varying driving pressures is based on studies using water pumps. Then, the Darcy-Weisbach equation [12] is used to get an approximation of the relevant flow rate of liquid nitrogen. After waiting for the steady flow of liquid nitrogen, the operator began the cutting procedure. Table 2 provides a summary of the 20% yearly depreciation rate used in calculating the capital cost tie-up.

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4. *ProcSI* Evaluation of Cryogenic Machining Process

It has been shown in prior work how to apply ProcSI assessment to an already established machining process. Experiment data currently being collected and in this article, we give the related analyses. Due to the lack of distinguishing factors between the two clusters, both operator safety and staff health concerns will be assigned a score of 10. The measurement of surface roughness (quality specification) and the expected statistical distribution are used to calculate the scrap rate. The surface quality of the work piece is assumed to follow a normal distribution with a variance of = 0.15, and a quality threshold of Ra = 0.25 m is used. Based on the current commodity price of the raw materials, we may calculate a unit price of $14 per finished product.

Experiment-specific machining settings are shown in Table 1.

Machining Parameter	Parameter Value	
Process Info	Process type	Orthogonal
	Starting diameter (mm)	130
	End diameter (mm)	80
Insert Grade	K420 uncoated carbide	
Tool Geometry	Edge radius (µm)	42.8±2.8
	Model	TNMG432
	Chip breaker	Yes
Cutting Geometry	Rake angle	-5°
	Clearance angle	5°
Machining Parameters	Cutting speed (m/min)	50, 100, 250, 500
	Feed (mm/rev)	0.2
Coolant Condition	Driving pressure (kPa)	17.2, 34.5, 51.7, 68.9

Table 2. Capital tie-up summary.

Equipment	Purchase Price	Residual Value	Cost Tie-up
CNC Lathe	$ 35,000	$ 22,400	$ 3.15 / hour
Air Compressor	$ 500	$ 320	$ 0.02 / hour
Liquid Nitrogen Dispenser	$ 500	$ 320	$ 0.02 / hour

The normalization from internal comparison is used to provide a score between 0 and 10 in many categories. The worst-case scenario has a score of 4, while the best-case scenario has a score of 1. A ten-point total. Then, the middle instances are linearly normalized to fit the precise data range established by the worst and best examples. Scores of 10 and 0 are awarded, however, when the theoretical best and worst circumstances are realized. The impact of normalization may be affected by the three scenarios with an unusually high scrap rate. They spend so much time and energy fixing the broken pieces those variances in other metrics, if normalized, wouldn't make much of a difference. In actuality, this is not a steady process that should be assumed. As a result, the normalization process disregards these extremes when determining the best and worst possible outcomes. Their measurements are still standardized the same manner, and if the resulting score is less than 2, a score of 2 out of 10 is provided to signal the presence of unsuitable process parameters.

4.1. Manufacturing cost

In this group, we focus only on direct costs and capital expenditures. The capital cost is calculated, and variable costs like labour, energy use, and coolant expenses are included in. Procedure Time. The costs are not standardized until the cluster level, and then only to the total costs that have been measured. Chattering causes bad-quality products, which drives up costs, especially when the cutting speed is low? Because of the high scrap rate, the cutting time is extended, which raises the production costs. Good product quality and less cutting time are two advantages of working at faster cutting speeds. The little quantity of liquid nitrogen used in the cutting process is a major factor in the overall low cost. When cutting time is minimized by using the fastest possible cutting speed, however, the price difference between the various coolant flow rates is negligible.

4.2. Energy consumption

We factor in standby power, active power, and coolant supply system power. Total energy consumption is calculated in the same way that total cost is. Use of energy or power. Total energy usage is normalized for comparison purposes. When the internal coolant pump is not in operation, the estimated idle power consumption of a stationary machine tool is 200 watts. To calculate the energy used by the coolant supply system, just add up the time the compressor is active and its estimated 500W work load. Cutting power varies from 200W to 3100W depending on the circumstances. The liquid nitrogen in the present system is transported by an external compressed air source. Although this seems to increase energy usage compared to the self-pressurized case, it really reduces energy consumption by reducing the amount of liquid nitrogen needed to power the device. However, the raw consumption of liquid nitrogen was not fully addressed in the prior research, therefore the tank pressurization costs

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were not accounted for. Energy savings may be possible since the pump operates just while cutting is taking place rather than all the time.

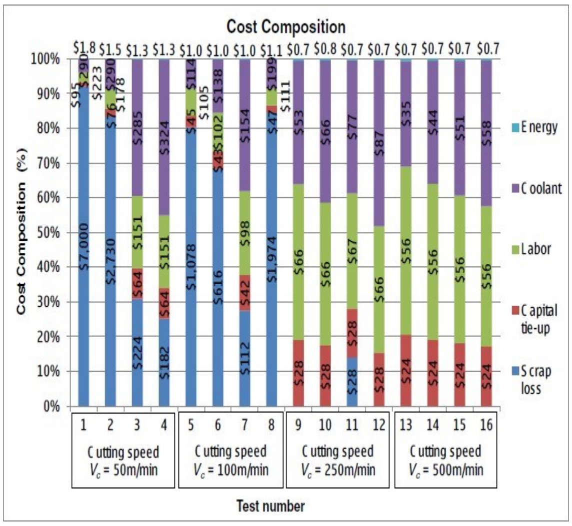

Figure 3: Cost breakdown under different reduction scenarios

The design of the liquid nitrogen system ensures that most of the liquid nitrogen's properties will be preserved even if it is given at varying flow rates. The by-pass valve releases pressurized air. Therefore, the rate of energy consumption by the delivery system is unaffected by changes in the driving pressure of liquid nitrogen. Therefore, the fact that most of the energy used is lost indicates a weakness in the delivery systems design. Even when accounting for the increased number of work pieces handled owing to greater scrap rate, the energy used on actual cutting is lower at lower cutting speeds. This is because there is less of a cutting force at play. However, the idle power and energy consumption on coolant supply system nullifies the savings on cutting energy at low cutting speed. These two energy sources have different energy needs depending on how long the job takes in total and how long the coolant is applied for. Although low-cutting-speed situations save energy during the actual cutting operation, they incur greater losses during the idle and coolant supply phases.

On the other side, cutting faster uses more energy overall but less when it comes to the actual cutting process. Figure 3 is a compilation of the energy mix across all scenarios. From the perspective of energy composition, it is clear that the cutting energy accounts for a greater fraction of the total at higher cutting speeds. As opposed to an uptick in energy conservation, this trend is driven by a general decrease in consumption. From this vantage point, it would seem that cutting at greater cutting speeds would be the most energy-efficient condition in terms of both overall energy consumption and the effective ratio of energy spent.

4.3. Waste management

It was anticipated that the usage of a variety of coolants would have no effect on the creation of chips or the coolants themselves. Generation of chips is shown average results after adding everything together. Based on the computed scrap rate and the typical mass of an unmachined work piece, the mass of scrap pieces may be determined. Table 3 provides a quick comparison. All scenarios when no scrap components are produced will result in the highest possible ratings because of the waste streams taken into account here. Cryogenic machining, on the other hand, seems to generate few by-products. One of the main benefits of cryogenic machining is that there is no residue from the coolant application. In this context, we distinguish between two potential waste streams: process chips and scrap components, in case their EOL treatment varies.

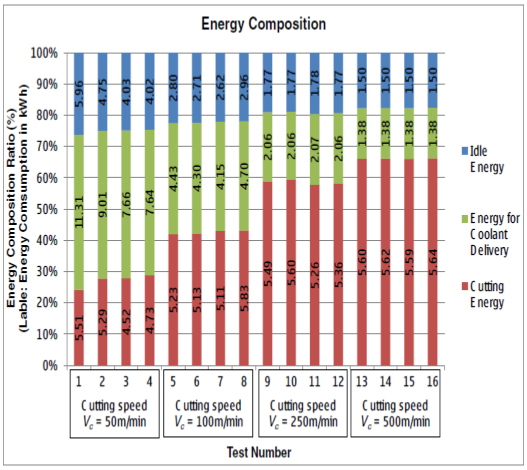

Figure 4: Energy composition of the different cutting conditions.

Table 3. Data summary for Waste Management.

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Cutting speed (m/min)	Driving Pressure (kPa)	Total mass of scrap parts (kg)	Total mass of chips (kg)	Waste Score
50	17.2	30.03	65.68	2.00
50	34.5	11.71	52.33	2.00
50	51.7	0.96	44.49	7.17
50	68.9	0.78	44.36	7.32
100	17.2	4.62	47.16	4.00
100	34.5	2.64	45.72	5.71
100	51.7	0.48	44.14	7.58
100	68.9	8.47	49.96	2.00
250	17.2	0.00	43.79	8.00
250	34.5	0.00	43.79	8.00
250	51.7	0.12	43.88	7.90
250	68.9	0.00	43.79	8.00
500	17.2	0.00	43.79	8.00
500	34.5	0.00	43.79	8.00
500	51.7	0.00	43.79	8.00
500	68.9	0.00	43.79	8.00

4.4. Environmental impact

The only aspect of this situation's environmental effect that is amenable to modification is the CO2 emissions caused by the use of energy. The Restricted Material category gets a perfect score of 10 points. Table 4 provides a summary of the information. The worst-case scenario is shown in red, while the best-case scenario is depicted in green. The findings are proportional to the total energy used in the process since only the indirect CO2 emission due to energy consumption is included. As was previously said, the environmental impact of cryogenic machining is minimal. There is no need for scarce resources or further waste generation in its implementation.

Summary of Environmental Impact Data Table 4.

Cutting speed (m/min)	Driving Pressure (kPa)	CO_2 (kg)	Environmental Score
50	17.2	20.50	5.39
50	34.5	17.14	6.33
50	51.7	14.59	7.05
50	68.9	14.75	7.00
100	17.2	11.21	7.99
100	34.5	10.92	8.07
100	51.7	10.69	8.14
100	68.9	12.14	7.73
250	17.2	8.39	8.78
250	34.5	8.49	8.76
250	51.7	8.19	8.84
250	68.9	8.27	8.82
500	17.2	7.62	9.00
500	34.5	7.64	8.99
500	51.7	7.62	9.00
500	68.9	7.66	8.99

4.5. ProcSI score results

Table 5 summarizes the results of the four-cluster analysis performed under varying process conditions. Take into account that the grouping of employees' well-being and the security of the machinery's operators, for reasons already given. However, the total ProcSI score is just the average of the six sub scores, with no adjustments for importance. The optimal situation involves the maximum possible cutting speed and the lowest possible liquid nitrogen flow rate. The rate of cutting is the single most important factor in determining how well a process performs in terms of sustainability. At higher cutting speeds of 250 m/min and 500 m/min, there is little variation across the various examples with varying flow rates.

Normalized scores and total ProcSI values are summarized in Table 5.

Cutting speed (m/min)	Driving Pressure (kPa)	Cost Score	Energy Score	Waste Score	Environmental Score	*ProcSI*
50	17.2	2.00	2.00	2.00	5.39	5.232
50	34.5	2.00	2.66	2.00	6.33	5.499
50	51.7	6.01	4.09	7.17	7.05	7.387
50	68.9	6.02	4.00	7.32	7.00	7.391
100	17.2	4.00	5.98	4.00	7.99	6.996
100	34.5	5.44	6.15	5.71	8.07	7.563
100	51.7	7.05	6.28	7.58	8.14	8.175
100	68.9	2.00	5.47	2.00	7.73	6.200
250	17.2	7.89	7.57	8.00	8.78	8.707
250	34.5	7.85	7.51	8.00	8.76	8.686
250	51.7	7.72	7.68	7.90	8.84	8.689
250	68.9	7.78	7.63	8.00	8.82	8.705
500	17.2	8.00	8.00	8.00	9.00	8.832
500	34.5	7.97	7.98	8.00	8.99	8.825
500	51.7	7.95	8.00	8.00	9.00	8.825
500	68.9	7.92	7.97	8.00	8.99	8.814

5. Summary

Using the Process Sustainability Index (ProcSI) technique, a thorough analysis of the process's long-term viability is performed. Energy and materials used in production composition of consumption is a topic of discussion. In most cases, fast cutting speeds result in the most environmentally friendly results because of the high quality of the finished product and the quick processing time required. A lower coolant flow rate is preferred over a greater flow rate, despite the fact that the impact of coolant flow rate is not very significant here. Once a suitable, but little, quantity of liquid nitrogen is delivered, the cooling performance is identical to that of a greater flow rate [8]. Therefore, cryogenic machining should be used in the same manner as machining with minimal quantity lubrication (MQL) in near-dry machining if a really sustainable state is to be

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achieved. When greater cooling capacity is required, increasing the coolant flow rate is not the best option. Instead, expanding the coolant covering area to extend the coolant exposure duration is the best course of action. One of the most important challenges in cryogenic machining is figuring out how much coolant flow is needed.

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