ENVIRONMENTAL BURDEN ANALYSIS DUE TO HIGH SPEED MILLING

H. Narita, H. Fujimoto
Department of Mechanical Engineering, Nagoya Institute of Technology
Gokiso-cho, Showa-ku, Nagoya, Aichi, 466-8555, Japan

Abstract
The reduction of environmental burdens is required to mitigate global warming, ozone layer depletion and etc. in manufacturing fields. Hence, prediction system of environmental burden for machining operation has been developed based on LCA (Life Cycle Assessment) policy in this research. The prediction system can evaluate cutting conditions from the view points of environmental burden due to electric consumption of machine tool components, coolant quantity, lubricant oil quantity, cutting tool status, metal chip and other factors. Global warming is selected as an impact category, and equivalent CO_2 emission including CH_4 and N_2O emissions is calculated due to a high speed milling in this paper.

Keywords: environmental burden, machine tool, high-speed milling

1 INTRODUCTION

Manufacturing technologies have been evolving with the goal of achieving high productivity, high accuracy and low cost. However, a reduction in burden to the earth's environment is indispensable, so some attempts have been carried out in recent years.

In this study, manufacturing processes are focused, and a prediction system for an environmental burden for machine tool operations, which is vital in a production system, has been developed [1] based on LCA [2] policy. Using the prediction system, the environmental burden due to a high speed milling is analyzed in this paper.

2 LITERATURE REVIEW

An evaluation system for environmental burden for machine tool operation has been developed so far [3]. This system, however, can evaluate only the difference among dry, minimal quantities of lubricant (MQL) and wet machining operations, but not that of the difference among depth of cuts, feed rate, spindle speed and tool path pattern. Furthermore, if removal volumes and a metal type are the same, the environmental burden becomes same value. In other words, the conventional evaluation system can't provide accurate environmental burden information and sufficient information for deciding the cutting conditions.

In a previous study, some eco-machining operations of a turning process were compared using the conventional evaluation system [4], but cutting conditions can't be examined in detailed. Manufacturing system planning with consideration of multi-endpoint environmental effects [5] and secondary effects of machine tools [6] have been discussed so far, but concrete evaluation methods for machining operation haven't been provided.

Hence, in order to realize true eco-friendly machining operation, an accurate evaluation system of environmental burden and analyzed results are required in the manufacturing field. Especially, high speed millings are used to manufacture many products, so this analysis results will be very important to keep productivities while reducing the environmental burdens.

3 ENVIRONMENTAL BURDEN ANALYZER

3.1 Processing flow of the analyzer

Figure 1 shows a processing flow of the developed environmental burden analyzer for machine tool operations. When workpiece & cutting tool models and NC program are input to the analyzer, all activities related to machining operation and machining process is estimated and calculate electric consumption of machine tool, cutting tool status, coolant quantity, lubricant oil quantity, metal chip quantity and so on. The analyzer output environmental burden from them using the emission intensities data and resource data, when a product is manufactured. Here, resource data means the data of machine tool spec, cutting tool spec.

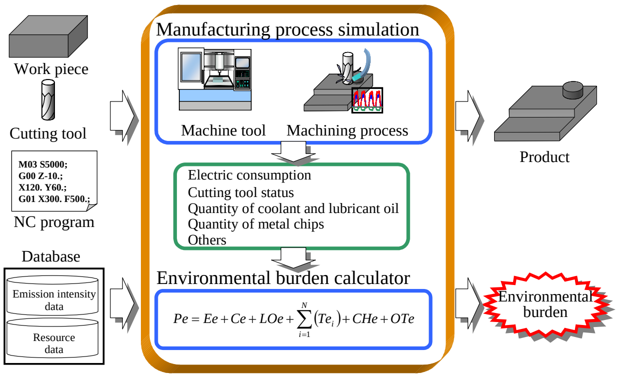

Figure 1: Processing flow of environmental burden analyzer for machine tool operations.

3.2 Calculation algorithms

Total environmental burden is calculated from the electric consumption of machine tool, coolant quantity, lubricant oil quantity, cutting tool status, metal chip quantity and other factors as shown in equation (1). The evaluation method introduced in this paper can basically be applied to all machine tool operations.

$$Pe = Ee + Ce + LOe + \sum_{i=1}^{N} Te_i + CHe + OTe \quad (1)$$

Pe: EB of machining operation [kg-GAS]
Ee: EB of erectric sonsumption of machine tool [kg- GAS]
Ce: EB of coolant [kg- GAS]
LOe: EB of lubricant oil [kg- GAS]
Te: EB of cutting tool [kg- GAS]
CHe: EB of metal chip [kg- GAS]
OTe: EB of other factors [kg- GAS]
N: Number of tool used in an NC program

EB: Environmental burden

Electric consumption of machine tool (*Ee*)

The environmental burden of the electric consumption of a machine tool is expressed as equation (2).

$$Ee = k \times (SME + SPE + SCE + CME + CPE + TCE1 + TCE2 + ATCE + MGE + VAE) \quad (2)$$

k: CO_2 Emission intensity of electricity [kg- GAS /kWh]
SME: EC of servo motors [kWh]
SPE: EC of spindle motor [kWh]
SCE: EC of cooling system of spindle [kWh]
CME: EC of compressor [kWh]
CPE: EC of coolant pump [kWh]
TCE1: EC of lift up chip conveyor [kWh]
TCE2: EC of chip conveyor in machine tool [kWh]
ATCE: EC of ATC [kWh]
MGE: EC of tool magazine motor [kWh]
VAE: Stand-by of machine tool [kWh]

EC: Electric consumption

In equation (2), the electric consumptions of auxiliary devices can be calculated from running time. But one of servo and spindle motors is varied dynamically according to a cutting force in an axis. Hence, a cutting process simulator [7], which can estimate cutting forces in each axis, is applied and one of servo and spindle motors is calculated. An output example of the simulator is shown in figure 2. Cutting coefficients, which is necessary to predict cutting forces in all axes, must be obtained in advance from a cutting test. These cutting coefficients are calculated by comparing the approximated average cutting forces, which are measured experimentally under various feed rates, with theoretical average cutting equations obtained using a cutting model. The cutting forces in all axes can be calculated under various cutting conditions, once these cutting coefficients are obtained. The validity of the cutting force model has been proven so far.

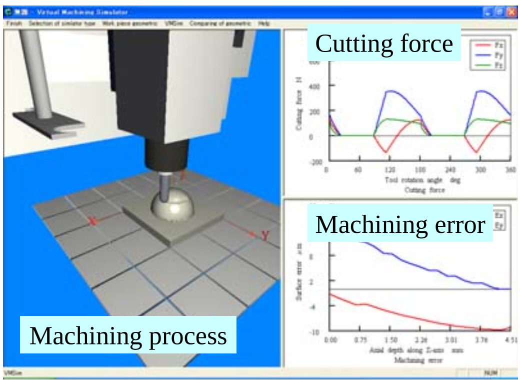

Figure 2: An output example of a cutting process simulator for end mill operations [7].

A load torque of the servo motors can be calculated as follows.

$$T_{L1} = T_U + T_M \quad (3)$$

T_{L1}: Load torque of servo motor [Nm]
T_U : Axis friction torque [Nm]
T_M : Application torque of ball screw [Nm]

Where T_U is the torque due to rubber sealing and can't be obtained theoretically, thus its value is determined experimentally. T_M is obtained from a friction coefficient of slide way, a transmissibility of ball screw system, a ball screw lead, a moving part weight and a cutting force in an axis. The load torque of the spindle motor, T_{L2}, is calculated from the cutting force model of the simulation. The calculated motor torqueses are converted to electric consumption as follows.

$$P = \frac{2\pi}{60} \times n \times T_L \times t \quad (4)$$

P: Electric consumption [Wh]
T_L: Load torque [Nm]
n: Motor rotation speed [rpm]
t: Time [hr]

The environmental burden due to various machining operations can be obtained by the aforementioned calculation.

Coolant (*Ce*)

There are two types cutting fluid, so two equations are proposed for *Ce* evaluation.

First, water-miscible cutting fluid is explained. A coolant is generally stored in a tank, and supplied to a cutting point by a coolant pump during machining. The coolant is evacuated with the metal chips, and re-stored in a tank and then reused after being separated from the chips at a catch pan. That is the coolant is circulated until the coolant is updated. Cutting oil is adhered to the metal chips, so they are reduced bit by bit until the coolant is updated. Hence, the cutting oil is supplied for compensation during this period. The dilution fluid (water) is also supplied at regular intervals due to loss through vaporization. Hence, the environmental burden due to the coolant is calculated as follows by considering the aforementioned process.

$$Ce = \frac{CUT}{CL} \times \{(CPe + CDe) \times (CC + AC) + WAe \times (WAQ + AWAQ)\} \quad (5)$$

CUT: Coolant usage time in an NC program [s]
CL: Mean interval of coolant update [s]
CPe: EI of cutting fluid production [kg- GAS /L]
CDe: EI of cutting fluid disposal [kg- GAS /L]
CC: Initial coolant quantity [L]
AC: Additional supplement quantity of coolant [L]
WAe: EB of water distribution [kg- GAS /L]
WAQ: Initial quantity of water [L]
AWAQ: Additional supplement quantity of water [L]

EI: Emission intensity

Second, water-insoluble cutting fluid is explained. In this case, discharge rate is an important factor. Hence, a following equation is applied.

$$Ce = \frac{CUT \times CS}{3600 \times 1000} \times (CPe + CDe) \quad (6)$$

CS : Discharge rate of cutting fluid [cc/h]

Lubricant oil (*LOe*)

Lubricant oil is utilized for spindle and slide way, so two equations are described. Minute amounts of oil are supplied to spindle part and slide way at decided interval time So, following equations are introduced to calculate the environmental burden due to lubricant oil. Grease lubricant is not mentioned, but almost same equations can be adopted to calculate environmental burden.

$$LOe = Se + Le \quad (7)$$

Se: EB of spindle lubricant oil [kg- GAS]
Le: EB of slide way lubricant oil kg- GAS]

$$Se = \frac{SRT}{SI} \times SV \times (SPe + SDe) \quad (8)$$

SRT: Spindle runtime in an NC program [s]
SV: Discharge rate of spindle lubricant oil [L]
SI: Mean interval between discharges [s]
SPe: EI of spindle lubricant oil production [kg- GAS /L]
SDe: EI of spindle lubricant oil disposal [kg- GAS /L]

$$Le = \frac{LUT}{LI} \times LV \times (LPe + LDe) \quad (9)$$

LUT: Slide way runtime in an NC program [s]
LI: Mean interval between supplies [s]
LV: Lubricant oil quantity supplied to slide way [L]
LPe: EI of slide way lubricant oil production [kg- GAS /L]
LDe: EI of slide way lubricant oil disposal [kg- GAS /L]

Cutting tool (*Te*)

Cutting tools are managed from the viewpoint of tool life. The cutting tools, particularly those for a solid end mill, are recovered by regrinding after reaching their life limit. In this study, environmental burden is calculated by comparing machining time with tool life and considering the aforementioned process.

$$Te = \frac{MT}{TL \times (TNR + 1)} \times ((TPe + TDe) \times TW + TNR \times RGe) \quad (10)$$

MT: Machining time [s]
TL: Tool life [s]
TPe: EI of cutting tool production [kg- GAS /kg]
TDe: EI of cutting tool disposal [kg- GAS /kg]
TW: Tool weight [kg]
T*NR*: Total number of recovery (re-grinding or dressing)
RGe: EI of re-grinding or dressing [kg- GAS]

Metal chip (*CHe*)

Metal chips are recycled in an electric heating furnace after they are accumulated and separated from the coolant. This process generates environmental burden. Input energies seems to be different for some metal types, but electric power consumption rate is represented [kWh/t] [8], so environmental burden is also calculated from the metal chip weight in this study.

$$CHe = (WPV - PV) \times MD \times WDe \quad (11)$$

WPV: Work piece volume [cm^3]
PV: Product volume [cm^3]
MD: Material density of work piece [kg/cm^3]
WDe: EI of metal chip processing [kg- GAS /kg]

3.3 System development

An environmental burden analyzer for machine tool operations shown in figure 3 has been developed on the basis of the aforementioned algorithms. The left part of the figure shows the machining process and right part of the figure shows calculated results of environmental burden. The developed system can simulate not only end milling processes but also turning, drilling and grinding processes with using respective cutting models.

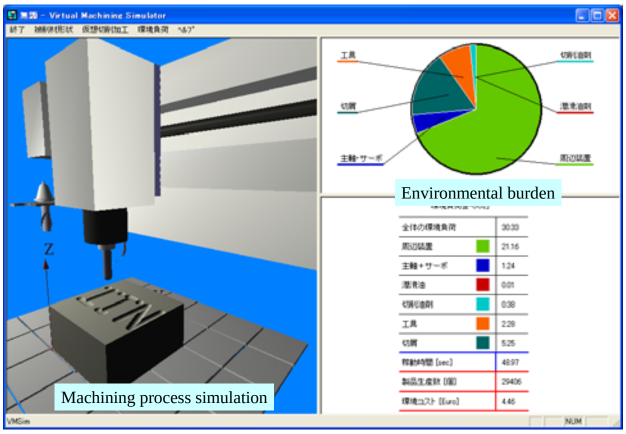

Figure 3: An output example of the environmental burden analyzer for machine tool operations.

4 CASE STUDY

4.1 A comparison of cutting conditions

This study focuses the global warming, so CO_2, CH_4 and N_2O are evaluated based on Japanese data. Here, global warming potential of 100 years [9] shown in table 1 is considered and equivalent CO_2 emission is evaluated as an environmental burden.

Table 1: Characterization factors of global warming [9].

	CO_2	CH_4	N_2O
Global warming potential	1	21	310

Emission intensities to predict the environmental budden in table 2, respectively. These data are obtained from enrironmental reports, technical reports, web sites and industrial tables [8, 10, 11, 12, 13]. Other parameters such as running conditions are summarized in table 3.

In order to show the feasibility of environmental burden analyzer, two NC programs manufacturing same product shape are evaluated, because conventional evaluation system can not be evaluated this kind of comparison. In this case study, machine tool is vertical machinng center (OKUMA Corp.), a cutting tool is carbide square end mill with 2 flutes, 12 mm diameter and 30 deg. helical angle and a workpiece is midium carbon steel (S50C).

A machined shape and a tool path pattern are shown in Figure 4. A spindle speed and a feed rate are 2500 rpm and 200 mm/min, respectively. A dry machining and a wet machining is compared. The cutting oil, wchich is water miscible type, is also used in the wet machining.

Table 2: Equivalent CO_2 emission intensities

Electricity[kg-CO_2/kWh]	0.381
Cutting fluid production [kg-CO_2/L]	0.9776
Cutting fluid disposal [kg-CO_2/L]	0.0029
Dilution fluid (water) [kg-CO_2/L]	0.189
Lubricant oil production [kg-CO_2/L]	0.469
Lubricant oil disposal [kg-CO_2/L]	0.0029
Cutting tool production [kg-CO_2/kg]	33.7478
Cutting tool disposal [kg-CO_2/kg]	0.01346
Re-grinding [kg-CO_2/number]	0.0184
Metal chip processing [kg-CO_2/kg]	0. 195

Table 3: Other parameters related to evaluation factors

Initial coolant quantity [L]	8.75
Additional supplement of coolant [L]	4.3
Total quantity of dilution fluid [L]	257.25
Mean interval between replacements of coolant in pump [Month]	5
Discharge rate of spindle lubricant oil [mL]	0.03
Mean interval between discharges for spindle lubrication [s]	480
Lubricant oil supplied to slide way[mL]	228
Mean interval between supplies [hour]	2000
Tool life [s]	5400
Total number of re-grinding	2
Material density of cutting tool [g/cm^3]	11.9

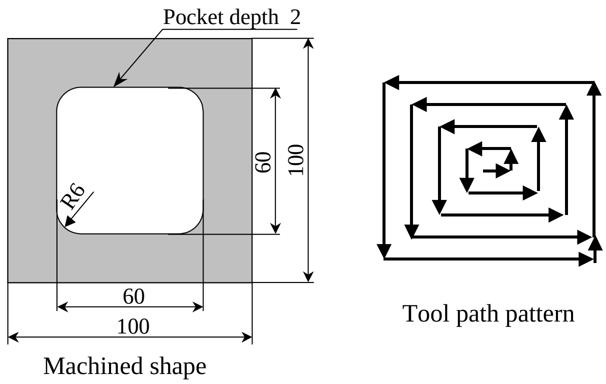

Figure 4 Product shape and tool path pattern.

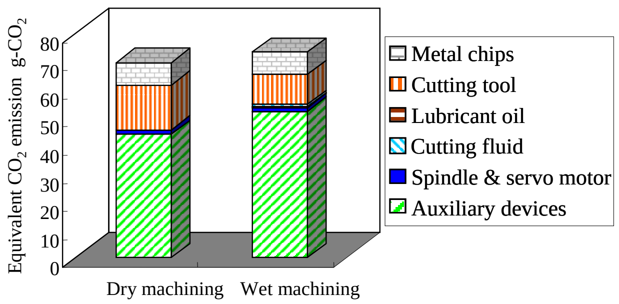

Figure 5: Analyzed equivalent CO_2 emission of a dry machining and a wet machining.

Calculated results of environmental burden analyzer are shown in figure 5. Here, it is assumed that tool life is extended to 2 times of original one. As shown in the figure, equivalent CO_2 emission of Program 2 is smaller than one of Program 1. So, this kinds of comparison, which can not be realized by conventional evaluation system, can be achieved by developed environmental burden analyzer. By the way, CO_2 emission and equivalent CO_2 emission of CH_4 and N_2O are compared. These are related to environmental burden of cutting fluid. Equivalent CO_2 emission of them is less than 0.001 of total CO_2 emission. In other word, CO_2 is dominant environmental burden in machining operation about the global warming.

4.2 Analysis for a high-speed milling

In order to verify the effect of high-speed milling, the equivalent CO_2 emission due to the simple machining operation is analyzed. a cutting tool is carbide square end mill with 2 flutes, 10 mm diameter and 30 deg. helical angle and a workpiece is SKD61. A radial depth of cut is 0.5 mm, an axial depth of cut is 5 mm, a cutting direction is the down cut and the coolant isn't used. A spindle speed and a feed rate are changed to a fixed feed per tooth of 0.02 mm/tooth. A cutting length is 1000 mm. Tool wear data is obtained in advance from cutting tests. Here, tool life is judged based on width of a flank wear land and upper limit of the flank wear is decided to 0.045 mm in this research.

Analyzed results are shown in figure 6. As shown in the figure, the equivalent CO_2 emission of the auxiliary devices decreases, but the one of the cutting tool increase as the spindle speed increase. That is to say there is a minimum point to realize the minimum environmental burden. The cutting time shorten due to the high speed millings, so the one of auxiliary devices decreases. However, the tool wear increases due to the high speed millings, so the one of the cutting tool increase. Thus, we can decide a cutting condition realizing the lowest environmental burden using tool wear information provided by cutting tool makers.

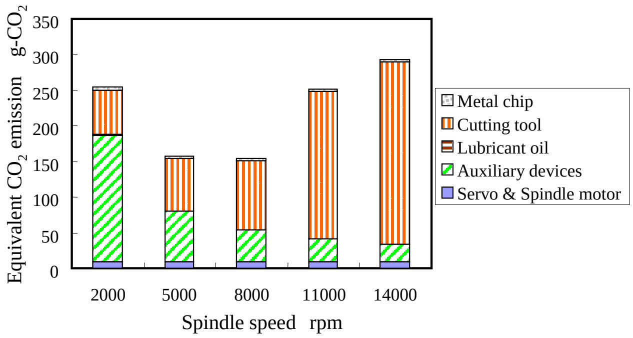

Figure 6: Analyzed equivalent CO_2 emission due to high speed millings.

5 CONCLUSIONS

1) An environmental burden analyzer for machine tool operations has been developed.
2) High-speed millings are analyzed based on tool wear information. The possibility that we can decide a cutting condition realizing the lowest environmental burden is demonstrated.

6 ACKNOWLEDGMENTS

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