5-21-2015

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Tao Lu
University of Kentucky, neeviour.tao.lu@uky.edu

I. S. Jawahir
University of Kentucky, is.jawahir@uky.edu

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Notes/Citation Information

Published in *Procedia CIRP*, v. 29, p. 520-525. This article was originally a part of the 22nd CIRP Conference on Life Cycle Engineering.

Digital Object Identifier (DOI)
http://dx.doi.org/10.1016/j.procir.2015.02.067

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 29 (2015) 520 – 525

www.elsevier.com/locate/procedia

The 22nd CIRP conference on Life Cycle Engineering

Metrics-based Sustainability Evaluation of Cryogenic Machining

Tao Lu[a], I.S. Jawahir[a,]*

[a]*Institute for Sustainable Manufacturing (ISM), University of Kentucky, Lexington, KY, 40506, USA*

* Corresponding author. Tel.: +1-859-323-3239; fax: +1-859-257-1071. *E-mail address:* is.jawahir@uky.edu

Abstract

Cryogenic machining is considered as the most sustainable alternative to conventional flood-cooled, near-dry and dry machining approaches in machining processes. This paper presents the application of a sustainability evaluation methodology for manufacturing processes, focusing on cryogenic machining processes. The methodology used here involves a metrics-based Process Sustainability Index (*ProcSI*) evaluation. To address the proper process conditions for cryogenic machining, different machining parameters, namely the cutting speed and the coolant flow rate, are used in the experiments as the controllable variables. The *ProcSI* assessment helps to decide on the best cutting conditions from the sustainable manufacturing viewpoint. During the evaluation procedure, the process behavior under different process conditions is considered and discussed in the analysis to understand the process mechanism and its controllability for achieving improved sustainability.

Peer-review under responsibility of the scientific committee of The 22nd CIRP conference on Life Cycle Engineering

Keywords: Sustainable manufacturing; Sustainability evaluation; *ProcSI*; Cryogenic machining;

1. Introduction

Evaluation of the impact of manufacturing processes must consider all three aspects of sustainability: economy, environment and society. It is stressed that sustainable manufacturing must demonstrate reduced negative environmental impact, offer improved energy and resource efficiency, generate minimum quantity of wastes, and provide greater operational safety and personnel health, while maintaining and/or improving the product and process quality [1]. Wanigarathne et al. [2] in their early work introduced six major interacting elements as significantly contributing to sustainable manufacturing processes as shown in Figure 1.

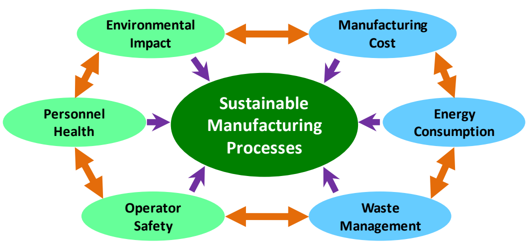

Figure 1. Six major elements of sustainable manufacturing processes [2]

Three of these six elements, manufacturing cost, energy consumption and waste management, can be modeled with analytical techniques due to their deterministic nature. Modeling of the other three elements, the environmental impact, personnel health and operator safety, due to their non-deterministic nature, would require the use of techniques such as fuzzy logic. Quantitative modeling and analysis of all six elements and integrating them to help decision making through an optimization process, require a considerable effort and case studies for validation with real practices.

This paper presents the application of a sustainability evaluation methodology for manufacturing processes, with focus on cryogenic machining processes. The methodology used here involves a Process Sustainability Index (*ProcSI*) evaluation. The metric set developed in this paper is based on the assessment of the physical behavior of the processes with total-life cycle considerations. The following section briefly reviews the *ProcSI* method. Different machining parameters, namely the cutting speed and the coolant flow rate, are used in the experiments as the controllable variables. The *ProcSI* assessment helps to decide on the best cutting conditions from the sustainable manufacturing viewpoint. During the procedure, the process behavior under different process conditions is considered to understand the process mechanism.

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2. Previous Work

Feng et al. [3] presented a review of prominent metrics and indicators for sustainability assessment in the manufacturing domain. The different methodologies are categorized based on the level of technical detail (from low to high) and the application domain (product, process, facility, corporation, sector, country and world). The categorization of these different methodologies is presented in **Error! Reference source not found.**.

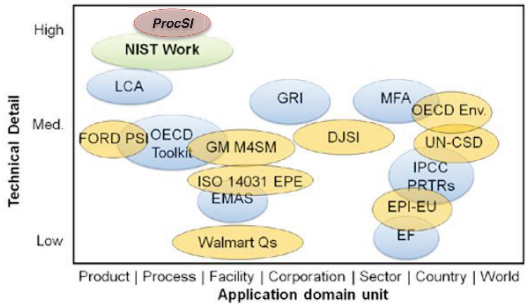

Figure 2. Categories of prominent sustainability evaluation methodologies, adapted from [3]

Despite significant effort in the past to model and understand the various individual aspects of process sustainability [4-5], no comprehensive method was attempted for evaluating the overall sustainability content of machining processes. Early work by Wanigarathne et al. [2] was subsequently extended by Granados et al. [6] by introducing a hybrid (deterministic and non-deterministic) model to evaluate machining process sustainability for optimized machining performance in near-dry machining. This work shows that more consistent sustainability evaluation can be made by developing and integrating the various science-based models with suitable optimization methods to achieve sustainable manufacturing. In general, these early attempts serve as a good foundation for quantitative understanding of the complexity of the process sustainability modeling tasks [7]. However, there is a need for a more comprehensive analysis of sustainability elements through a systematic metric-based approach, where more accurate and quantifiable data can be processed.

This leads to the development of the Process Sustainability Index (*ProcSI*) methodology. The Process Sustainability Index (*ProcSI*) is developed as a comprehensive and quantitative sustainability performance assessment methodology for universal discrete product manufacturing processes, and machining is taken as an example [8]. It serves as a process design tool to help addressing sustainability impact from a manufacturer's point of view. The major elements revisited and updated in this recent work may be summarized as follows.

The scope and system boundary are defined to help manufacturers decide the optimal manufacturing processes and the corresponding process parameters. Thus, the system boundary is set around the physical boundary of the manufacturing facility under concern [8]. The whole metric set is developed according to previously established requirements. The data flow of the *ProcSI* methodology is organized in a four-level hierarchical structure. The index is segregated into clusters, then sub-clusters and finally individual metrics. The measurements come from bottom to top, going through the procedure of normalization, weighting and aggregation. [7]. Focusing on the organization within a manufacturing facility, the *ProcSI* methodology can be applied at the operation, workstation and plant levels [8].

Cryogenic machining is an alternative to the conventional flood cooling method, with a great potential in achieving the currently best sustainability performance of a machining process [9-10]. But the process sustainability impacts of cryogenic machining due to different process parameters are not comprehensively studied. Thus an operation level study on the issue would help to establish better understanding of cryogenic machining application.

3. Experiments

The experimental setup developed for the current work is similar to that in Pu's work [11]. However, the major variables under consideration are cutting speed and coolant flow rate.

The material used in machining is hard rolled *AZ31B* magnesium alloy sheet with a 3mm thickness. The uncoated carbide inserts, type TNMG432, Kennametal tool grade K420, is held on a MTFNL2525M22 tool holder, and the tool was mounted on a Haas TL2 CNC lathe. The selected cutting speed range was from 50 m/min to 500 m/min, at a constant feed rate of 0.2 mm/rev. This will give a cutting time per workpiece ranges from approximately five seconds to fifty seconds. And the total operation time for each workpiece ranges from 27s to 71s. The machining parameters are summarized in Table 1. A custom-made, low-pressure liquid nitrogen delivery system is used. The system uses a 207kPa low pressure air compressor as mechanical power source. The flow rate at different driving pressure is calibrated based on water pumping experiments. Then the corresponding liquid nitrogen flow rate is estimated based on Darcy-Weisbach equation [12]. The operator waited till the liquid nitrogen flow becoming stable then the cutting process is carried out. The capital cost tie-up is based on 20% annual depreciation rate, as summarized in Table 2.

4. *ProcSI* Evaluation of Cryogenic Machining Process

The procedure of applying *ProcSI* evaluation on an existing machining process has been demonstrated in previous work. Collected data in the current experiments and corresponding analysis are presented here.

As there were no known differences in operator safety and personnel health issues identified, the score of the two clusters will be simply set at the full score of 10. The scrap rate is estimated based on the surface roughness measurement (quality specification) and the assumed statistical distribution. An assumed quality threshold of R_a = 0.25μm is applied and the workpiece surface quality is assumed to follow a normal distribution with variance ϵ = 0.15. The unit price of the workpiece is estimated as $14 per piece according the market value of the material.

Table 1. Machining parameters used in the experiments.

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

Scores are calculated based on normalization from internal comparison, based on a 0 to 10 scale. Unless otherwise noted, the worst case is given a score of 4 and the best case is given a score of 10. Then the behavior in between the worst and the best are normalized linearly according to the exact data range set by the worst/best cases. However, when the theoretically best and worst cases are achieved, the score of 10 and 0 are given, respectively.

There are three cases showing exceptionally high scrap rate, which may influence the effect of normalization. This is because they consume so many resources to fix the scrap parts that the differences of other parameters would only have very marginal impact on the results after normalization. In practice, such situation should not be considered as a stable process. Thus, when deciding the best and worst cases in the normalization, these cases are not considered. But, their measurements are still normalized in the same way, and if their calculated score is lower than two, a score of two out of ten is given to indicate the inappropriate process parameters.

4.1. Manufacturing cost

Only direct cost and capital cost are considered in this cluster. Labor cost, operation energy cost and coolant-related cost are considered, along with the capital cost assigned to the operation time. It should be noted that the cost data is not normalized until the cluster level, and, the normalization is done directly to the measured *Total cost*.

For the cases at low cutting speeds, the poor product quality induced by chattering is the major cost contributor. The high scrap rate behavior leads to further, prolonged cutting time, which results in a poor overall manufacturing cost performance.

The processes at higher cutting speeds benefit from both good product quality and the reduced cutting time. The reduced cutting time leads to a minimal amount of liquid nitrogen consumption, which is critical in reducing the cost. However, when the cutting time is kept minimal by applying the highest cutting speed, the difference of coolant cost at different coolant flow rates is minor.

The cost composition is summarized in Figure 2. Note that Tests 1, 5, 9 and 13, Tests 2, 6, 10 and 14, Tests 3, 7, 11 and 15, and 4, 8, 12 and 16 are conducted at driving pressures of 17.2kPa, 34.5kPa, 51.7kPa and 68.9kPa, respectively.

From the cost composition point of view, at the lower cutting speeds of 50 m/min and 100 m/min, the major contributor is the scrap loss. Even under these situations, the long cutting time requires a significant period of coolant application, which results in a significant amount of coolant consumption and the corresponding high coolant cost.

For the conditions of higher cutting speed, where the product quality (i.e., surface roughness) is no longer a problem, the coolant cost and labor cost contribute to the major part of the overall cost. It should be noted that it is based on a much reduced total cost. As a certain amount of coolant is wasted during the idling process, the different coolant flow rates have a limited impact on the total consumption of coolant. Thus, the difference of cost at different flow rates is noticeable but relatively minor. In all these conditions, the energy cost is a minor part compared to other categories.

4.2. Energy consumption

The idle energy, cutting energy and the energy spent on coolant supply system are considered here. Similar to the cost data, the energy consumption data is summed up as the total energy consumption. The normalization is done to the measured *Total energy consumption*. The idle power is considered as the fixed machine tool energy consumption when turned on but not operating, which is estimated as 200W while built-in coolant pump is not used. The power consumption for coolant delivery system is better addressed by counting the approximately 500W compressor work load and the duration of working. The cutting power ranges from 200W to 3100W at different cutting conditions.

The current system uses an external compressed air source to deliver the liquid nitrogen. This could introduce more energy consumption compared to the self-pressurized case, but in fact it saves the consumption of liquid nitrogen used as a power source. However, in the previous study the raw consumption of liquid nitrogen was not comprehensively addressed to include those used for pressurizing the tank. Also, the pump runs only when the cutting is under-going, which could potentially reduce energy consumption compared to a constantly-running pump.

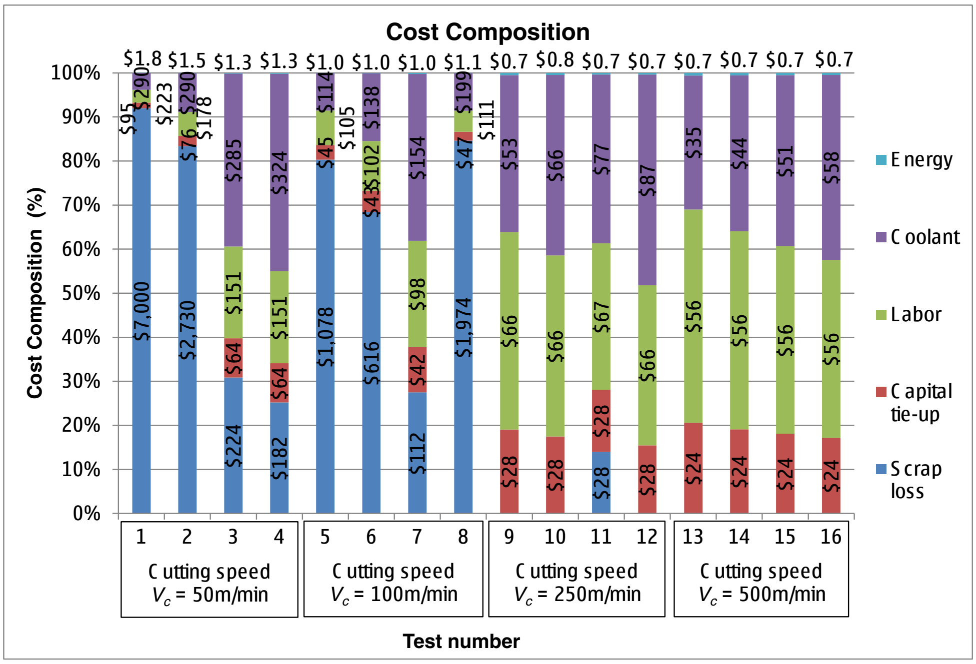

Figure 3. Cost composition at varying cutting conditions

Due the design of the liquid nitrogen system, even if the liquid nitrogen is delivered at different flow rates, most of the compressed air is released from the by-pass valve. Thus, the energy consumption rate of the delivery system remains constant at different liquid nitrogen driving pressure. Thus, it is a design flaw of the delivery system that most of the energy consumed is wasted.

The energy consumed on actual cutting is lower at lower cutting speeds, even when considering the additional number of workpieces processed due to higher scrap rate. This is caused by the lower cutting force in these cases. However, the saving of cutting energy at low cutting speed is overwhelmed by the idle power and energy consumption on coolant delivery system. The energy consumption of these two energy streams rely on the total amount of time consumed for all the work and coolant application time, respectively. As a result of the much longer cutting time consumed at low cutting speed, the low cutting speed conditions save energy at the cutting process, but lose more on idling and coolant delivery system. From the other point of view, cutting at higher cutting speeds consumes more cutting energy while saving energy consumed in other categories. The energy compositions for all the conditions are summarized in Figure 3.

From the energy composition point of view, it is evident that the cutting energy takes higher ratio at higher cutting speeds. The trend is more caused by the reduction of energy consumption in other categories, rather than the increase of cutting energy itself. From this point of view, cutting at higher cutting speeds could be considered as energy-efficient condition for both total energy consumption, and also the effective ratio of energy consumed.

4.3. Waste management

From the point of view of used coolants and chip generation, it was assumed that nothing will be changed due to different coolant applications. The chip generation is given a medium score in aggregation. The mass of scrap parts is calculated based on the calculated scrap rate and average mass of an un-machined workpiece. The comparison is summarized in Table 3.

Due to the waste streams considered here, all conditions that have no scrap parts made will lead to the optimal scores. On the other hand, it could be seen that there are very few waste streams in the case of cryogenic machining. No residue from the coolant application is one of the major advantages of cryogenic machining. To be specific, the chips from the process and the scrap parts are considered as two waste streams here, in case they are subjected to different end-of-life (EOL) treatment methods.

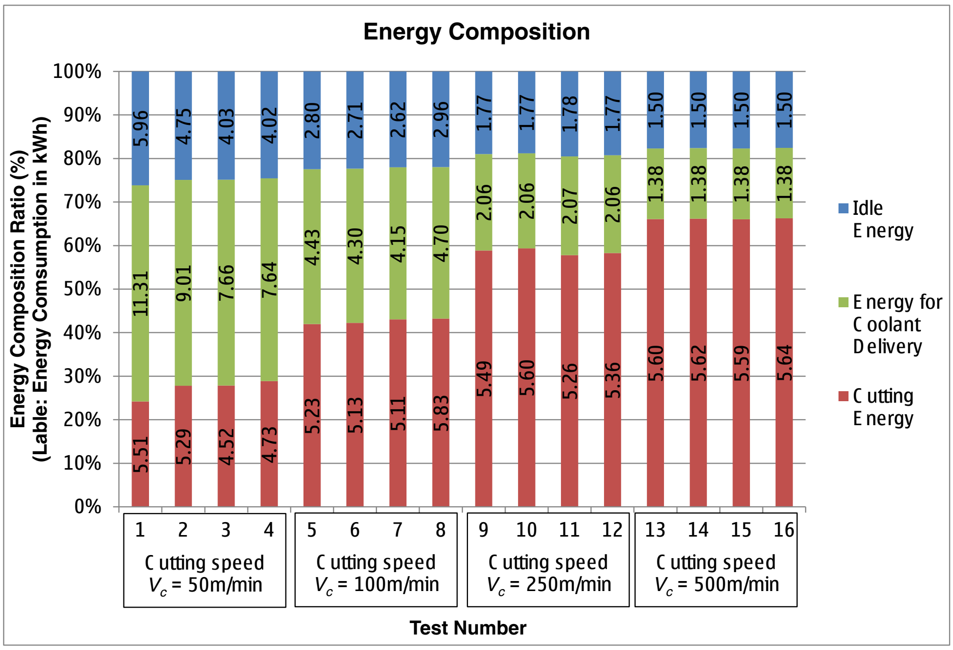

Figure 4: Energy composition of the different cutting conditions.

Table 3. Data summary for Waste Management.

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 environmental impact factor that could be addressed here is the CO_2 emission due to the energy consumption. A score of 10 is given to the sub-cluster of Restricted Material. The data is summarized in Table 4. The worst case and the best cases are shown in red and green, respectively.

As only the indirect CO_2 emission due to energy consumption is taken into calculation, the results are directly related to the total energy consumption of the process. Again, it could be seen that cryogenic machining has very limited environmental burden in its application. No restricted material usage or extra waste streams is involved in its application.

Table 4. Data summary for Environmental Impact.

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

The scores of the four clusters taken into calculation for different conditions of the process, and are summarized in Table 5. Note that a score of 10 is given to the cluster of personnel health and operator safety, respectively, as justified previously. The overall *ProcSI* score is however calculated by taking the average of all the six clusters with no weighting factors applied.

The best case among all the conditions is the one at the highest cutting speed and lowest liquid nitrogen flow rate. Cutting speed has the most obvious influence on the overall process sustainability performance. In general, all the cases with different flow rates at higher cutting speeds of 250 m/min and 500 m/min are not much different from each other.

Table 5. Summary of normalized score and the overall *ProcSI* score.

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

A comprehensive process sustainability evaluation based on the Process Sustainability Index (*ProcSI*) method is carried out. The manufacturing cost composition and energy consumption composition are discussed. In general, the conditions where high cutting speed is used give the best overall sustainability performance, due to their excellent performance in product quality and short processing time. Although the influence of coolant flow rate is not major in this case, a lower flow rate is favored against a higher flow rate. This could be understood as once a sufficient, but small amount of liquid nitrogen is applied, it will give the same cooling performance as higher flow rate [8]. Thus, to achieve a truly sustainable condition, the cryogenic machining should be applied in a similar way as the machining with minimum quantity lubrication (MQL) in near-dry machining. When more cooling capacity is needed, the solution is to enlarge the coolant coverage area to increase the coolant exposure time instead of increasing coolant flow rate. Determining the minimal, but sufficient amount of coolant flow rate is a key issue in cryogenic machining applications [8].

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