공학석사학위논문

선반 공작기계의 에너지 소비 모델 수립 및 저감 전략

Modeling of Specific Energy Consumption and Reduction Strategies for Lathe Machine Tools

2015년 8월

서울대학교 대학원

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Modeling of Specific Energy Consumption and Reduction Strategies for Lathe Machine Tools

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Owing to the increasing price of energy sources and global environmental regulation such as carbon dioxide emissions, reduction of energy consumption is currently at the top of the global issue in manufacturing industry. Especially, a machine tool uses electricity whose major source is coal or natural gas that contributes largely to the increase of carbon dioxide level. Thus, a machine tool needs to adopt more energy-efficient techniques. This study focuses on controlling cutting parameters without any replacement of hardware components of a machine tool to improve the energy efficiency. The aim of this research is to develop new models and methodologies to reduce the energy consumption and manufacturing costs in turning process on lathe machine tools. The energy consumption model was composed of basic, stage, spindle and machining components, and was clearly described in terms of cutting parameters. Similar to the energy consumption model, the manufacturing cost model was comprised of the energy costs and the tool life, concretized by cutting parameters. This resulting model was verified by empirical approaches using measured data. The constructed model fitted the measured data well on various lathe machine tools. Using the model, two optimum cutting parameters reducing the energy consumption and manufacturing cost were obtained respectively. Therefore, the model is applicable for the working of a process planner based on energy-saving or cost cutting strategies.

Keywords: Energy consumption model, Material removal rate, Modeling, Reduction strategies and Optimum parameters

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Chapter 1. Introduction

1.1 Background

Owing to the increasing price of energy sources and global environmental regulation such as carbon dioxide emissions, reduction of energy consumption is currently at the top of the global issue in manufacturing industry [1]. In 2012, 61.8% of total energy consumption in U.S. consisted of electric power plant and industry which employs 99.8% of coal and 69% of natural gas annually as primary energy source [2]. A machine tool is operated by electricity whose major source is coal or natural gas that contributes largely to the increase of carbon dioxide and other greenhouse gases [3]. Thus, a machine tool needs to adopt more energy-efficient techniques.

Regarding the strategies and technologies for improvement of the energy efficiency of machine tools, efficiency improvements of machine tools can be categorized into direct and indirect methods. Direct methods include controlling the cutting conditions and hardware replacement such as a spindle motor or frames. Indirect methods include improvements of quality or productivity [4].

This study focuses on controlling cutting parameters without any replacement of hardware components of machine tools to improve the energy efficiency. In order to achieve this, first of all, total energy profiles in machine tools are decomposed into each component. And then, an energy equation of each component should be developed. Finally, total energy consumption and cost models can be derived and optimum cutting conditions can be calculated.

1.2 Decomposition of energy consumption profiles

Being measured at the main supply power, energy consumption profiles of machine tools represent overall consumption energy of all components included in machine tools. So, total energy profiles of machine tools are decomposed into each component. Energy consumption of each component could be measured directly or indirectly by measurement procedure. In Figure 1.1, the graph on the left shows a typical energy consumption profile. After decomposition, this graph is divided into four components such as basic, spindle, stage and machining energy.

Table 1 shows the decomposition of energy components by related works. Many researchers have strived to decompose the energy consumption profiles in detail. Kordonowy divided energy consumption for milling process into constant power in startup process and runtime operations and variable machining power [5]. Park *et al.* defined that energy profiles consist of fixed power within pure grinding and idling time and variable power within pure grinding time [6]. Neugebauer *et al.* [7], Santos *et al.* [8] and Salonitis *et al.* [9] divided energy consumption profiles into stand-by energy consumption in constant and additional energy consumption during machining process. He *et al.* defined stage energy in addition to basic and machining energy [10]. Li *et* *al* defined specific energy consumption which means energy consumption per unit cutting volume such as specific fixed energy, specific operational energy and specific tooltip energy [11]. Furthermore, Yoon *et al.* [12] , Campatelli *et al.* [13] and Jia *et al.* [14] divided the energy consumption profiles into basic, stage, spindle and machining energy. In this research, the definition of Yoon *et al.* is adopted into the derived energy consumption model.

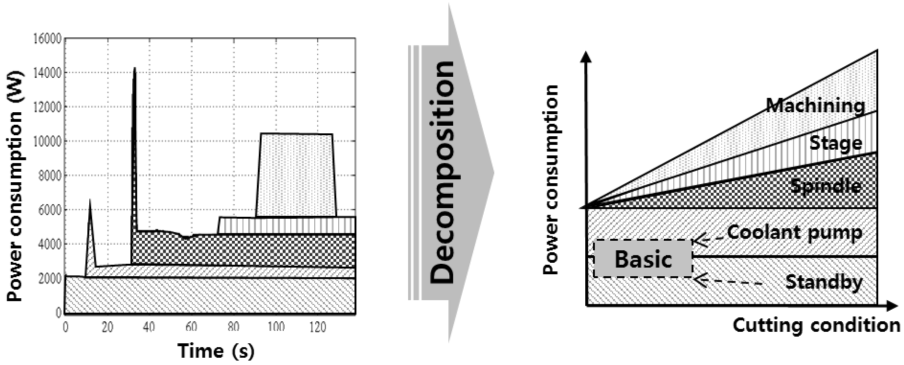

Figure 1.1 Decomposition of typical power consumption profile

Table 1 Decomposition of energy components by related works

Energy components	**Basic energy**	**Momentum energy**		**Additional process energy**
Author(s)	E_{basic}	E_{stage}	$E_{spindle}$	$E_{machining}$
Kordonowy (2002, [5])	Constant power in startup process and runtime operations	Variable machining power		
Park et al. (2009, [6])	Fixed power within pure grinding and idling time	Grinding (variable) power within pure grinding time		
He *et al.* (2011, [10])	$E_{tool} + E_{fix} + E_{cool}$	E_{feed}	$E_{spindle} = E_{motor} + E_{cutting}$	
Li *et al.* (2011, [11])	SFE (specific fixed energy)	SOE (specific operational energy)		STE and SUE (specific tooltip energy, specific unproductive energy)
Neugebauer *et al.* (2011, [7])	$E_{machine}$			$E_{process}$
Santos *et al.* (2011, [8])	$E_{stand\text{-}by}$	$E_{work\ mode}$		
Salonitis *et al.* (2013, [9])	$E_{background} = E_{peripherals} - E(load)$	$E_{process} + E(load)$		
Yoon *et al.* (2013, [12])	E_{basic}	E_{stage}	$E_{spindle}$	$E_{machining}$
Campatelli *et al.* (2014, [13])	E_{idle}	$E_{axes\text{-}movement}$	$E_{spindle}$	$E_{machining}$
Jia *et al.* (2014, [14])	$E_{total} - E_{activity}$	E_{feed}	$E_{spindle}$	$E_{machining}$

1.3 Set up of an energy consumption equation

Founded on energy decomposition, energy consumption of each component could be calculated through cutting parameters such as cutting speed (V_c), feed rate (f_r) and depth of cut (a_p). In Figure 1.2, power and time of each component can only be expressed by cutting parameters in machining process. So, an energy consumption equation which is well simplified consists of only cutting parameters and some coefficients, as follows:

$$E_{total} = \sum_{i=0}^{n} P_i \times t_i \xrightarrow{\text{simplified}} = f(V_c, f_r, a_p, C_i) \quad (1.1)$$

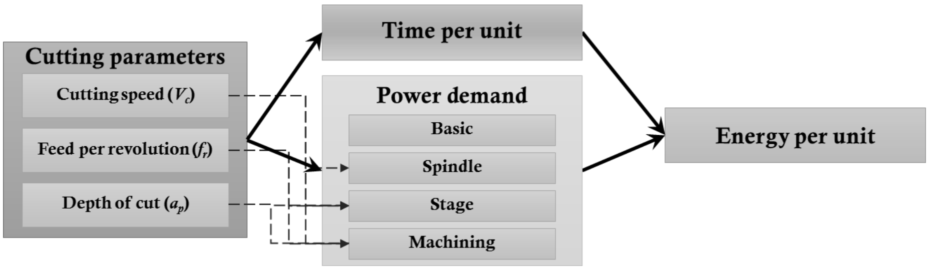

Figure 1.2 Influence of cutting parameters on the energy per unit manufactured (redrawn with specific cutting parameters from Diaz *et al.* [15])

1.4 Characteristics and limitations of current energy models

Numerous researches have derived energy consumption models of machine tools and put efforts to build energy saving strategies. Table 2 and Table 3 show energy consumption models by related works and a summary of these models. In terms of various energy consumption models in its entirety, the characteristics will be analyzed and the limitations of these models will be sought.

The graph in Figure 1.3 was drawn in accordance with the energy consumption models of Table 2 and Table 3. In this graph, the x-axis and y-axis represent decomposition of energy components and correlation of energy equation variables, respectively. As chapter 1.2, decomposition of energy components means how many components an energy consumption profile was divided into. As chapter 1.3, high correlation of energy equation variables represents an energy consumption equation which is well simplified and consists of only cutting parameters and some coefficients.

Looking at this graph, there are some limitations. Especially, the more decomposed energy equation, the lower the correlation of variables. For example, on the top of y-axis, the equations consist of only cutting parameters like Kara *et al*. [16] and Guo *et al*. [17]. But, on the right of x-axis, the well decomposed equations consist of inaccurately undefined time and power like Calvanese *et al*. [18] owing to the complexity of energy consumption equation of each component.

Table 2 A summary of other energy consumption models – part 1

Author(s)	Summary of energy model
Draganescu *et al.* (2003, [19])	$E_{cs} = \frac{P_c}{60\eta Z}$ where P_c is the necessary cutting power at main spindle (kW), η is the machine tool efficiency, Z is the materal removal rate (cm^3/min), and E_{cs} is the specific consumed energy (kw h/cm^3)
Gutowski *et al.* (2006, [20])	$E_{total} = (P_o + k\dot{v}) \times t$ where P_o is idle power (kW), $\dot{v}$ is the rate of material processing (cm^3/s), k is a constant with units of kJ/cm^3 and t is total time (s)
Rajemi *et al.* (2010, [21])	$E_{total} = P_o t_1 + (P_o + k\dot{v})t_2 + P_o t_3 (\frac{t_2}{T}) + y_E (\frac{t_2}{T})$ where P_o is power consumed by machine modules without the machine cutting (W), t_1 is machine setup time (s), $P_o + k\dot{v}$ is the same as the equation of Gutowski *et al.*, t_2 is actual cutting time (s), t_3 is tool change time (s), T is tool-life (s) and y_E is energy footprint per tool cutting edge (J)
Diaz *et al.* (2011, [22])	$E_{total} = (P_{cut} + P_{air})\Delta t$ where P_{cut} is the cutting power, P_{air} is air cutting and Δt is processing time (s)
Kara *et al.* (2011, [16])	$E_{machining} = SEC \times V = (C_o + \frac{C_1}{\text{MRR}}) \times V$ where SEC is specific energy consumption which means energy per cutting volume, C_o and C_1 are the machine specific coefficients and V is cutting volume
Kong *et al.* (2011, [23])	$E_{total} = E_{const} + E_{run-time-transient} + E_{run-time-steady} + E_{cut}$ where E_{const} is constant energy without cutting (J), E_{cut} is cutting energy (J), $E_{run\text{-}time\text{-}transient}$ is the transient run-time energy (J) and $E_{run\text{-}time\text{-}steady}$ is the steady run-time energy (J). $E_{run\text{-}time\text{-}transient}$ and $E_{run\text{-}time\text{-}steady}$ are dependent on the cutting parameters (feed rate and spindle speed)
Mori *et al.* (2011, [24])	$E_{total} = P_1(T_1 + T_2) + P_2(T_2) + P_3(T_3)$ where P_1 is the constant power consumption during the total machine operation (W), T_1 is the cycle time during non-cutting state (h), T_2 is the cycle time during cutting state (h), P_2 is the power consumption for cutting process (W), P_3 is the power consumption to position the work and to accelerate/decelerate the spindle (W) and T_3 is the cycle time during P_3 state (s)
Guo *et al.* (2012, [17])	$E_{total} = \left(C_0 \cdot v_c^{\alpha} \cdot f^{\beta} \cdot a_p^{\gamma} \cdot D^{\varphi} + \frac{C_1}{v_c \cdot f \cdot a_p} \right) \times V$ where v_c is cutting speed (m/min), f is feed rate (mm/rev), a_p is depth of cut (mm), D is final work piece diameter (mm) and the constant values of $C_0, C_1, \alpha, \beta, \gamma$ and φ for steel are obtained and represent 1.9205, 85.4442, 0.4486, -0.6851, -0.8214 and -0.0840, respectively

Table 3 A summary of other energy consumption models – part 2

Author(s)	**Summary of energy model**
He *et al*. (2011, [10])	$$E_{total} = E_{spindle} + E_{feed} + E_{tool} + E_{cool} + E_{fix} = \int_{t_{ms}}^{t_{me}} p_m \cdot \mathrm{d}t + \int_{t_{cs}}^{t_{ce}} p_c \cdot \mathrm{d}t + \sum_{i=1}^{m} \int_{t_{fs_i}}^{t_{fe_i}} p_i \cdot \mathrm{d}t + p_{tool} \cdot t_{tool} + p_{cool} \cdot (t_{coe} - t_{\cos}) + (p_{servo} + p_{fan}) \cdot (t_e - t_s)$$ where p_m is the power for enabling the operating state of the spindle transmission module (W), p_c is the power for material removal from the workpiece (W), p_i is the power for federate (W), t_{ms}, t_{me}, t_{cs}, t_{ce}, t_{fe} and t_{fe} are respectively the starting time and the ending time for spindle running, cutting and stage (s), p_{tool} is the power of the tool change motor (W), t_{tool} is the turret rotation time (s), p_{cool} is the power of the coolant pump motors (W), (t_{coe}-t_{cos}) represents the running time of the coolant pump motors (s), p_{servo} and p_{fan} are the power of the servos system and fan motors (W), respectively and (t_e-t_s) shows the entire running time of the machine tool (s)
Balogun *et al*. (2013, [25])	$$E_{total} = P_b t_b + (P_b + P_r)t_r + P_{air} t_{air} + (P_b + P_r + P_{cool} + k\dot{v})t_c$$ where P_b, P_r and P_{cool} are the basic, ready time and coolant power (W) respectively, t_b and t_r are the basic and ready time (s) respectively, P_{air}, t_{air}, $k\dot{v}$ and t_c are the same parameters of Gutowski *et al*. and Diaz *et al*. in Table 2
Calvanese *et al*. (2013, [18])	$$E_{total} = E_{fixed} + E_{axes} + E_{axis\,chillers} + E_{spindle} + E_{spindle\,chiller} + E_{chip\,conveyor} + E_{tool\,changer} + E_{pallet\,clamp}$$ where E_{fixed}, E_{axes}, $E_{axis\,chillers}$, $E_{spindle}$, $E_{spindle\,chiller}$, $E_{chip\,conveyor}$, $E_{tool\,changer}$ and $E_{pallet\,clamp}$ are the fixed, axes, axis chillers, spindle chiller, chip conveyor, tool changer and pallet clamp energy (J), respectively
Aramcharoen *et al*. (2014, [26])	$$E_{total} = P_{basic} \cdot t_{basic} + P_{tool} \cdot t_{tool} \cdot n_{tool} + P_{spindle} \cdot t_{spindle} + k \cdot Q \cdot t_{cutting} + \int_{t_{x,y,z_{start}}}^{t_{x,y,z_{end}}} P_{x,y,z}^{f} \cdot \mathrm{d}t + P_{cutting-fluid} \cdot t_{cutting-fluid}$$ where P_{basic}, P_{tool}, $P_{spindle}$ and $P_{cutting\text{-}fluid}$ are the basic, tool change motor, spindle transmission module and cutting fluid pump power (W) respectively, t_{basic}, t_{tool}, $t_{spindle}$ and $t_{cutting\text{-}fluid}$ are respectively total time, tool change time, spindle time (M03 code) and fluid pump time (s), n_{tool} is the number of cutting tools used in one cutting operation, Q is material removal rate (mm^3/s), $t_{cutting}$ is the cutting time (s), k is specific constant value, $P^f_{x,y,z}$ is the power required to move the work table in x, y and z direction (W), and $t_{x,y,z}$ is the feed time (s)

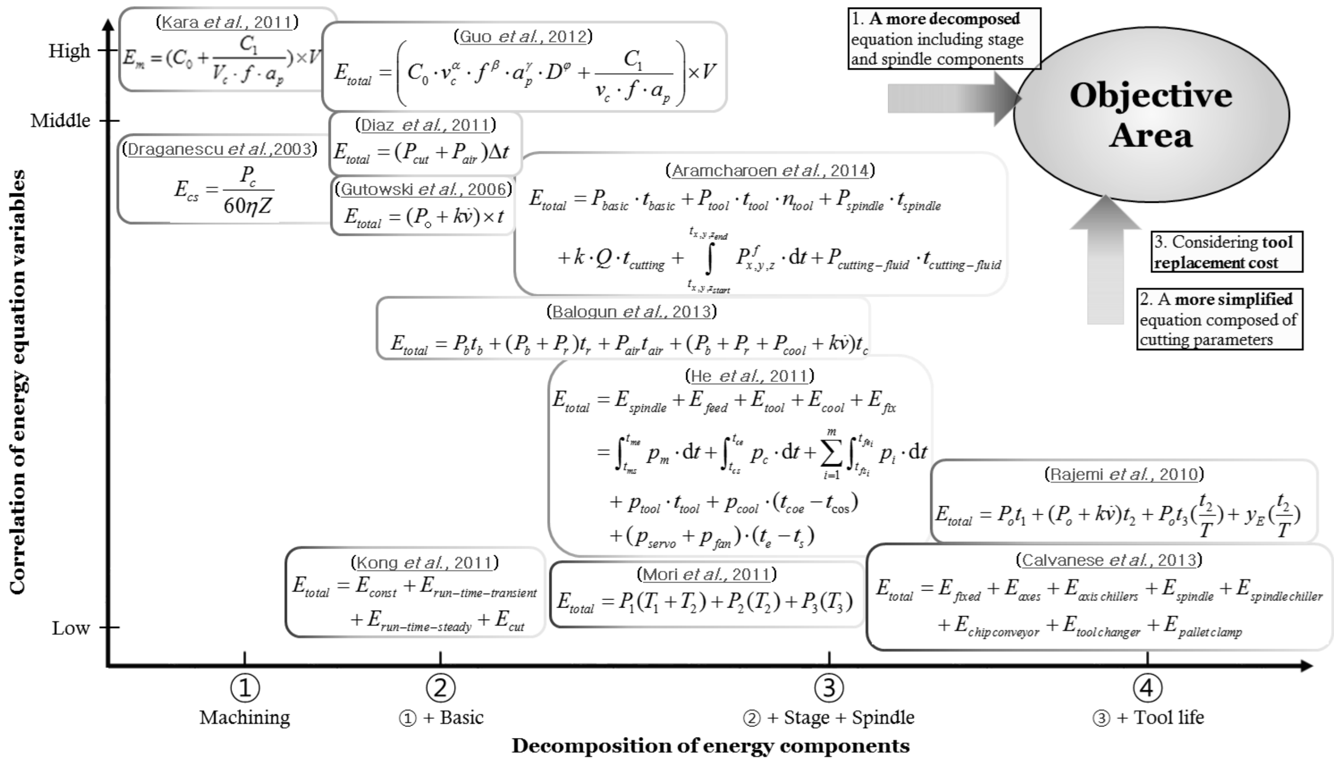

Figure 1.3 Characteristics and limitations of current energy consumption models

1.5 Goals of research

As mentioned in chapter 1.4, the more decomposed equation is just calculated in accordance with time and power inaccurately defined. However, a well decomposed energy consumption equation should be expressed by cutting parameters. The reason is that energy is inner product of time and power made up of cutting parameters. So, the ultimate tasks of this research are to build a well decomposed equation including basic, stage, spindle and machining components, to simplify this equation to compose only of cutting parameters, and to find the optimum cutting parameters in order to reduce energy and manufacturing cost such as tool replacement cost. The ultimate tasks are shown in Figure 1.3.

The goal of this research is to develop new models and methodologies to reduce the energy consumption and manufacturing cost in turning process on lathe machine tools. The energy consumption model is composed of basic, stage, spindle and machining components, and is clearly described in terms of cutting parameters. Similar to the energy consumption model, the manufacturing cost model is comprised of the energy costs and the tool life, concretized by cutting parameters. This resulting model is verified by empirical approaches using measured data. The constructed model fitted the measured data well on various lathe machine tools. Finally, two optimum cutting parameters reducing the energy consumption and manufacturing cost are obtained respectively. The model is applicable for the working of a process planner based on energy-saving or cost cutting strategies.

Chapter 2. Model derivation

2.1 Energy consumption model

The total energy consumption equation E_{total} can be defined as the sum of the individual energy consumption such as basic, stage, spindle and machining energy as follows:

$$E_{total} = E_{basic} + E_{stage} + E_{spindle} + E_{machining} \tag{2.1}$$

E_{basic} refers to the basic energy consumption of the machine tool including idle and coolant energy, and can be measured earlier than starting the machining process. In the machining process, a machine tool consumes more energy such as the momentum and machining energy. Momentum energy which means parts moving energy, is composed of two parts; one is the stage energy (E_{stage}), and the other is spindle energy ($E_{spindle}$). $E_{machining}$ is the machining for material removal.

In this thesis, peripheral energy components including chip conveyer, tool exchange or efficiency of workers are not considered because of complexities of variables [27].

2.1.1 **Definition of power consumption**

First of all, power consumption of each component should be defined as a linear function by cutting parameters, respectively:

$$
\begin{aligned}
P_{total} &= P_{basic} + P_{stage} + P_{spindle} + P_{machining} \\
P_{basic} &= c_0^{basic} \\
P_{stage} &= c_1^{stage} \cdot feed + c_0^{stage} \\
&= c_1^{stage} \cdot (f_r N) + c_0^{stage} \\
&= c_1^{stage} \cdot \frac{1000 V_c f_r}{\pi D} + c_0^{stage} \\
P_{spindle} &= c_1^{spindle} \cdot N + c_0^{spindle} = c_1^{spindle} \cdot \frac{1000 V_c}{\pi D} + c_0^{spindle} \\
P_{machining} &= c_1^{machining} \cdot \text{MRR} + c_0^{machining} \\
&= c_1^{machining} \cdot (V_c \cdot f_r \cdot a_p) + c_0^{machining}
\end{aligned}
\tag{2.2}
$$

where $c_{0,\,1}$ is a constant value, V_c is the cutting speed (m/min), N is the spindle speed (rev/min), f_r is the cutting feed rate (mm/rev), a_p is the depth of cut (mm) and D is material diameter (mm). P_{basic} represents the basic power consumption which is constant. The stage drive (P_{stage}) and spindle ($P_{spindle}$) were modelled using 1st order polynomial by cutting parameters, the feed rate and spindle speed [28]. The machining power ($P_{machining}$) is proportional to material removal rate (MRR, mm^3/min).

2.1.2 **Definition of process time**

Turning process in a lathe machine tool is composed of repeat cycle times from 1st to *i*th. Figure 2.1 shows turning process diagram at the *i*th cycle time. In *i*th cycle time, the process time is the sum of the cutting interval time and non-cutting interval time is as follows:

$$t_{cycle\_i} = t_{mi} + t_{mi}^{\ *} \tag{2.3}$$

$$t_{mi} = \frac{L}{f_{ri} N_i} = \frac{\pi L (D_i - 2a_{pi})}{1000 V_{ci} f_{ri}} \tag{2.4}$$

$$t_{mi}^{\ *} = \frac{\pi \left(2\left(s^x - (D_i - 2a_{pi} \right) + (2s^z + L) \right) \cdot (D_i - 2a_{pi})}{1000 V_{ci} f_{ri}^{\ *}} \tag{2.5}$$

where t_{cycle} is cycle time (s), t_m is cutting interval time (s), L is cutting length (mm), $s^{x,\, z}$ is safe distance (mm), f_r is cutting feed rate (mm/rev), $f_r^{\ *}$ is non-cutting feed rate (mm/rev), and these parameters including D, N, V_c and a_p were already mentioned in chapter 2.1.1 .

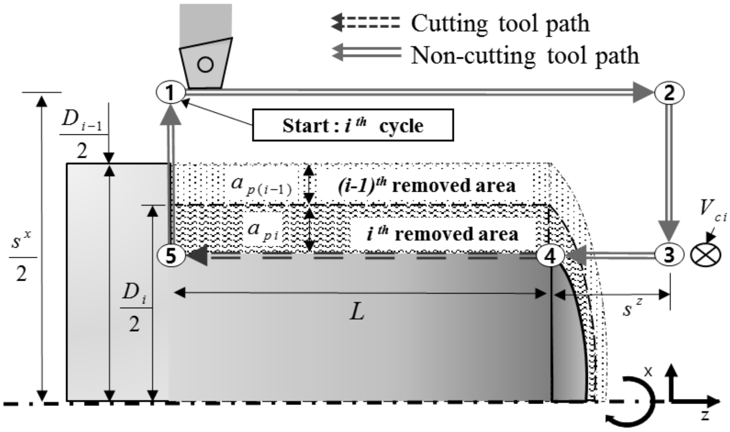

Figure 2.1 Turning process diagram in lathe machine tool

Table 4 Turning process simplifications

Variable	**General energy equation**	**Simplified energy equation**
Unify cutting parameters of each cycle		
Depth of cut	a_{pi} = various	$a_{pi} = a_p$
Cutting speed	$V_{ci} = \frac{\pi D_i N_i}{1000}$	$V_{ci} = \frac{\pi D_e N}{1000}$
Cutting feed rate	f_{ri} = various	$f_{ri} = f_r$
Non-cutting feed rate	f_{ri}^* = various	$f_{ri}^* = f_r$
The number of cycles	n depends on a_p	$n = \frac{D_s - D_e}{2a_p}$
$D_i \gg a_p$ **: material diameter is much bigger than depth of cut**		
Cutting interval time	$t_{mi} = \frac{\pi L(D_i - 2a_{pi})}{1000 V_{ci} f_{ri}}$	$t_{mi} = \frac{\pi L D_e}{1000 V_c f_r}$
Cycle time	$t_{mi}^* = \frac{\pi L(D_i - 2a_{pi})}{1000 V_{ci} f_{ri}} + \frac{\pi\left(2\left(s^x - (D_i - 2a_{pi}\right) + (2s^z + L)\right)\cdot(D_i - 2a_{pi})}{1000 V_{ci} f_{ri}^*}$	$t_{mi}^* = \frac{2\pi\left(L + s^x + s^z - D_s\right)\cdot D_e}{1000 V_c f_r^*}$

2.1.3 **General total energy equation**

According to the definition of energy, total energy can be calculated by using defined power and time. That is to say, the general total energy equation is the inner product of Eq. (2.2) and (2.3), as follows:

$$
\begin{aligned}
E_{total} &= \sum_{i=1}^{n}(E_{basic\_i} + E_{stage\_i} + E_{spindle\_i} + E_{machining\_i}) \\
&= \sum_{i=1}^{n}\left(\begin{aligned} & P_{basic\_i} \cdot (t_{mi} + t_{mi}{}^{*}) + \left(P_{stage\_i}^{4\to5} \cdot t_{mi} + P_{stage\_i}^{w/o\,4\to5} \cdot t_{mi}{}^{*}\right) \\ & + P_{spindle\_i} \cdot (t_{mi} + t_{mi}{}^{*}) + P_{machining\_i} \cdot t_{mi} \end{aligned}\right)
\end{aligned}
\tag{2.6}
$$

But Eq. (2.6) is too complicated to calculate total energy consumption because of various cutting parameters of each cycle. So this equation needs to be simplified by some assumptions to be calculated in embedded software or to employ analytic methods in order to find optimum cutting parameters.

2.1.4 **Simplified total energy equation**

In order to simplify the total energy equation, I assumed the turning process consists of only the same rough machining processes such as Shin *et al.* [29]. Adopting Eq. (2.6) and turning process simplifications shown in Table 4, the specific energy consumption (SEC, J/mm^3) which means simplified total energy consumption per cutting volume, is calculated. Finally the simplified total energy equation that only consists of cutting parameters and coefficients was achieved as follows:

$$\begin{aligned}\mathrm{SEC} &= \frac{E_{total}}{\text{Cutting volmume}} = \frac{\sum_{i=1}^{n}(E_{basic\_i} + E_{stage\_i} + E_{spindle\_i} + E_{machining\_i})}{\pi L({D_s}^2 - {D_e}^2)} \\ &= \frac{k_0^{total}}{V_c f_r a_p} + \frac{k_1^{stage}}{a_p} + \frac{k_1^{spindle}}{f_r a_p} + k_1^{machining}\end{aligned} \tag{2.7}$$

where

D_s = Original diameter (mm)

D_e = Final diameter after process (mm)

$$k_0^{total} = (c_0^{basic} + c_0^{stage} + c_0^{spindle}) \cdot \frac{\left(L + s^z + s^x - D_s\right) \cdot D_e}{1000L(D_s + D_e)} + c_0^{machining} \cdot \frac{D_e}{2000(D_s + D_e)}$$

$$k_1^{spindle} = \frac{c_1^{spindle} \cdot \left(L + s^z + s^x - D_s\right)}{\pi L(D_s + D_e)}$$

$$k_1^{stage} = \frac{c_1^{stage} \cdot \left(L + s^z + s^x - D_s\right)}{\pi L(D_s + D_e)}$$

$$k_1^{machining} = \frac{c_1^{machining} \cdot D_e}{2000(D_s + D_e)}$$

2.2 Manufacturing cost model

To account for the manufacturing cost of turning process, only the tool replacement cost is considered. The tool replacement cost depends on tool life T, and can be defined using the extended Taylor's equations as follows:

$$V_c T^n a_p{}^x f_r{}^y = c_{life} \quad \rightarrow \quad T = \frac{c_{life}{}^{1/n}}{V_c^{1/n} a_p{}^{x/n} f_r{}^{y/n}} = \frac{c_{life}{}^*}{V_c^\alpha a_p{}^\beta f_r{}^\gamma} \tag{2.8}$$

where x, y and n are Taylor's coefficients.

Combining Eq. (2.8) and Table 4, the specific tool cost which means tool replacement cost per cutting volume can be expressed as follows:

$$\begin{aligned} SC_{tool} &= \eta_{tool} \cdot \frac{\sum_{i=1}^{n} t_{mi}}{T} \cdot \frac{1}{\text{cutting volume}} \\ &= \eta_{tool} \cdot \frac{\frac{D_s - D_e}{2a_p} \cdot \frac{\pi L D_e}{1000 V_c f_r}}{\frac{c_{life}{}^*}{V_c^\alpha a_p{}^\beta f_r{}^\gamma}} \cdot \frac{1}{\pi L (D_s + D_e) \cdot (D_s - D_e)} \\ &= \frac{\eta_{tool} \cdot D_e}{2000 \cdot c_{life}{}^* \cdot (D_s + D_e)} \cdot (V_c^{\alpha-1} a_p{}^{\beta-1} f_r{}^{\gamma-1}) = k_{tool}^* \cdot (V_c^{\alpha-1} a_p{}^{\beta-1} f_r{}^{\gamma-1}) \end{aligned} \tag{2.9}$$

where η_{tool} is the tool cost per edge (USD/edge) and t_{mi} is the i^{th} cutting interval time.

2.3 Specific total cost and optimum parameters

The specific total cost (SC_{total}), total manufacturing cost per unit cutting volume, is the sum of the specific energy cost (SC_{energy}) and tool cost (SC_{tool}). SC_{energy} is the product of SEC and electricity bill per joule (η_{energy} , USD/J). SC_{total} can be expressed as:

$$\begin{aligned} SC_{total} &= SC_{energy} + SC_{tool} = \eta_{energy} \cdot \mathrm{SEC} + SC_{tool} \\ &= \frac{k^*_{basic}}{V_c f_r a_p} + \frac{k^*_{stage}}{a_p} + \frac{k^*_{spindle}}{f_r a_p} + k^*_{machining} + k^*_{tool} \cdot (V_c{}^{\alpha-1} a_p{}^{\beta-1} f_r{}^{\gamma-1}) \end{aligned} \quad (2.10)$$

According to Eq. (2.10), the specific total cost is determined by cutting parameters and some coefficients.

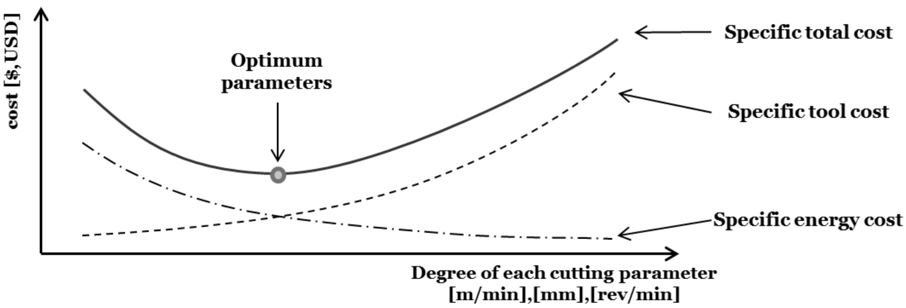

Figure 2.2 Optimum parameters satisfying minimum total cost

Looking at the graph in Figure 2.2, if the degree of each cutting parameters increases, the specific tool cost also increases but the specific energy cost decreases. In other words, fast machining process decreases not only the specific energy consumption, but also the tool life. So, finding minimum cutting parameter between SC_{energy} and SC_{tool} is a key point.

Employing analytic methods, the optimum parameter satisfying minimum total cost can be calculated by partial differentiation of SC_{total}, respectively:

$$\partial SC_{total} / \partial V_c = \partial SC_{total} / \partial f_r = \partial SC_{total} / \partial a_p = 0 \tag{2.11}$$

Chapter 3. Experimental details

3.1 Purpose of experiment

The energy consumption model made up of basic, stage, spindle and machining components was clearly described in terms of cutting parameters in Chapter 2.1.4. This resulting model needs to be verified by empirical approaches through these experiments. The purpose of these experiments is to achieve the coefficients of the energy consumption model such as k_0^{basic}, k_1^{stage}, $k_1^{spindle}$ and $k_1^{machining}$ of Eq. (2.7) by empirical analysis, and to verify whether the measured data fit this constructed model well on various lathe machine tools or not.

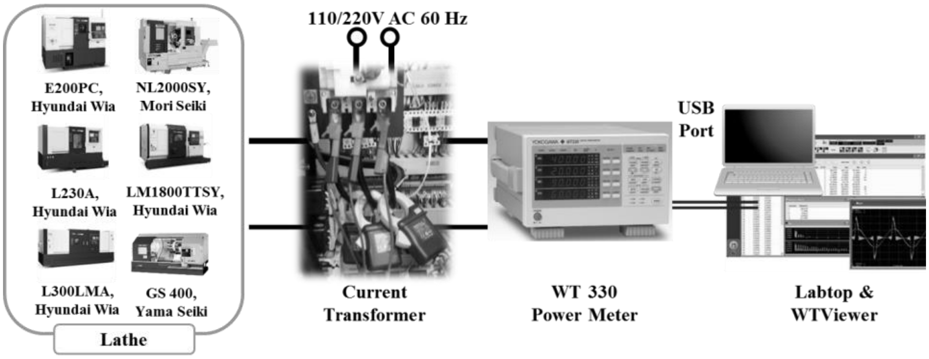

Figure 3.1 Schematic diagram of power measuring system

3.2 Experimental setup

Figure 3.1 is a schematic diagram in order to acquire energy consumption profiles. A total six different machine tools were examined, including E200PC, L2300LA, LM1800TTSY, L300LMA (Hyundai WIA, Korea), NL2000SY (Mori Seiki, USA) and GS400 (Yama Seiki, USA). Table 5 lists the specifications of these machine tools.

The energy consumption was measured using a power meter (WT330, YOKOGWA, Japan). This device had a 10-Hz sampling rate without any data processing filter and was installed in the main supply power. The energy consumption of each component was measured and calculated individually for specific experiment procedure.

Table 5 Machine tool specifications

Item	E200PC	NL2000SY	L230LA	LM1800TTSY	L300LMA	GS400
Spindle speed [RPM]	4000	5000	4000	5000	3500	2000
Spindle power (max./const.) [kW]	15/11	15/11	15/11	22/11	22/18.5	45/37
Work area [mm]	Φ 350 × 280	Φ 355 × 508	Φ 355 × 560	Φ 230 × 673	Φ 410 × 1,280	Φ 610 × 2,000
Dimension L x W x H [mm]	2,050 ×1,763 ×1,820	2,705 ×2,000 ×2,120	3,372 ×1,685 ×1,860	3,660 ×2,000 ×2,089	4,171 ×2,002 ×1,997	4,830 ×2,465 ×2,465
Machine weight [kg]	3900	5800	4600	8500	7700	11000
NC system	Sinumerik 828D	Fanuc	Fanuc 0i-TD	Fanuc 31i-A	Fanuc 32i-A	Fanuc 0i-TC

3.3 Measurement procedure.

By only one experiment, to achieve the coefficients of the energy consumption model such as k_0^{basic}, k_1^{stage}, $k_1^{spindle}$ and $k_1^{machining}$ of Eq. (2.7), the energy consumption measurement procedure was adopted. The accurate measurement procedure is described below (see Figure 3.2 and Figure 2.1).

- Start of power measurement
  - ⓢ Idle state of basic component
  - ⓞ Coolant pump of basic component
- Stage, spindle and machining powers measurement
  - ① Spindle On
  - ①→② +z axis travel
  - ②→③ –x axis travel
  - ③→④ –z axis travel
  - ④→⑤ Cutting
  - ⑤→① +x axis travel
- Repeat
  - ①→①* Changing conditions every cycle
- End of power measurement

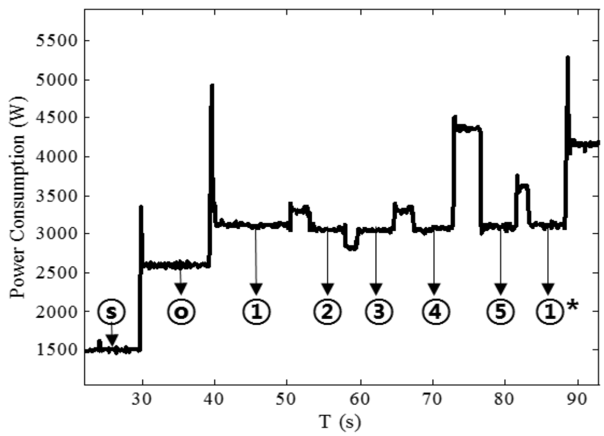

Figure 3.2 An energy profile example of the measurement procedure

The measurement procedure was progressing step by step with the same insert tool (CNMG 12 04 08-PF 4315, Sandvik Coromant, Sweden) for uniformity. To separate the energy consumption of each component, a dwell time (over 5 seconds) was included between each step. After identifying the interval per step in the energy profile, the power value of each component (represents y-axis of the graph in Figure 3.2) was determined from the difference between the average value of the saturated step profile and the average of the saturated dwelling profile.

The basic power value including idle state and coolant pump was measured for 10 seconds during the interval from 'ⓢ' to 'ⓞ'. The stage, spindle and machining (cutting) steps from '①' to '①*' were repeated over 39 times. The conditions of the +x, –x, +z and –z stages and the spindle were automatically changed to use empirical analysis. Machining process was performed with Φ 60 × 150 mm, AISI1045 mild steel rod and the three sets of the Box-Behnken experimental method (described in Table 6).

Table 6 Cutting conditions (Box-Behnken experimental method)

	Level -1	**Level 0**	**Level 1**
Cutting speed (V_c) [m/min]	250	300	350
Feed rate (f_r) [mm/rev]	0.2	0.3	0.4
Depth of cut (a_p) [mm]	0.125	0.312	0.5
Material removal rate ($V_c \cdot f_r \cdot a_p$) [mm^3/min]	**13 conditions X 3 sets** (7500~60000)		

Chapter 4. Results and Discussions

4.1 Verification by empirical analysis

As mentioned in chapter 2.1.1, power consumption of each component should be defined as a linear function by cutting parameters at Eq. (2.2). And the coefficients of each linear power consumption model were calculated by empirical analysis, and are described in Table 7.

$$\begin{pmatrix} P_{basic} & P_{stage} \\ P_{spindle} & P_{machining} \end{pmatrix} = \begin{pmatrix} c_0^{basic} & c_1^{stage} \cdot feed + c_0^{stage} \\ c_1^{spindle} \cdot N + c_0^{spindle} & c_1^{machining} \cdot \mathrm{MRR} + c_0^{machining} \end{pmatrix} \tag{2.2}$$

Table 7 Coefficients of each linear power consumption model

Component	Coefficient	E200PC	NL2000-SY	L230LA	LM1800-TTSY	L300-LMA	GS400
Basic	c_0^{basic} [W]	1703.5	2483	1497.25	4872	2465	4871.6
Stage	c_1^{stage} [W·min/mm]	0.002	0.048	0.015	-0.004	0.061	0.089
	c_0^{stage} [W]	42.2	-50.7	35.5	23.6	-89.4	-119.9
	R^2 (Determination)	-0.159	0.874	0.722	-0.086	0.665	0.833
Spindle	$c_1^{spindle}$ [W·min/rev]	0.624	1.775	1.162	0.839	1.575	6.646
	$c_0^{spindle}$ [W]	-17.9	-1029.5	-739.9	-662.9	-1300.1	-6654.2
	R^2	0.967	0.996	0.981	0.969	0.981	0.998
Machining	$c_1^{machining}$ [W·min/mm^3]	20.27	23.94	25.88	25.02	23.86	23.93
	$c_0^{machining}$ [W]	203.3	254.5	328.3	204.3	247.1	296.7
	R^2	0.992	0.996	0.995	0.994	0.995	0.994

The basic power is constant as it is directly related to the NC controller, fans and the coolant pump itself.

Looking at the x-axis (gravity direction) stage power consumption (see Figure 4.1), there is the symmetry between +x and –x axis because of the weight of lathe turret. The x-axis power trends increased with the feed rate speed along the +x-axis direction, but decreased along the –x-axis direction. The accuracy of the x-axis stage power is medium (Coefficient of determination, *COD:* $R_2 > 0.5 \sim 0.9$).

In the z-axis stage power consumption (Figure 4.2), there are the equal values between z directions. Since the z-axis stage was less influenced by the weight of lathe turret, the z-axis power trends gradually increased with the feed rate speed and had a large variation (*COD:* $R_2 < 0.8$).

The power trends of different spindles increased with the spindle speed for no-load conditions (Figure 4.3). And the spindle coefficient, $c_1^{spindle}$, depended on the motor output power and the weight of lathe turret. The spindle power was well modeled with high accuracy (*COD:* $R_2 > 0.9$).

The power trends of machining are similar values without regarding to the scale of a machine tool, but slightly different between controllers (Figure 4.4). The machining power is perfectly proportional to material removal rate with high accuracy (*COD:* $R_2 > 0.99$).

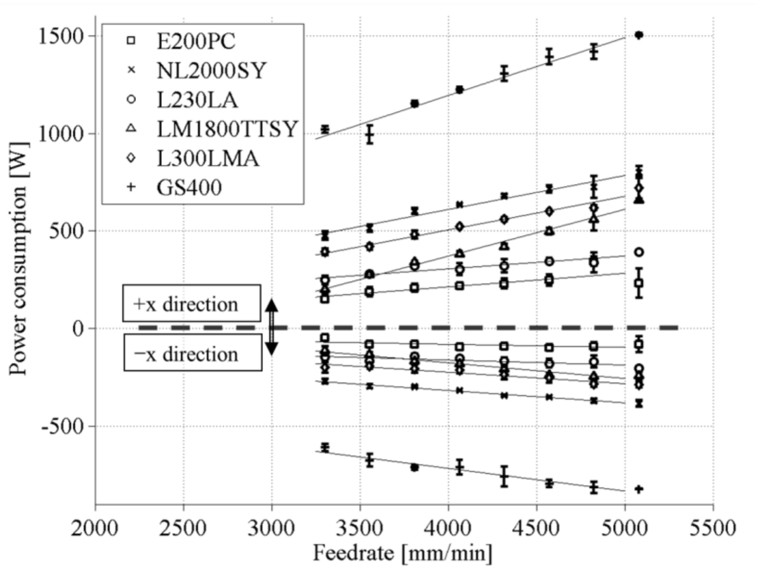

Figure 4.1 Trends of x-axis stage power consumption

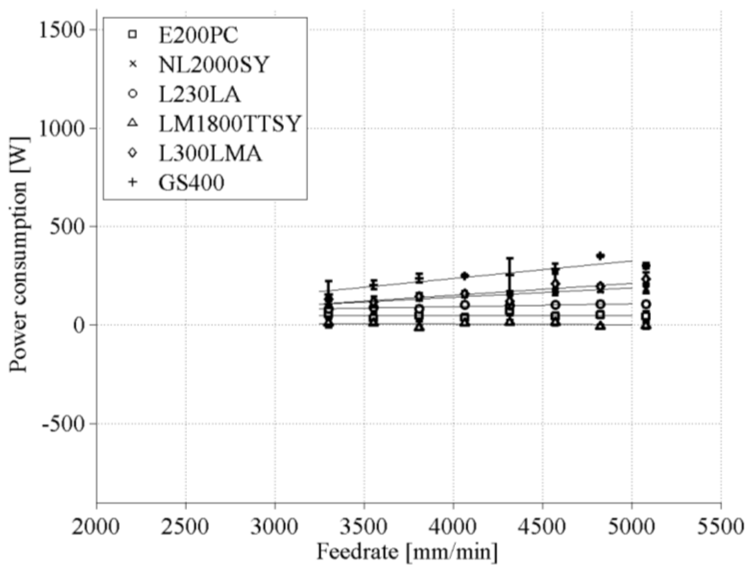

Figure 4.2 Trends of z-axis stage power consumption

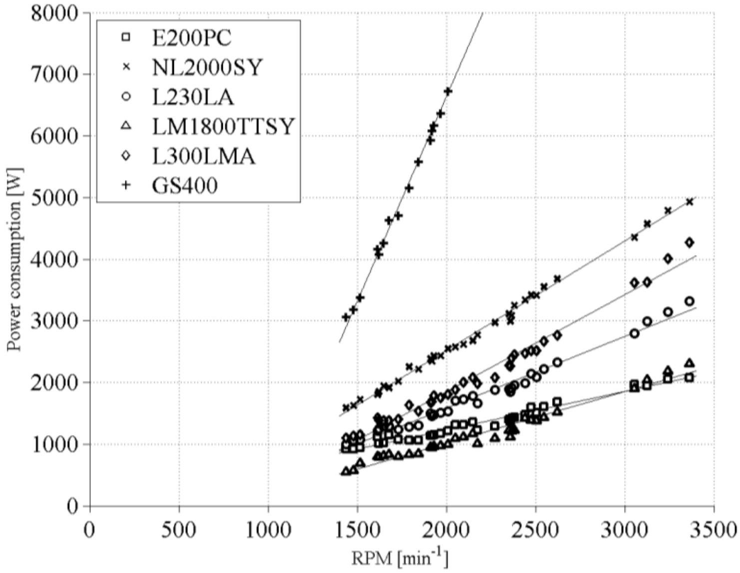

Figure 4.3 Trends of spindle power consumption

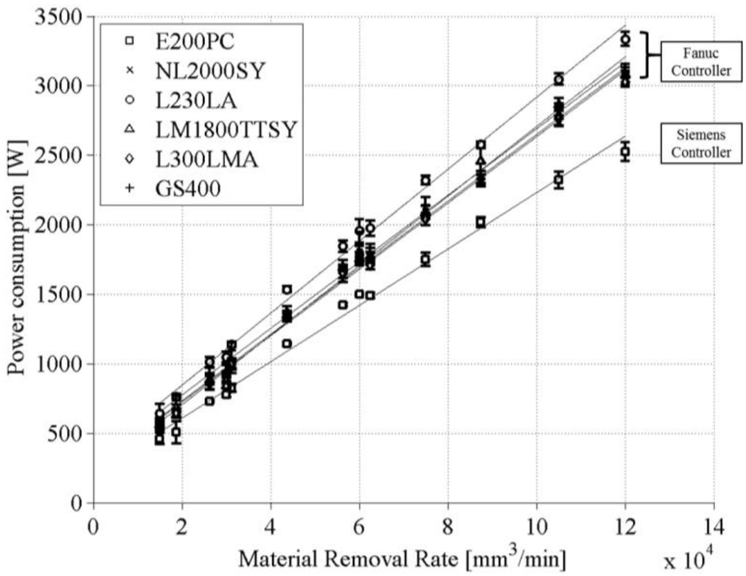

Figure 4.4 Trends of machining power consumption

4.2 Model coefficients

By using coefficients of each linear power consumption model in Table 7 and detailed information of tool and cost in Table 8, the coefficients of the specific total cost (SC_{total}, Eq. (2.10)) could be calculated and are described in Table 9.

$$SC_{total} = \frac{k^*_{basic}}{V_c f_r a_p} + \frac{k^*_{stage}}{a_p} + \frac{k^*_{spindle}}{f_r a_p} + k^*_{machining} + k^*_{tool} \cdot (V_c^{\alpha-1} a_p^{\beta-1} f_r^{\gamma-1}) \qquad (2.10)$$

Table 8 Detailed information of tool and cost (consulted from Sandvik Inc.)

Coefficient	Value	Coefficient	Value
n	0.15	α	6.67
x	0.15	β	1
y	0.6	γ	4
c_{life}	400	η_{energy} [USD/J]	2.74E-08
c_{life}*	2.22E+17	η_{tool} [USD/edge]	2.21

Table 9 Derived coefficients of the specific total cost

Machine tool	k^*_{basic} [USD/min]	k^*_{stage} [USD/mm^2]	$k^*_{spindle}$ [USD·rev^{-1}·mm^{-1}]	$k^*_{machining}$ [USD/mm^3]	k^*_{tool}
E200PC	3.50E-08	2.14E-13	6.66E-11	1.36E-10	2.44E-21
NL2000SY	2.90E-08	5.12E-12	1.90E-10	1.61E-10	2.44E-21
L230LA	1.76E-08	1.60E-12	1.24E-10	1.74E-10	2.44E-21
LM1800TTSY	8.37E-08	-4.27E-13	8.96E-11	1.68E-10	2.44E-21
L300LMA	2.26E-08	6.51E-12	1.68E-10	1.61E-10	2.44E-21
GS400	-3.50E-08	9.50E-12	7.10E-10	1.61E-10	2.44E-21

4.3 Optimum parameters for reducing energy or cost

Using the derived models including Eq. (2.7) and (2.10), and the determined coefficients in Table 9, the specific energy consumption (SEC) and total cost (SC_{total}) were calculated within standard cutting conditions of an insert tool from Sandvik Inc. (Figure 4.5, Figure 4.6 and Table 10).

Looking at Figure 4.5, the main topic of the color graphs means the SEC in accordance with a total six different machine tools. The x, y and z-axis represent cutting speed (V_c), feed rate (f_r) and depth of cut (a_p), respectively. The legends indicate that dark color shows a relatively small amount of the SEC and bright color describes a relatively large amount of the SEC. In other five machine tools except GS400, the SEC was perfectly proportional to the degree of each cutting parameters. Thus, fast machining process decreased the SEC. But, in case of GS400, the fast spindle speed increased the SEC because of the heavy weight of lathe turret.

The color graphs of Figure 4.6 show the SC_{total} of a total six different machine tools. The legends indicate that dark color shows a relatively small amount of the SC_{total} and bright color describes a relatively large amount of the SC_{total}. The SC_{total} was the minimum value in the opposite cutting conditions compared to the SEC. It means that fast machining process increased the SC_{total} due to a tool life reduction. In other words, since the tool cost itself is more expensive than electricity bill, the SEC generally depends on the scale of machine tools, but the SC_{total} is almost the same.

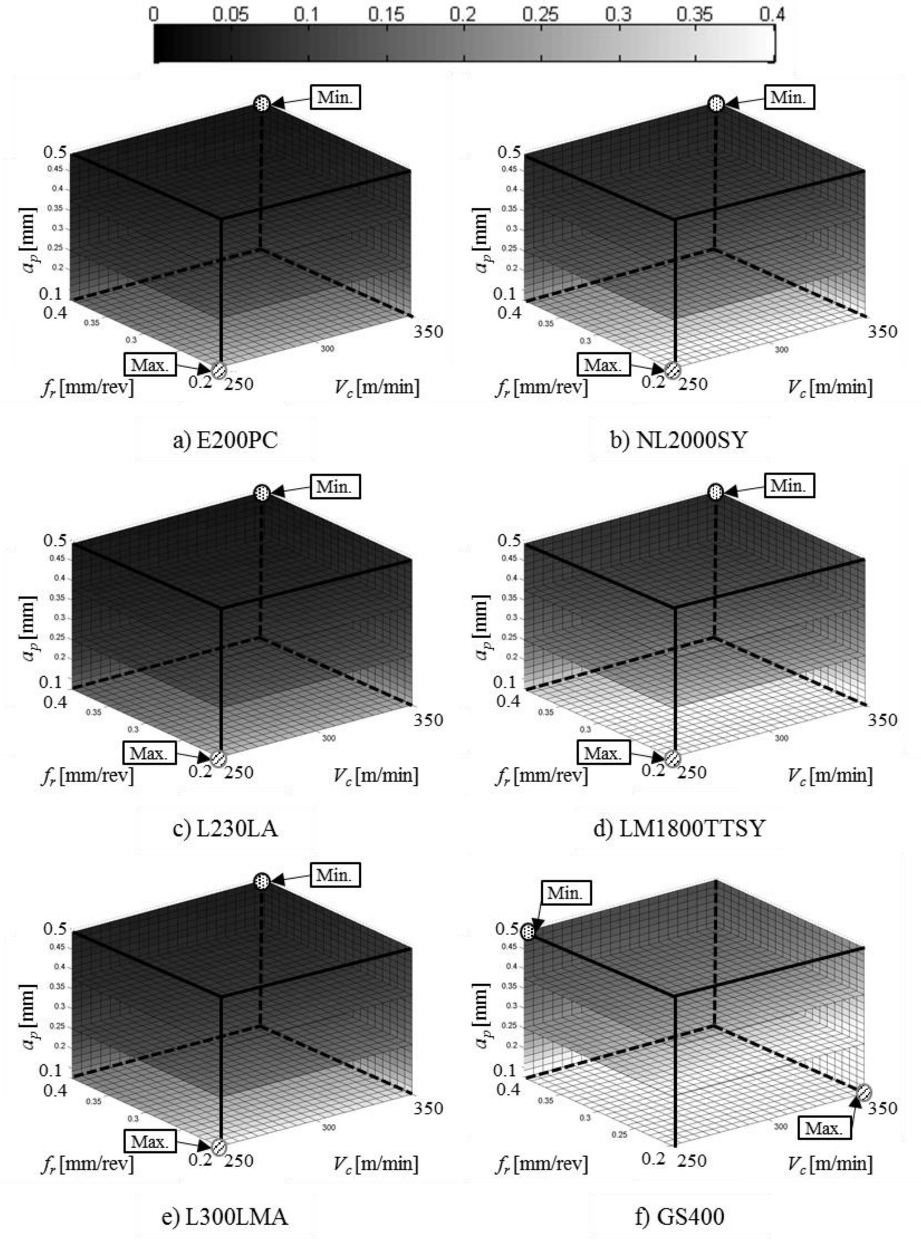

Figure 4.5 Trends of optimum specific energy consumption

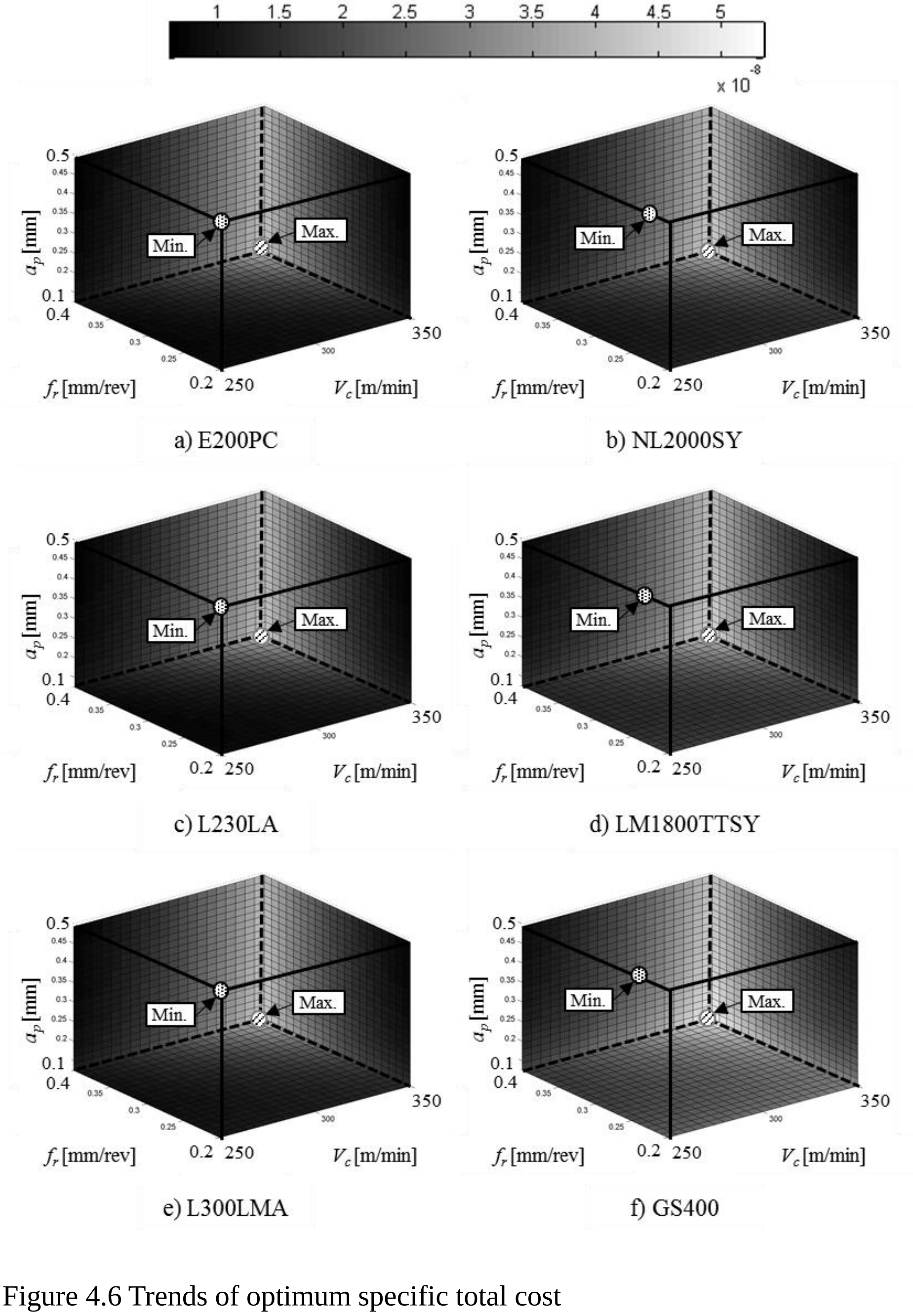

Figure 4.6 Trends of optimum specific total cost

Table 10 Optimum points of specific energy consumption and total cost

Cutting parameter			E200PC	NL2000-SY	L230LA	LM1800-TTSY	L300-LMA	GS400
Specific energy consumption (SEC)	Optimum point (min.)	**SEC [J/mm^3]**	3.54E-02	5.59E-02	3.83E-02	6.61E-02	4.88E-02	1.11E-01
		V_c [m/min]	350	350	350	350	350	250
		f_r [mm/rev]	0.4	0.4	0.4	0.4	0.4	0.4
		a_p [mm]	0.5	0.5	0.5	0.5	0.5	0.5
	Expensive point (max.)	**SEC [J/mm^3]**	3.07E-01	4.54E-01	2.91E-01	6.26E-01	3.85E-01	8.99E-01
		V_c [m/min]	250	250	250	250	250	350
		f_r [mm/rev]	0.2	0.2	0.2	0.2	0.2	0.2
		a_p [mm]	0.125	0.125	0.125	0.125	0.125	0.125
Specific total cost (SC_{total})	Optimum point (min.)	**SC_{total} [USD/ mm^3]**	2.96E-09	3.96E-09	2.88E-09	5.01E-09	3.51E-09	6.22E-09
		V_c [m/min]	250	250	250	250	250	250
		f_r [mm/rev]	0.2	0.214	0.2	0.229	0.2	0.257
		a_p [mm]	0.5	0.5	0.5	0.5	0.5	0.5
	Expensive point (max.)	**SC_{total} [USD/ mm^3]**	4.42E-08	4.64E-08	4.44E-08	4.75E-08	4.56E-08	5.23E-08
		V_c [m/min]	350	350	350	350	350	350
		f_r [mm/rev]	0.4	0.4	0.4	0.4	0.4	0.4
		a_p [mm]	0.125	0.125	0.125	0.125	0.125	0.125

Chapter 5. Conclusion

The new models and optimum cutting parameters to reduce the energy consumption and manufacturing cost for a total six lathe machine tools were well developed. Being composed of basic, stage, spindle and machining components, the energy consumption model was clearly described in terms of cutting parameters, and defined as the specific energy consumption. Similar to the energy consumption model, the manufacturing cost model was comprised of the energy costs and the tool life, concretized by cutting parameters, and defined as the specific total cost. This resulting model was verified by empirical approaches using measured data. The constructed model fitted the measured data well on various lathe machine tools. The model is applicable for the working of a process planner based on energy-saving or cost cutting strategies.

Two optimum cutting parameters reducing the energy consumption and manufacturing cost were obtained respectively. Considering the reduction of the energy consumption on a machine tool, the manufacturing process should be as fast as possible. However, the tool cost takes a significant portion of the manufacturing cost, compared to the electricity bill. Consequently, the slow manufacturing process is essential to reducing the manufacturing cost in order to increase a tool life.

Bibliography

[1] Anderberg, S., Kara, S., and Beno, T., 2010, "Impact of energy efficiency on computer numerically controlled machining," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 224(4), pp. 531-541.

[2] Kialashaki, A., and Reisel, J. R., 2014, "Development and validation of artificial neural network models of the energy demand in the industrial sector of the United States," Energy, 76(0), pp. 749-760.

[3] Jeswiet, J., and Kara, S., 2008, "Carbon emissions and CES™ in manufacturing," CIRP Annals - Manufacturing Technology, 57(1), pp. 17-20.

[4] Yoon, H. S., Kim, E. S., Kim, M. S., Lee, J. Y., Lee, G. B., and Ahn, S. H., 2013, "Towards Greener Machine Tools - A review on Energy Saving Strategies and Technologies," Renewable and Sustainable Energy Reviews.

[5] Kordonowy, D. N., 2002, "A power assessment of machining tools," Massachusetts Institute of Technology.

[6] Park, C.-W., Kwon, K.-S., Kim, W.-B., Min, B.-K., Park, S.-J., Sung, I.-H., Yoon, Y. S., Lee, K.-S., Lee, J.-H., and Seok, J., 2009, "Energy consumption reduction technology in manufacturing—A selective review of policies, standards, and research," International Journal of Precision Engineering and Manufacturing, 10(5), pp. 151-173.

[7] Neugebauer, R., Schubert, A., Reichmann, B., and Dix, M., 2011, "Influence exerted by tool properties on the energy efficiency during drilling and turning operations," CIRP Journal of Manufacturing Science and Technology, 4(2), pp. 161-169.

[8] Santos, J. P., Oliveira, M., Almeida, F. G., Pereira, J. P., and Reis, A., 2011,

"Improving the environmental performance of machine-tools: influence of technology and throughput on the electrical energy consumption of a press-brake," Journal of Cleaner Production, 19(4), pp. 356-364.
[9] Salonitis, K., and Ball, P., 2013, "Energy efficient manufacturing from machine tools to manufacturing systems," Procedia CIRP, 7, pp. 634-639.
[10] He, Y., Liu, F., Wu, T., Zhong, F., and Peng, B., 2011, "Analysis and estimation of energy consumption for numerical control machining," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, p. 0954405411417673.
[11] Li, W., and Kara, S., 2011, "An empirical model for predicting energy consumption of manufacturing processes: a case of turning process," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225(9), pp. 1636-1646.
[12] Yoon, H.-S., Moon, J.-S., Pham, M.-Q., Lee, G.-B., and Ahn, S.-H., 2013, "Control of machining parameters for energy and cost savings in micro-scale drilling of PCBs," Journal of Cleaner Production, 54, pp. 41-48.
[13] Campatelli, G., Lorenzini, L., and Scippa, A., 2014, "Optimization of process parameters using a Response Surface Method for minimizing power consumption in the milling of carbon steel," Journal of Cleaner Production, 66, pp. 309-316.
[14] Jia, S., Tang, R., and Lv, J., 2014, "Therblig-based energy demand modeling methodology of machining process to support intelligent manufacturing," Journal of Intelligent Manufacturing, 25(5), pp. 913-931.
[15] Diaz, N., Helu, M., Jarvis, A., Tönissen, S., Dornfeld, D., and Schlosser, R., 2009, "Strategies for Minimum Energy Operation for Precision Machining."
[16] Kara, S., and Li, W., 2011, "Unit process energy consumption models for material removal processes," CIRP Annals - Manufacturing Technology, 60(1),

pp. 37-40.
[17] Guo, Y., Loenders, J., Duflou, J., and Lauwers, B., 2012, "Optimization of energy consumption and surface quality in finish turning," Procedia CIRP, 1, pp. 512-517.
[18] Calvanese, M. L., Albertelli, P., Matta, A., and Taisch, M., 2013, "Analysis of energy consumption in CNC machining centers and determination of optimal cutting conditions," Re-engineering Manufacturing for Sustainability, Springer, pp. 227-232.
[19] Draganescu, F., Gheorghe, M., and Doicin, C., 2003, "Models of machine tool efficiency and specific consumed energy," Journal of Materials Processing Technology, 141(1), pp. 9-15.
[20] Gutowski, T., Dahmus, J., and Thiriez, A., "Electrical energy requirements for manufacturing processes," Proc. 13th CIRP international conference on life cycle engineering.
[21] Rajemi, M. F., Mativenga, P. T., and Aramcharoen, A., 2010, "Sustainable machining: selection of optimum turning conditions based on minimum energy considerations," Journal of Cleaner Production, 18(10–11), pp. 1059-1065.
[22] Diaz, N., Redelsheimer, E., and Dornfeld, D., 2011, "Energy Consumption Characterization and Reduction Strategies for Milling Machine Tool Use."
[23] Kong, D., Choi, S., Yasui, Y., Pavanaskar, S., Dornfeld, D., and Wright, P., 2011, "Software-based tool path evaluation for environmental sustainability," Journal of Manufacturing Systems, 30(4), pp. 241-247.
[24] Mori, M., Fujishima, M., Inamasu, Y., and Oda, Y., 2011, "A study on energy efficiency improvement for machine tools," CIRP Annals - Manufacturing Technology, 60(1), pp. 145-148.
[25] Balogun, V. A., and Mativenga, P. T., 2013, "Modelling of direct energy requirements in mechanical machining processes," Journal of Cleaner

Production, 41, pp. 179-186.
[26] Aramcharoen, A., and Mativenga, P. T., 2014, "Critical factors in energy demand modelling for CNC milling and impact of toolpath strategy," Journal of Cleaner Production, 78, pp. 63-74.
[27] Jönsson, M., Andersson, C., and Ståhl, J.-E., 2008, "A general economic model for manufacturing cost simulation," Manufacturing Systems and Technologies for the New Frontier, Springer, pp. 33-38.
[28] Mativenga, P., and Rajemi, M., 2011, "Calculation of optimum cutting parameters based on minimum energy footprint," CIRP Annals-Manufacturing Technology, 60(1), pp. 149-152.
[29] Shin, Y. C., and Joo, Y. S., 1992, "Optimization of machining conditions with practical constraints," International Journal of Production Research, 30(12), pp. 2907-2919.

초 록

원자재 가격의 상승에 따른 산업체들의 경제적 부담과 이산화탄소 배출 제한을 위한 국제 환경 규약의 활성화로 인해, 생산제조분야에서 에너지 저감 문제는 가장 중요한 국제적 이슈 중 하나로 부상하고 있다. 특히, 공작기계는 전통적인 기계 제조 분야뿐만 아니라 전자 제품 분야에까지 널리 사용되고 있고 이산화탄소 배출에 가장 큰 영향을 미치는 석탄과 천연가스를 원자재로 하는 전기 에너지로 가동되고 있으므로 에너지 효율을 높일 수 있는 기술을 공작기계에 적용하는 것이 필수적이다.

본 연구에서는 공작기계의 기계적 설비를 바꾸지 않으면서도 절삭 공정 변수만을 조절하여 에너지 효율을 높일 수 있는 방법을 연구하였다. 선반 공작기계의 선삭 공정에서 에너지 소비와 제조 비용을 줄일 수 있는 새로운 에너지 모델과 측정 방법론을 제시하였다. 에너지 소비 모델은 기초, 이송축, 주축, 절삭 에너지로 구성되며 각각 절삭 공정 변수로 이루어진 함수로 구체화하였다. 제조 비용 모델은 공작기계의 에너지 소비에 따른 전기 요금과 절삭 공구의 교체 비용으로 구성되며 에너지 소비 모델과 마찬가지로 절삭 공정 변수로 이루어진 함수로 구체화 하였다. 유도된 에너지 소비 모델과 제조 비용 모델은 경험적 접근방법론 (Empirical approach) 을 이용하

여 측정된 데이터를 통해 검증하였다. 총 6개 공작기계의 데이터를 측정하였고 해당 모델들은 측정된 데이터와 높은 경향성을 보였다. 또한, 해당 모델을 이용하여 에너지 소비나 제조 비용을 줄일 수 있는 각각의 최적 절삭 공정 변수를 제시하였다. 결론적으로, 설계된 모델을 에너지나 비용 저감을 중점적으로 하는 절삭 공정 계획표에 적용할 수 있다.

Keyword: 에너지 소비 모델, 절삭률, 공구 수명, 저감 전략, 최적 절삭 공정 변수

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