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Procedia CIRP 7 (2013) 217 – 221

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Forty Sixth CIRP Conference on Manufacturing Systems 2013

A Study of Automatic Determination of Cutting Conditions to Minimize Machining Cost

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Abstract

Machining cost is a most important factor for manufacturing a product. The machining cost for each machine tool is often estimated from the total cost of a factory according to the conventional method used for industrial management. The total income and expenditure of a factory can be obtained, however the operation status of machine tools is different. That is to say that an accurate machining cost for each part can't be estimated and then cutting conditions realizing minimum machining cost cannot be discussed before a real machining operation. Hence, an estimation method of machining cost is proposed with using ABC (activity-based costing). The activities related to electric consumption of a machine tool, coolant, lubricant oil, cutting tool and metal chip are considered for total machining cost in this research. Based on the estimation method, the calculation method of cutting conditions achieving minimum machining cost is introduced and discussed. An adequate cutting condition can be obtained by calculating an approximate equation with using least-square method and exploring a cutting condition achieving the minimum machining cost with using iterative calculation in this paper. The feasibility of the proposed estimation method of machining cost and the calculation method of cutting conditions achieving minimum machining cost is demonstrated through some case studies.

Selection and peer-review under responsibility of Professor Pedro Filipe do Carmo Cunha

Keywords: Machining cost, Activity-based costing, Cutting conditions

1. Introduction

Machining cost is vital for manufacturing a product and managing a factory, generally. Traditionally, the machining cost for each machine tool is often estimated from the total cost of a factory. The total income and expenditure of a factory is easy to obtain, however the operation status of each machine tool is different. In other words, the machining cost prediction is very difficult and then a smooth discussion of cutting conditions realizing minimum machining cost cannot be carried out.

Hence, an estimation method of machining cost is proposed with using ABC (activity-based costing). ABC can allocate cost to activities and is applied to a sequence of machining process of a part.

The activities related to electric consumption of a machine tool, coolant, lubricant oil, cutting tool and metal chip are modeled to predict a total machining cost in this research. Furthermore, the calculation method of cutting conditions achieving minimum machining cost is introduced and discussed based on the proposed cost estimation method.

There are a lot of researches regarding machining cost. The cutting conditions optimizing the machining cost have been discussed widely [1]. The cost of cutting tool has been considered mainly, other cost such as maintenance cost has been ignored. The production scheduling in consideration of the cost calculated by ABC has been tried [2], the machining process has not been evaluated, and then it is difficult to calculate the accurate machining cost. An innovative method called "Material flow cost accounting" [3] has been proposed for the purpose of reducing environmental burden and cost, but this is not suitable to discuss the cutting conditions. Several cost estimations for machined parts for decision-making has been proposed [4, 5], but a machining process is not evaluated in detail.

Selection and peer-review under responsibility of Professor Pedro Filipe do Carmo Cunha
doi:10.1016/j.procir.2013.05.037

The cost estimation method of machining operation a evaluating machining process in detail and the calculation method of cutting conditions achieving minimum machining cost are proposed in this paper.

2. Estimation method of machining cost

2.1. Activity-based costing

ABC (Activity-based costing) concept [6] shown in Fig. 1 is applied to calculate the machining cost. All activities related to machining operation consume resources incurring cost. A unit driving cost of a particular activity is called a cost driver. For example, an operation time of a machine corresponds to the cost driver.

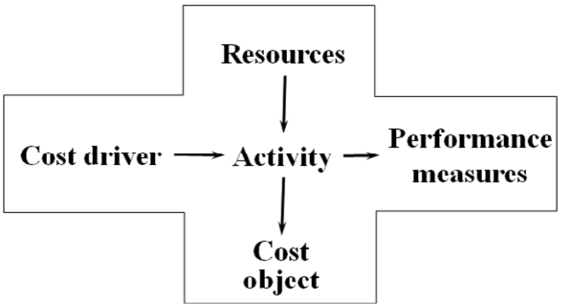


Fig. 1. Concept of activity-based costing [4]

ABC's purpose is to allocate direct and indirect costs to activities. All process related to machining operation are broken down to the activities, and then accurate machining costs can be derived with accurate activity costs.

The machining operation is predicted by the process simulator. The cost is estimated by the predicted machining operation and an adequate cutting condition can be obtained in this research.

2.2. Calculation Algorithms for machining cost

Total cost can be calculated by the following equation. JPY (Japanese Yen) is used as currency in this research.

$$Pc = Ec + Cc + LOc + \sum_{i=1}^{N} Tc_i + CHc \qquad (1)$$

Pc: Cost of machining operation [JPY]
Ec: Cost of machine tool electric consumption [JPY]
Cc: Cost of coolant [JPY]
LOc: Cost of lubricant oil [JPY]
Tc: Cost of cutting tool [JPY]
CHc: Cost of metal chip [JPY]
N: Number of tool used in an NC program

The cost of labour and machine tools investment is also important. It is difficult to calculate the labour cost automatically. For example, "How many labours will work for that machining?" or "How long will they work for that machining?" These information input are time consuming process, hence the consideration of labour cost is expected to be not feasible and then labour cost is ignored in this study. The cost of machine tools investment can be calculated from depreciation accounting [7] and this cost is very small in a machining, hence the cost of machine tools investment is also ignored.

The detailed calculation algorithms of *Ec*, *Cc*, *LOc*, *Tc* and *CHc* are described as follows.

Machine tool electric consumption (Ec)
The cost of electric consumption of machine tool is expressed by equation (2). Here, basic rate of electricity is ignored.

$$Ec = ER \times CE \qquad (2)$$

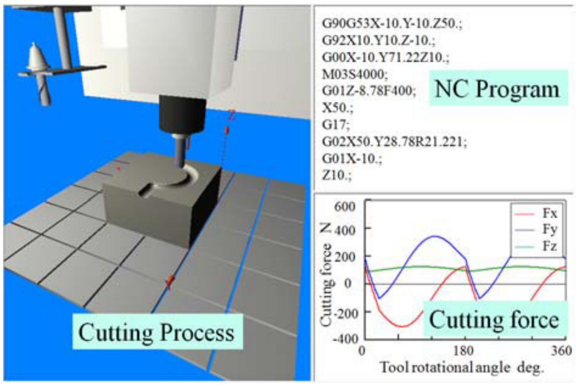
ER: Electricity bill [JPY/kWh]
CE: Electric consumption of machine tool [kWh]

CE in equation (2) is expressed by equation (3) and correspond to electric consumption of peripheral devices, servo and spindle motors.

$$CE = SME + SPE + SCE + CME + CPE + TCE1 + TCE2 + ATCE + MGE + SBE \qquad (3)$$

SME: Electric consumption of servo motors [kWh]
SPE: Electric consumption of spindle motor [kWh]
SCE: Electric consumption of cooling system of spindle [kWh]
CME: Electric consumption of compressor [kWh]
CPE: Electric consumption of coolant pump [kWh]
$TCE1$: Electric consumption of lift up chip conveyor [kWh]
$TCE2$: Electric consumption of chip conveyor in machine tool [kWh]
$ATCE$: Electric consumption of ATC [kWh]
MGE: Electric consumption of tool magazine motor [kWh]
SBE: Standby energy of machine tool [kWh]

The electric consumption of peripheral devices can be predicted from machining time and each electric power easily. However, in order to estimate the electric consumption of the servo and spindle motors, cutting force in each axis and cutting torque are indispensable. These values can be estimated by applying a cutting process simulator shown in Fig.2 [8]. Hence, various cutting conditions and machining processes can be estimated from an NC program.



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G90G53X-10.Y-10.Z50.;
G92X10.Y10.Z-10.;
G00X-10.Y71.22Z10.;
M03S4000;
G01Z-8.78F400;
X50.;
G17;
G02X50.Y28.78R21.221;
G01X-10.;
Z10.;
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Fig. 2. Cutting process simulator [5]

Coolant (Cc)

Coolant (water-miscible cutting fluid type) is considered. This is circulated in a machine tool by coolant pump until coolant is updated. Some cutting oil is eliminated due to the adhesion to metal chips, and water escape as vapor until coolant update. Hence additional quantity of coolant and water has to be considered. The following equation is used..

$$Cc = \frac{CUT}{CL} \times \left\{ \begin{aligned} &(CPc + CDc) \times (CC + AC) \\ &\qquad + WAc \times (WAQ + AWAQ) \end{aligned} \right\} \tag{4}$$

CUT: Coolant usage time in an NC program [s]
CL: Mean interval of coolant update [s]
CPc: Purchase cost of cutting fluid [JPY/L]
CDc: Disposal cost of cutting fluid [JPY/L]
CC: Initial coolant quantity [L]
AC: Additional quantity of coolant [L]
WAc: Water distribution cost [JPY/L]
WAQ: Initial quantity of water [L]
$AWAQ$: Additional quantity of water [L]

Lubricant oil (LOc)

Lubricant oil is generally used for spindle and slide way. Here, oil-air lubricant is treated for spindle lubricant. Following equations are applied. Grease lubricant is not mentioned, but almost same equations can be applied to calculate the cost.

$$\begin{aligned} LOc = &\frac{SRT}{SI} \times SV \times (SPc + SDc) \\ &+ \frac{LUT}{LI} \times LV \times (LPc + LDc) \end{aligned} \tag{5}$$

SRT: Spindle runtime in an NC program [s]
SV: Discharge rate of spindle lubricant oil [L]
SI: Mean interval between discharges [s]
SPc: Purchase cost of spindle lubricant oil [JPY/L]
SDc: Disposal cost of spindle lubricant oil [JPY/L]
LUT: Slide way runtime in an NC program [s]
LI: Mean interval between supplies [s]
LV: Lubricant oil quantity supplied to slide way [L]
LPc: Purchase cost of slide way lubricant oil [JPY/L]
LDc: Disposal cost of slide way lubricant oil [JPY/L]

Cutting tool (Tc)

A cutting tool is checked from the view point of tool life. Hence, the tool life should be compared with machining time to calculate the cost in a machining. Also, some cutting tools, for example solid end mill, are made a recovery by re-grinding. This point is taken into consideration to make a cost equation.

$$Tc = \frac{MT}{\sum_{j=1}^{RN+1} TL_j} \times \left((TPc + TDc) \times TW + RN \times RGc \right) \tag{6}$$

MT: Machining time [s]
TL: Tool life [s]
TPc: Purchase cost of cutting tool [JPY/kg]
TDc: Disposal cost of cutting tool [JPY/kg]
TW: Tool weight [kg]
RN: Total number of re-grinding
RGc: Cost of re-grinding [JPY]

Metal chip (CHc)

Metal chips are recycled to material by electric heating furnace. The following equation is applied by considering weight of metal chips. This also becomes a benefit of users, hence WDc in the following equation becomes minus generally.

$$CHc = (WPV - PV) \times MD \times WDc \tag{7}$$

WPV: Work piece volume [cm^3]
PV: Product volume [cm^3]
MD: Material density of work piece [kg/cm^3]
WDc: Processing cost of metal chip [JPY/kg]

2.3. Calculation method for minimum machining cost

A relationship between the machining cost and the cutting speed (spindle speed) is discussed when feed per tooth, a radial depth and an axial depth of cuts are constant.

The machining cost of the metal chip is constant even if the cutting speed is changed, because a part shape is same. Hence the one of the metal chip is ignored here. The one due to the electric consumption, coolant and lubricant oil is proportional to operation time according to the equations (2), (3), (4) and (5). The tool wear becomes extremely large in high speed cutting and the tool life will shorten generally. There is also an optimum cutting speed to realize minimum tool wear and maximum tool life. With consideration of the aforementioned facts, a tendency against cutting speed is expected.

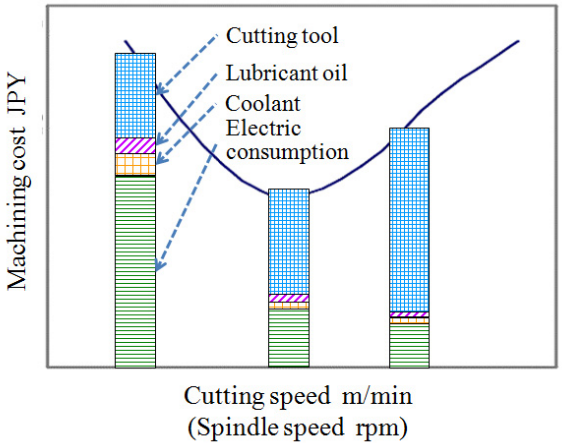

Fig. 3. Expected tendency according to cutting speed increase

Fig. 3 shows an expected tendency according to the cutting speed increase. The machining cost due to the electric consumption, coolant and lubricant oil decreases according to cutting speed increase, because the machining time will shorten. The one due to the cutting tool becomes minimum, and then increase according to the cutting speed increase show in Fig.3. That is to say there is a cutting speed to realize the machining cost.

Hence, an optimum cutting speed (spindle speed) can be calculated by obtaining an approximate equation with using least-square method and exploring the cutting speed achieving the minimum machining cost by iterative calculation. A parabolic equation is applied for the approximate equation in this research. A step size of cutting speed for the iterative calculation is also 0.5 m/min, and then a cutting speed realizing minimum machining cost is calculated.

3. Calculation example

A machine tool is a vertical machining center (MB-46VA, OKUMA Corp.), a cutting tool is carbide-ball end mill with R5 and 2-flute, and a workpiece is a PX5 for a calculation example. Cutting speed is varied from 50 to 550m/min, the axial depth is 0.5 mm, the radial depth is 0.8 mm, the feed/tooth is 0.15 mm/tooth and the cutting length is 56.25m. The coolant is also used for this cutting. Real tool wear data [9] are used to estimate the tool life. A flank wear is also used to distinguish its tool life and then the threshold of maximum tool wear is assumed to be 0.8 mm

Table 1. Cost parameters for machine tool operation

Electricity [JPY/kWh]	12.48
Cutting fluid production [JPY/L]	505
Cutting fluid disposal [JPY/L]	30
Dilution liquid (water) [JPY/L]	311.85
Spindle lubricant oil production [JPY/L]	430
Spindle lubricant oil disposal [JPY/L]	43.5
Slide way lubricant oil production [JPY/L]	447.05
Slide way lubricant oil disposal [JPY/L]	40
Cutting tool production [JPY/kg]	10,200
Cutting tool disposal [JPY/kg]	0
Regrinding for a ball end mill [JPY/number]	600
Metal chip processing [JPY/kg]	-13.5

Fig. 4 shows a calculated machining cost according to cutting speed. As show in Fig.4, there is a cutting speed realizing the minimum machining cost described in section 2.3. An approximate equation, which is a solid line in Fig.4, is obtained from the plotted data as follows.

$$y = 4.73 \times 10^{-3} x^2 - 2.51x + 3.80 \times 10^2 \qquad (8)$$

Where, y means the machining cost and x means the cutting speed, respectively. A coefficient of determination R^2 is 0.96 and the approximate equation fits a set of data well. The optimum cutting speed is obtained by the iterative calculation and becomes about 265 m/min. As shown in this example, the optimum cutting speed achieving minimum machining cost can be obtained automatically if the real tool wear data is given. It is found that the calculation method of optimum cutting speed introduced in this paper is feasible, because the real tool data is often provided by tool maker.

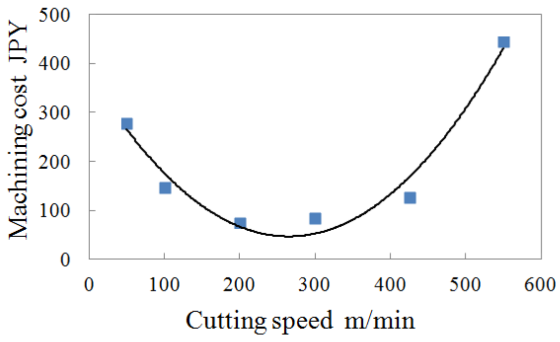

Fig. 4. Calculated machining cost according to cutting speed increase

4. Conclusions

An estimation method of a machining cost is proposed with using ABC (activity-based costing). Based on the proposed estimation method, the calculation method of cutting conditions achieving minimum machining cost is introduced and discussed.

Acknowledgements

This research has been supported by MAZAK foundation.

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