Prediction Model of Power Consumption for Variable Material Removal Rate Machining Process

Yasuo Kondo, Yuko Itoh, Mitsugu Yamaguchi, Satoshi Sakamoto, and Kenji Yamaguchi

***Abstract*—We tried to examine the power consumption for material-cutting in the variable-material removal rate (MRR) machining process. In the case of constant-MRR process, the power consumption is almost in proportion to the MRR and independent of feed rate of cutting tool and depth of cut. Namely, the MRR has been identified as the main factor for power consumption for material cutting. While in the variable-MRR machining process, the power consumption is in proportion to the MRR and its proportional constant notably depended on the depth of cut and the variation pattern of MRR during the operation. The machining with a shorter interval of MRR changes tended to show a larger power consumption than that of the machining with a longer interval of MRR changes. These facts indicate that the power consumption for metal cutting depends on the tool path and there would be an optimal tool path to minimize the power consumption and tool wear in response to a machining shape.**

***Index Terms*—Power consumption, cutting, material removal rate, variation pattern of MRR, tool path.**

I. Introduction

Machining represents one of the main energy-consuming activities in manufacturing industries and energy consumption determines 20% of machine tool operating cost [1]. Reducing the energy consumption by machining process has been identified as the important strategies to improve the tool life as well as the environmental performance [2].

According to the characteristics of material removal rate (MRR), machining process can be grouped into two types; constant-MRR and variable-MRR machining processes. Constant-MRR process is defined as the process that all of the cutting parameter remain unchanged during machining, while variable MRR process is defined as the process that at least one of the cutting parameters change time during machining. The energy consumption characteristics of constant-MRR and variable-MRR machining process are different.

Most of existing studies focused on power or energy modelling of constant-MRR machining process [3]-[9]. The cutting speed, feed rate and depth of cut in constant-MRR machining process are all constant. Hence, the cutting force is a constant value during cutting process. The situation is significantly different, when it comes to variable-MRR process. As the MRR is changing during machining process, cutting force will change with the varying cutting parameters such as the cutting speed, feed rate and depth. Consequently, the power consumption for material cutting will be a dynamic changing value as well. For instance, grooving and end face turning are typical variable-MRR machining processes.

It is easy to be seen that the power consumption of variable-MRR machining process are more complicated than that of constant-MRR machining process. However, up to now, research specially focused on the energy consumption of variable-MRR machining process is really rare [10], [11]. In this study, we tried to examine the power consumption for material cutting in variable-MRR machining process through the plane machining of bakelite sheet with four-depth of grooves.

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II. Experimental Procedure

A. Measurement of Power Consumption

The experimental setup for measuring the power consumption for material cutting is shown in Fig. 1. Only electric power consumed by the spindle motor $P_{measure}$ was measured at 0.2 seconds interval by using a power tester (Hioki model 3333). Then the net power consumption in the cutting process P_{cut} was estimated by subtract the power consumption at idle running P_{idle} from the measured spindle power. The evolution of net power consumption is a picture of the evolution of cutting force and a fairly accurate measure of the deterioration of tool condition as shown in equation (1).

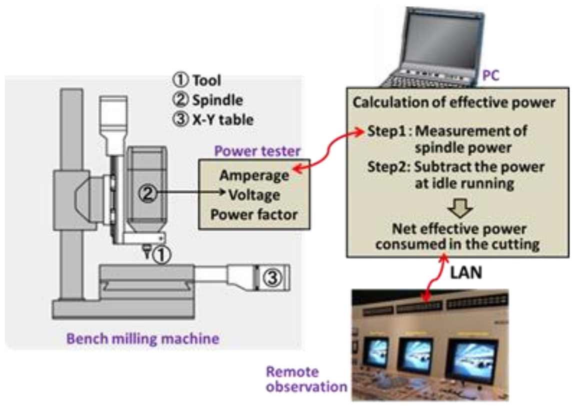

Fig. 1. Experimental set-up for measuring power consumption.

$$P = F_c \cdot V / (60 \times 1000 \times \eta) \quad (1)$$

where, P [kW] is net effective power, F_c [N] is principal

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cutting force, V [m/min] is cutting speed and η is mechanical efficiency.

B. Grooving

A grooving operation was conducted on a vertical bench type CNC machine with an AC spindle motor under the grooving conditions of Table I. The workpiece material used in grooving was a commercial brass plate and the cutting tool was a standard HSS two-flute end mill with a diameter of 4mm. The power consumption had been measured at 0.2 seconds interval during the machining of grooves with the depth of 0.5, 1.0 and 1.5mm at the feed rate of 60, 120 and 180m/min. In this experiment, the MRR had been kept a constant value during the machining.

TABLE I: GROOVING CONDITIONS

Bench type CNC machine
Work : Brass 50 × 50 × 5
Tool : two-flute end mill ϕ4
Cutting fluid : none
Feed rate : 60~180 mm/min
Spindle speed : 7,200 rpm
Depth of cut : 0.5, 1.0, 1.5 mm
Overhanging of tool : 12mm

C. Plane Working

To evaluate the power consumption at variable-MRR process, a plane working of bakelite sheet was conducted. A square bakelite sheet having four grooves with the depth of 1.0, 2.0, 3.0 and 4.0mm were prepared as the workpiece. Then a flat surface was formed by a plane processing using Φ2.0mm of HSS two-flute end mill. The cut has a straight shape with the width of 2mm and the depth of 1.0, 2.0 or 4.0mm. The cutting tool had been moved parallel (Y-direction) and vertical (X-direction) to the longitudinal direction of groove to examine the effect of MRR changing condition on power consumption. In the case of moving the tool in Y-direction, the MRR gradually changes at a relatively long interval, while the MRR would vary in a short period when the tool is moved in X-direction as shown in Fig. 2. The depth of cutting is considered as a steady-state load constantly acting on the tool during the machining.

III. RESULTS AND DISCUSSIONS

A. Power Consumption at Constant-MRR Process

Fig. 3 shows the power consumption changes when the grooves with the depth of 0.5, 1.0 and 1.5mm were machined at the feed rate of 60, 120 and 180 m/min. In general, the power consumption measured by the wattmeter $P_{measure}$ is expressed as $P_{idle} + P_{cut}$. Where P_{idle} is the idle power and can be decomposed spindle standby power and spindle rotation power. P_{cut} is the power consumption to cut the material by cutting edge and is a main factor for dynamic changes of power consumption in the machining. In this study, the power consumption for metal cutting P_{cut} is defined as the power consumption in the cutting process. The power consumption has been kept an almost constant value during the machining as far as the cutting was conducted under the same condition. The unit power consumption per second of machining. P_{unit} is almost in proportion to both the feed rate and the depth of cut, namely P_{unit} is in proportion to MRR as shown in Fig. 4. This situation can be modelled in Eq. (2).

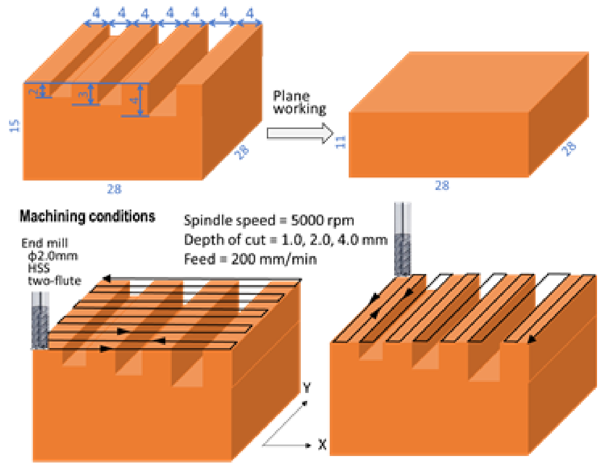

Fig. 2. Summary of plane working.

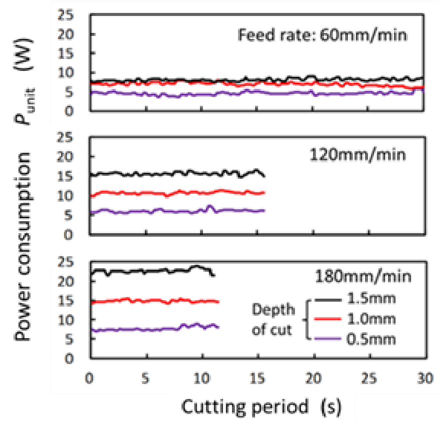

Fig. 3. Power consumption change in grooving.

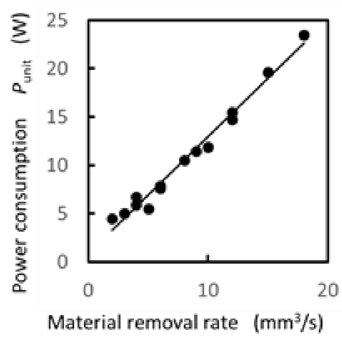

Fig. 4. Relation between power consumption and MRR.

$$P_{unit} = k_0 \cdot MRR \tag{2}$$

where k_0 is a constant in kJ/mm^3 and MRR is the material removal rate in mm^3/s. This equation shows that the MRR has been identified as the main factor for power consumption for metal cutting in the constant-MRR machining process.

B. Power Consumption at Variable-MRR Process

Fig. 5 shows the measured power consumption, $P_{measure}$, change when the workpiece was machined in X-direction at 1mm of depth of cut. The cutting was conducted three cycles in a law using the same cutting tool. The measured power consumption tended to increase with increasing of machining cycle N_c. Fig. 6 shows the measured power consumption change when the workpiece was machined in X and Y-direction at 4mm of depth of cut. In the case of the cutting in Y-direction, the measured power consumption had been changed at a relatively long interval, while the cutting in X-direction varied power consumption in a short period as expecting from the MRR changes.

The relation between the depth of cut and the unit power consumption P_{unit} in the 1st cycle of machining is summarized in Fig. 7. In the case of variable-MRR process, it is difficult to estimate the material removal rate (MRR) since the MRR has been varied every moment with the cutting time. Therefore, the depth of cut can be considered as the substitute parameter of MRR, because the depth of cut is proportion to MRR theoretically. The unit power consumption is proportion to the depth of cut but showed a difference between the machining in X-direction and Y-direction. The unit power consumption in the cutting of X-direction tended to be enlarged as compared with those of the cutting in Y-direction. These facts mean that the proportional constant k_0 in equation (2) notably depends on the variation pattern of MRR during the cutting in the variable-MRR process, while k_0 seems to be a constant value in the constant-MRR process.

C. MODELLING of Power Consumption for Variable-MRR Process

Fig. 8 summarizes the total power consumption $P_{total.}$ the total power consumption P_{total} is the overall power consumption consumed by the spindle motor over the entire plane working of grooved workpiece. It is expecting that the total power consumption P_{total} would show the same value unless the tool diameter (groove width), feed rate and rotational speed of tool are invariable. However, the actual P_{total} was proportional to the depth of cut, in other words P_{total} was proportional to mean MRR (MRR_{mean}) over the entire plane working and its proportion coefficient k_t depends on the cutting direction and the number of cutting cycle.

Fig. 9 shows the slope k_t and y-interception P_{base} obtained from the linear regression equation between the depth of cut and total power consumption. The slope and y-interception have a linear relation with the depth of cut. The total power consumption tended to increase with the depth of cut, i.e. mean material removal rate MRR_{mean} and its increasing rate depends on the cutting direction and the number of machining cycle N_c i.e. tool wear. Therefore, the total power consumption of variable-MRR machining process can be formulated as follows;

$$P_{total} = (1+\alpha \cdot N_c)\cdot k_t \cdot MRR_{mean} + (1+\beta \cdot N_c)\cdot P_{base1} \qquad (3)$$

where P_{base1} is the y-interception obtained from the linear regression equation in the 1st cycle of machining, α is a correction coefficient depending on the cutting direction and β is a correction coefficient depending on the tool wear. $\alpha > 0$ and $\beta \fallingdotseq 0$ in the machining with a shorter interval of MRR changes (X-direction), while $\alpha \fallingdotseq 0$ and $\beta > 0$ in the case of the machining with a longer interval of MRR changes (Y-direction).

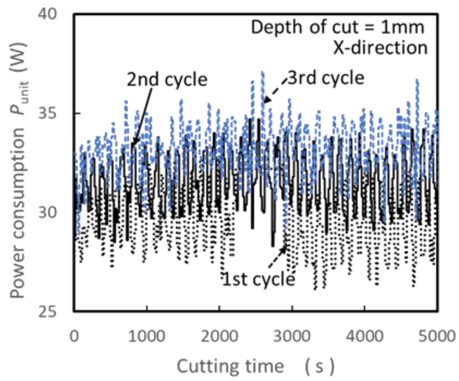

Fig. 5. Power consumption change in plane working.

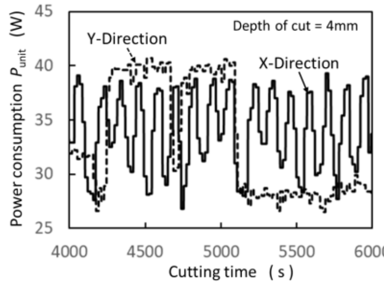

Fig. 6. Relation between power consumption and cutting time.

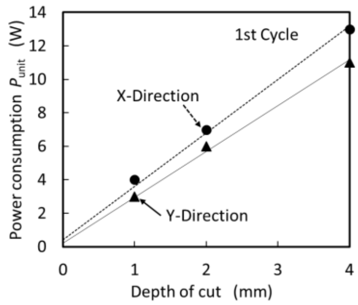

Fig. 7. Relation between depth of cut and power consumption.

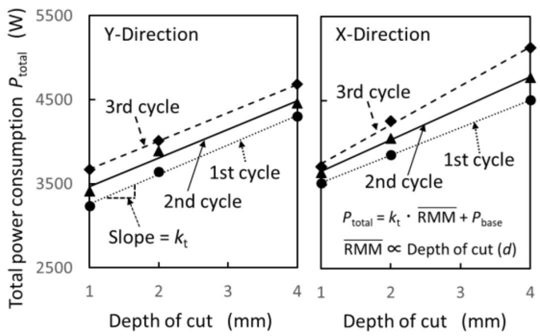

Fig. 8. Total power consumption in plane working.

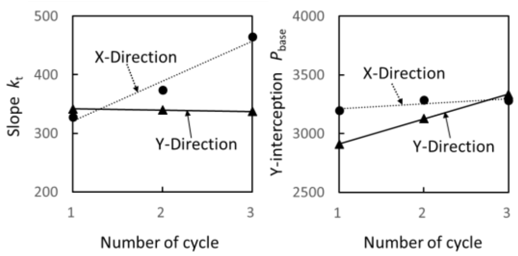

Fig. 9. Slope k_t and y-interception P_{base}.

IV. CONCLUSION

We tried to examine the power consumption for material-cutting in variable-material removal rate (MRR) machining process through the plane machining of bakelite sheet. In the case of constant-MRR process, the power consumption is almost in proportion to the MRR and independent of feed rate of cutting tool and depth of cut. Namely, the MRR has been identified as the main factor for power consumption for material cutting. While in the variable-MRR machining process, the power consumption is in proportion to the MRR and its proportional constant notably depended on the depth of cut and the variation pattern of MRR during the cutting. The machining with a shorter interval of MRR changes tended to show a larger power consumption than that of the machining with a longer interval of MRR changes. These facts indicate that the power consumption for metal cutting depends on the tool path and there would be an optimal tool path to minimize the power consumption and tool wear in response to a machining condition.

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