Environmental Burden Analysis for Machining Operation Using LCA Method

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Abstract

We have developed an environmental burden analyzer for machine tool operations, which can evaluate an NC program from the view point of an environment burden by simulating a cutting process and using emission intensities. In this paper, global warming is selected as an impact category and the environmental burden analysis of dry, wet and MQL machining operations are carried out by using this analyzer with consideration of various situations. The influence of the peripheral devices of a machine tool, the spindle and the servo motors, the coolant, the lubricant oil, the cutting tool and the metal chips to global warming is introduced in detail.

Keywords:
Environmental burden, Machine tool, LCA, End mill operation

1 INTRODUCTION

Due to the recent requirement of the environmental protection, some approaches are tried for manufacturing processes [1, 2]. The concrete evaluation methods for machining operations, however, haven't been provided, yet. That is to say the detailed cutting conditions can't be evaluated by the conventional system.

In this research, an environmental burden analyzer for machine tool operations, which can calculates the accurate environmental burden, is developed based on LCA (Life Cycle Assessment) concept. Then, The influence of the peripheral devices of a machine tool, the spindle and the servo motors, the coolant, the lubricant oil, the cutting tool and the metal chips to global warming is analyzed in detail. The cutting fluid type and the disposal process of the cutting fluid are especially considered in this paper.

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2 ENVIRONMENTAL BURDEN ANALYZER FOR MACHINE TOOL OPERATIONS

2.1 System overview

Conventional commercial analysis systems can evaluate just compare the differences of dry, wet, semi-dry machining, but this can't evaluate the differences of other cutting conditions such as depth of cuts, feed rate, tool path patter, etc. Furthermore, if the removal volume and the material type are same, environmental burden is calculated to same value. In other word, the conventional evaluation system can't provide enough information to decide the machining strategies. The analyzer developed in this research can solve the aforementioned problems.

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

This study focuses global warming, hence CO_2, CH_4 and N_2O are evaluated based on Japanese data. Here, global warming potential of 100 years [3] shown in table 1 is considered and equivalent CO_2 emission is evaluated as the environmental burden.

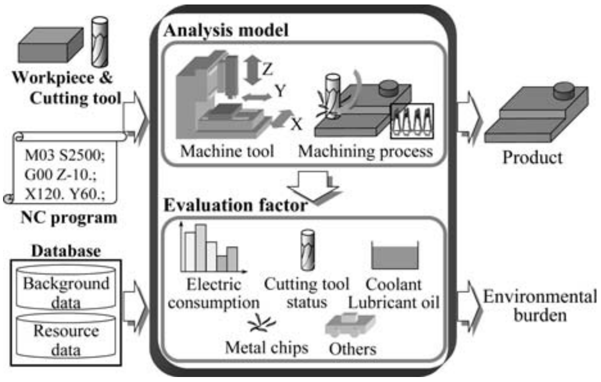

Figure 1: Processing flow of the developed environmental burden analyzer for machine tool operations.

Table 1: Characterization factors of global warming [3]

	CO_2	CH_4	N_2O
Global warming potential	1	21	310

2.2 Calculation algorithm for environmental burden

Total environmental burden is calculated from the following equation in this research.

$$Pe = Ee + Ce + LOe + \sum_{i=1}^{N} Te_i + CHe \tag{1}$$

Pe: EB of machining operation [kg-CO_2]
Ee: EB of machine tool component [kg-CO_2]
Ce: EB of coolant [kg-CO_2]
LOe: EB of lubricant oil [kg-CO_2]
Te: EB of cutting tool [kg-CO_2]
CHe: EB of metal chip [kg-CO_2]
N: Number of tool used in an NC program
EB: Environmental burden

Electric consumption of machine tool (*Ee*)

The environmental burden due to the electric consumption of machine tool is calculated as follows.

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

k: EI of electricity [kg-CO_2/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]
*ATC*E: EC of ATC [kWh]

EI: Emission intensity
EC: Electric consumption

In equation (2), the electric consumption of peripheral devices can be calculated from a running time. But one of servo and spindle motors is varied dynamically according to the machining process. Hence, a cutting force and a cutting torque models [4] are applied to estimate the electric consumption for these motors.

Coolant (*Ce*)

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

First, water-miscible cutting fluid is explained. The coolant is generally circulated by coolant pump until coolant is updated. The cutting fluid is adhered to the metal chips, hence they are reduced bit by bit until the coolant is updated. Hence, the cutting fluid is supplied for compensation during this period. The dilution fluid (water) is also supplied at regular intervals due to loss through vaporization. Here, the environmental burden due to the coolant is calculated as follows by considering the aforementioned process.

$$Ce = \frac{CUT}{CL} \times \left\{ \begin{array}{r} (CPe + CDe) \times (CC + AC) \\ + WAe \times (WAQ + AWAQ) \end{array} \right\} \tag{3}$$

CUT: Coolant usage time in an NC program [s]
CL: Mean interval of coolant update [s]
CPe: EI of cutting fluid production [kg-CO_2/L]
CDe: EI of cutting fluid disposal [kg-CO_2/L]
CC: Initial coolant quantity [L]
AC: Additional supplement quantity of coolant [L]
WAe: EB of water distribution [kg-CO_2/L]
WAQ: Initial quantity of water [L]
AWAQ: Additional supplement quantity of water [L]

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

$$Ce = \frac{CUT \times CS}{3600 \times 1000} \times (CPe + CDe) \tag{4}$$

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

Lubricant oil (*LOe*)

The lubricant oil is mainly used for a spindle and a slide way, so two equations are introduced. Minute amounts of oil is infused to the spindle part and the slide way in decided intervals. Hence, the following equations are adapted to calculate the environmental burden due to lubricant oil. Here, grease lubricant is not mentioned, but same equations can be adapted.

$$LOe = Se + Le \tag{5}$$

Se: EB of spindle lubricant oil [kg-CO_2]
Le: EB of slide way lubricant oil kg-CO_2]

$$Se = \frac{SRT}{SI} \times SV \times (SPe + SDe) \tag{6}$$

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-CO_2/L]
SDe: EI of spindle lubricant oil disposal [kg-CO_2/L]

$$Le = \frac{LUT}{LI} \times LV \times (LPe + LDe) \tag{7}$$

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-CO_2/L]
LDe: EI of slide way lubricant oil disposal [kg-CO_2/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.

$$Te = \frac{MT}{TL \times (TNR + 1)} \times ((TPe + TDe) \times TW + TNR \times RGe) \tag{8}$$

MT: Machining time [s]
TL: Tool life [s]
TPe: EI of cutting tool production [kg-CO_2/kg]
TDe: EI of cutting tool disposal [kg-CO_2/kg]

TW: Tool weight [kg]
T*NR*: Total number of recovery (re-grinding or dressing)
RGe: EI of re-grinding or dressing [kg-CO_2]

Metal chip (*CHe*)

Metal chips are accumulated, and coolant is separated from them. Then, they are recycled to material by electric heating furnace. This materialization process has to be considered. This equation is supposed to consider material kind, but electrical intensity of this kind of electric heating furnace is represent by kWh/t [5], so equation constructed in this research is calculated from total metal chip weight.

$$CHe = (WPV - PV) \times MD \times WDe \quad (9)$$

WPV: Workpiece volume [cm^3]
PV: Product volume [cm^3]
MD: Material density of workpiece [kg/cm^3]
WDe: EI of metal chip processing [kg-CO_2/kg]

3 NUMERICAL EXAMPLE

3.1 Parameter setting

Emission intensities related to evaluation factors are summarized in table 2. These values are listed from some reports, which are environmental report, technical report, home page and industrial table [5, 6, 7, 8, 9, 10, 11, 12]. About these data, production and disposal processes are considered and transportation and other processes are ignored, because these values are different by users.

We would like to focus the coolant influences to the environment in this paper, hence the emission intensities related to cutting fluid is summarized in detail. Regarding to the water-miscible cutting fluid, the disposal process related to A1, A2 and A3 types, and the distilling and condensing process are considered. The distilling and condensing process, which is often used recently, can be applied for all type of the water-miscible cutting fluid.

In order to decide the emission intensities of them, the electric consumption of the processing devices and the emissions due to the thermal disposal are investigated. Regarding to the water- insoluble cutting fluid, the thermal and the material recycles are considered. For the thermal recycle, the CO_2 emission of the disposal process is reduced by the electric consumption due to the calorific value of the waste oil. For the material recycle, the emission due to the thermal disposal is eliminated.

3.2 Comparison of cutting method

For the numerical example, the machine tool is MB-46VA (OKUMA Corp.), the cutting tool is carbide-square end mill with 10 mm diameter, two-flute and a 30° helical angle, and the workpiece is mideum carbon steel (S50C). The parameters of MB-46VA peripheral devices are shown in table 3 and other parameters input by machine tool users shown in table 4.

Figure 2 shows the product shape and the tool path pattern used for the evaluation. The spindle speed is 2500 rpm and the feed rate is 200 mm/min. Here, the tool life is assumed to be increased to twofold the original one due to the coolant effect.

Table 2: CO_2 Emission intensities

Electricity[kg-CO_2/kWh]	0.381
Cutting fluid production [kg-CO_2/L]	0.469
Cutting fluid disposal (water-miscible cutting fluid;A1 type) [kg-CO_2/L]	3.782
Cutting fluid disposal (water-miscible cutting fluid;A2 type) [kg-CO_2/L]	5.143
Cutting fluid disposal (water-miscible cutting fluid; A3 type) [kg-CO_2/L]	8.103
Cutting fluid disposal (distilling and condensing process) [kg-CO_2/L]	3.425
Cutting fluid disposal (water-insoluble cutting fluid: normal) [kg-CO_2/L]	2.555
Cutting fluid disposal (water-insoluble cutting fluid: thermal recycle) [kg-CO_2/L]	1.778
Cutting fluid disposal (water-insoluble cutting fluid: material recycle) [kg-CO_2/L]	0.261
Dilution fluid (water) [kg-CO_2/L]	0.189
Spindle and slide way lubricant oil production [kg-CO_2/L]	0.469
Spindle and slide way 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]	0.0634

Table 3: Electric consumption of peripheral devices

NC controller [kW]	0.16
Cooling system of spindle [kW]	0.45
Compressor[kW]	1
MQL compressor[kW]	0.75
Coolant pump[kW]	0.25
Lift up chip conveyor[kW]	0.1
Chip conveyor in machine tool [kW]	0.6
ATC [Wh]	0.08
Tool magazine[Wh] (1 round)	0.087
Vampire energy[kW]	0.64

Table 4: Other parameters related to evaluation factor

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
Discharge rate for coolant of MQL[mL/h]	7
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
Material density of workpiece [g/cm^3]	7.1
Air blow for MQL [NL/min]	150
Air pressure of MQL [MPa]	0.7

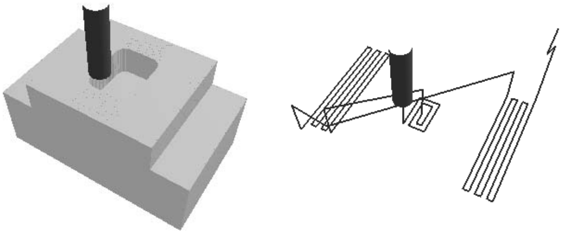

Figure 2: Machined shape and tool path pattern

Analyzed results are shown in figure 3. The MQL machining is preferable for this machining operation. When we use this evaluation system, we can decide the cutting conditions realizing the minimum environmental burden.

The electric consumption of the peripheral devices of the machine tool, except for the servo motors and the spindle motor and the cutting tool are the main factors in the machining operation from the viewpoint of global warming.

Anyway, the emission intensities of the coolant are very different and not small, however the environmental burden of the coolant is small. It is found that the values of the peripheral devices and the cutting tool must be reduced in order to reduce the equivalent CO_2 emission effectively.

Futhermore, the comparison of the impacts of CO_2, CH_4 and N_2O is carried out. CH_4 and N_2O emissions are occured by the thermal disposal. The impacts of CH_4 and N_2O calculated from table 1 correspond to below 0.001 g-CO_2 by comparing the amount of the emission of each condition. In other words, CO_2 is the dominant environmental burden in the machining operation concerning global warming.

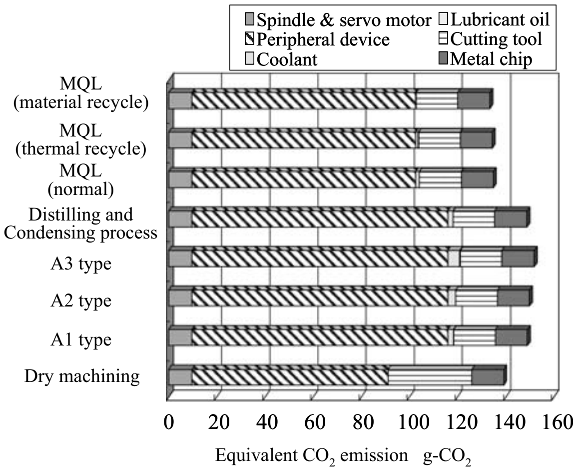

Figure 3: Analyzed environmental burden results of numerical example

4 CONCLUSIONS

1) The environmental burden analyzer for machine tool operations was introduced.
2) The influence of the peripheral devices of a machine tool, the spindle and the servo motors, the coolant, the lubricant oil, the cutting tool and the metal chips to global warming was analyzed. The electric consumption of the peripheral devices of the machine tool and the cutting tool is the main factors in the machining operation when an impact category is global warming.
3) CO_2 is the dominant environmental burden in machining operation concerning global warming by comparing CO_2 emission with the equivalent CO_2 emission of CH_4 and N_2O.

5 REFERENCES

[1] Sheng, P., Bennet, D., Thurwachter, S., / B.F. von Turkovich, 1998, Environmental-Based Systems Planning for Machining, Ann. of the CIRP, 47/1, 409-414.

[2] Shimoda, M., LCA Case of Machine Tool, Symposium of 2002 Japan Society for Precision Engineering Spring Annual Meeting “Leading-Edge Trend of Environmental Impact Evaluation for Inverse Type Design and Manufacturing”, (2000), 37-41, (in Japanese).

[3] Japan Meteorological Agency, 1995, Climate Change 1995, Science of Climate Change.

[4] Narita, H., Shirase, K., Wakamatsu, H., Tsumaya, A. and Arai, E., 2002, Real-Time Cutting Simulation System of a Milling Operation for Autonomous and Intelligent Machine Tools, Int. J. of Production Research, 40, 15, 3791-3805.

[5] Mizukami, H., Yamaguchi, R., Nakayama, T., Maki, T., 2002, Off-gas Treatment Technology of ECOARC, NKK Technical Report, No.176, 1-5, (in Japanese).

[6] Tokyo Electric Power Company, 2005, The Earth, People & Energy TEPCO Sustainability Report 2004.

[7] Tokyo Waterworks, 2003, Environmental Report of Tokyo Waterworks 2002. (in Japanese)

[8] Nansai, K., Moriguchi, Y. and Tohno, S., 2002, Embodied Energy and Emission Intensity Data for Japan Using Input-Output Tables (3EID)–Inventory Data for LCA-, Center for Global Environment Research, National Institute of Environmental Studies, Japan.

[9] New Energy and Industrial Technology Development Organization (NEDO), 2003, Development of Environment-Conscious Technology Laboratory, First Section Meeting of “Development of Energy Saving Wastewater Treatment Technique”, Program Original Register of Development of Energy Saving Wastewater Treatment Technique, (in Japanese)

[10] Ministry of Economy, Trade and Industry, 2002, About Declaration of Evaluation Report related to Budget Request in Fiscal Year 2002 (Policy Evaluation), Section 6 Construction of Industrial Facilities (Regional Economic Industry U), Development of Wastewater Treatment Technique, (in Japanese).

[11] Osaka prefecture, 2004, Osaka prefectural statistical yearbook, (in Japanese)

[12] Touma, S., Ohmori, S., Kokubo, K., Tateno, M., 2003, Evaluation of Environmental Burden in Eco-friendly Machining Method using Life Cycle Assessment Method – Estimation of Carbon Dioxide Emission in Eco-friendly Turing Method– J. of JSPE, 69, 6, 825-830, (in Japanese).