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A study on energy consumption of a CNC milling machine based on cutting force model

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Abstract. Machining operations are performed by machine tools with a large amount of energy consumed for material removal. Understanding and characterizing the energy consumption is essential to explore the potential of energy-saving in energy-efficient machining. For this purpose, this paper proposes a method for modeling energy consumption of end milling operation which is based on cutting theory. The cutting power model is verified with experiments on a CNC milling machine. According to the calculated and experimental results, it is clear that the theoretical prediction can predict the mean cutting power successfully as validated by actual measurements.

Introduction

Improving resource efficiency has recently been recognized as a must in factories of the future. In the machine tool manufacturing industry, developing energy-saving machine tools is one of the important trends in the 2lst century. With the increasingly widespread use of CNC machine tools, the energy consumption issue has become a hot research topic today. For this reason, a model for energy consumption is necessary. In the past years, a large number of researchers have conducted research in this regard. Murari et al. [1] proposed machine tool power losses and efficiency analysis models, assuming that the output power of a machine tool is the basis of the input power and spindle speed function in order to draw their quantitative relationship on multiple linear regression analysis method. The experimental analysis which they used is complex and it needs more experiments to identify the parameter. Gutowshi et al. [2] analyzed the impact on the environment during the machining process from the view of system level. The energy consumption of the material removal model, tool life model, cutting fluid model, and material discarded model were established. Note that they did not specify the parameters for which it is clearly defined and it is not clear about the value and the specific derivation of each parameter. Peng et al. [3] have also made efforts in this field.

The main objective of this study is to develop a cutting power model to predict the power actually consumed. Taking advantage of cutting theory, a modeling method of energy consumption for end milling operation, which can calculate the theoretical value, is presented. The intended contribution of this paper is to provide a theoretical model for understanding how the energy is consumed with the potential for improving energy efficiency of machining systems.

Cutting power modeling in end milling

Infinitesimal dividing of end mill. As the milling force is constantly changing, normal cutting theory cannot be directly used for the milling process. To be able to use cutting theory, a variation of the milling process is used. As shown in Fig.1, the milling process is discretized into simple oblique cutting process.

Tangential cutting force in end milling. The geometry of a cutting edge is shown in Fig. 2. A set of curvilinear coordinate systems normal to the ball envelope are used to specify the resultant cutting forces acting on the flute. The elemental tangential, radial and axial cutting forces dF_t, dF_r and dF_a, acting on the cutter are given by [4-6]

$$\begin{cases} dF_t = K_{tc} \cdot h \cdot dz + K_{te} \cdot ds \\ dF_r = K_{rc} \cdot h \cdot dz + K_{re} \cdot ds \\ dF_a = K_{ac} \cdot h \cdot dz + K_{ae} \cdot ds \end{cases} \quad (1)$$

where dF_t, dF_r and dF_a represent differential cutting forces in tangential, radial and axial directions in milling, respectively; ds is the cutting edge length element, dz is the axial depth of cut element, h is the depth of cut, K_{tc}, K_{rc} and K_{ac} are the tangential, radial and axial edge force coefficients, respectively; K_{te}, K_{re} and K_{ae} are the tangential, radial and axial force shearing coefficients, respectively.

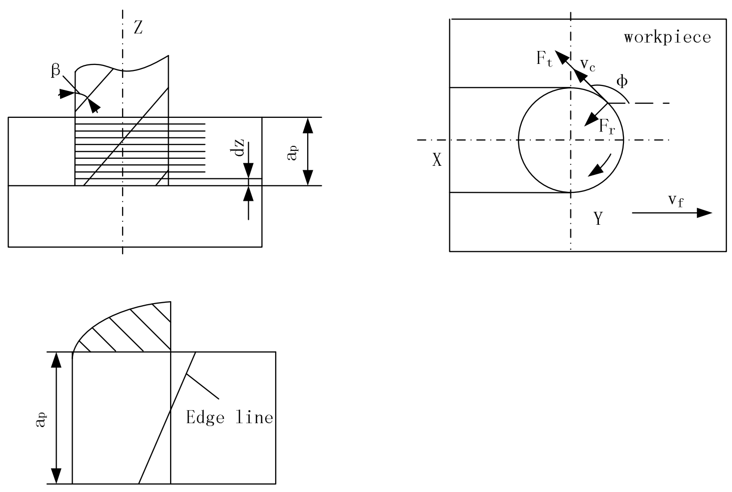


Fig.1 Schematic diagram of discrete cutting process

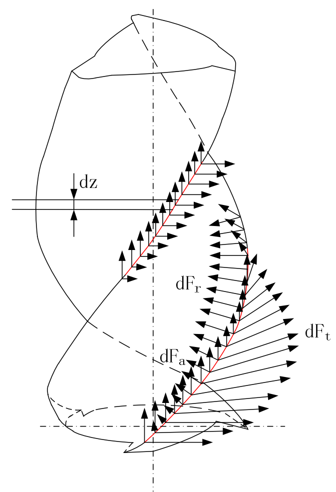


Fig.2 Schematic diagram of infinitesimal element force

However, the edge coefficients' impacts are generally very small when compared to the cutting force coefficient in the actual cutting process. Therefore, for the ease of calculation, set $K_{te} = 0$, $K_{re} = 0$, $K_{ae} = 0$. The milling force model in this paper can thus be expressed as

$$\begin{cases} dF_t = K_{tc} \cdot h \cdot dz \\ dF_r = K_{rc} \cdot h \cdot dz \\ dF_a = K_{ac} \cdot h \cdot dz \end{cases} \quad (2)$$

Denote the number of teeth on the cylindrical milling cutter N, the helix angle β, the radius R, the axial depth of cut a_p, the radial depth of cut a_e. Cutting edgeis divided into the infinitesimal element M along the axial direction of the milling cutter. Because of the helix angle β, the points on the cutting edge lag at the bottom edge milling endpoint. The instantaneous radial contact angle on the flute *j* at infinitesimal element *l* is referenced by its angular position ϕ_{jl} in the global coordinate system $\phi_{jl} = \phi_{10} + (j-1)\phi_P + a_p l \tan\beta/(MR)$, where $\phi_P = 2\pi/N_f$ is the pitch angle of the cutter and ϕ_{10} is the rotation of reference flute $j=1$, $l=0$, ϕ_{10} is measured clockwise from the y-axis, and from the center point 0.

Chip thickness changes with the angular position of the cutting edge and can be approximated as: $h(\phi_{jl}) = f_t \sin\phi_{jl}$,where f_t is feed per tooth. Therefore, the elemental tangential, radial and axial cutting forces dF_{tjl}, dF_{rjl} and dF_{ajl} acting on the cutter are given by

$$\begin{cases} dF_{tjl} = g(\phi_{jl})K_{tc} \cdot h \cdot dz \\ dF_{rjl} = g(\phi_{jl})K_{rc} \cdot h \cdot dz \\ dF_{ajl} = g(\phi_{jl})K_{ac} \cdot h \cdot dz \end{cases} \tag{3}$$

where $g(\phi_{jl})$ is unit step function when using slot milling, which can be expressed as

$$\begin{cases} g(\phi_{jl}) = 1, & 2k\pi \le \phi_{jl} < 2k\pi + \pi \\ g(\phi_{jl}) = 0, & 2k\pi + \pi \le \phi_{jl} < 2k\pi + 2\pi \end{cases} \tag{4}$$

Modeling of instantaneous cutting power in end milling. When $2k\pi + \pi \le \phi_{jl} < 2k\pi + 2\pi$, the power $P = 0$; when $2k\pi \le \phi_{jl} < 2k\pi + \pi$, φ is the angle between the direction of tangential force and the direction of feed($0 \le \varphi \le \pi$)

（1）When $0 \le \varphi \le \pi/2$, instantaneous power can be expressed as

$$P_{ins1} = F_{tjl} \cdot v_c + (F_{tjl}\cos\varphi - F_{rjl}\sin\varphi)v_f \tag{5}$$

(2) When $\pi/2 \le \varphi \le \pi$, instantaneous power can be expressed as

$$P_{ins2} = F_{tjl} \cdot v_c + (F_{rjl}\sin\varphi - F_{tjl}\cos\varphi)v_f \tag{6}$$

where $v_c = \pi dn/1000$ and $v_f = f \cdot n = f_t \cdot n \cdot z$. The milling force coefficients were obtained from the test in literature[7] in which $K_{rc} = 893$, $K_{tc} = 1880$ and $K_{ac} = 157$.

Mean cutting power model in end milling. The average power is the result of accumulation of the instantaneous power. Thus, the mean cutting power of end milling can be expressed as follows:

when $0 \le \varphi \le \pi / 2$,

$$P_{m1} = \sum_{j=1}^{N} \sum_{l=1}^{M} P_{ins1} \tag{7}$$

when $\pi / 2 \le \varphi \le \pi$,

$$P_{m2} = \sum_{j=1}^{N} \sum_{l=1}^{M} P_{ins2} \tag{8}$$

$$P_m = P_{m1} + P_{m2} \tag{9}$$

Experiments and analysis

Experimental procedures. The cutting experiments were carried out on a Huazhong CNC three axis milling machine. The data acquisition device Fluke 1730 Three-Phase Electrical Energy Logger was used during the machining process (Fig.3).

Fig.3 A power meter is used to measure power consumption (a) ,and end product of experiments carried out on a piece of 45 steel in dry machining(b).

Milling experiments were carried out under different cutting conditions (Table1).In the experiments, the Flex current probe were clipped to the wire during the milling. The two voltage clamps were clipped to the high-voltage and low-voltage sides of the transformer during the milling, respectively. Note that the same cutter, workpiece material, and cutting parameters are used for theoretical modeling and the experimental results presented in this paper.

Table 1 Experimental conditions

Workpiece	Cutter	Cutting condition
Material: 45 steel (HRC18-23)	Material: high-speed steel	Depth of cut: 1-1.6mm
Size:135×70×70 mm^3	Number of teeth: 3	Rotational speed: 400-700r/min
	Diameter: 100 mm	Feed rate: 20-50mm/min
		Type of cut: slotting
		No cutting fluid

Results and discussions. As shown in Fig.4, the results obtained from Fluke 1730 Three-Phase Electrical Energy Logger show the power consumption data for different cutting conditions. After measuring power consumption of the spindle, the greatest impact on the total power consumption P was studied. Using the results from Fig.4, the power required for milling slot was expressed as P_m mentioned above.

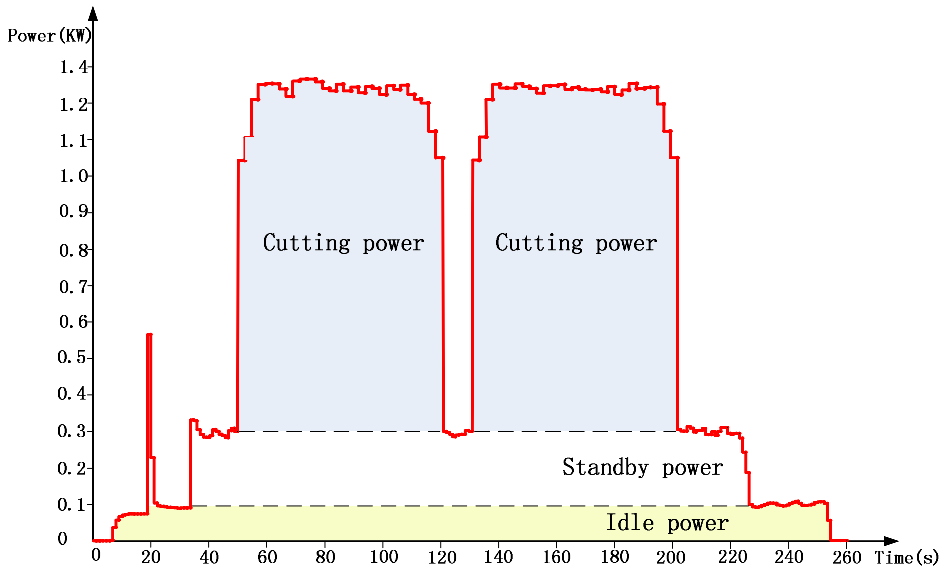
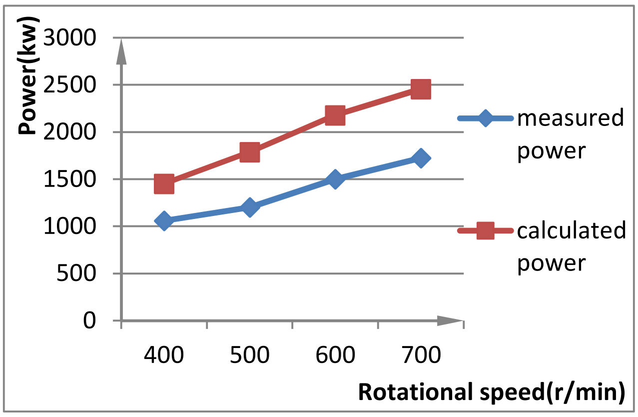


Fig.4 An example of the entire energy consumption profile of a machining process



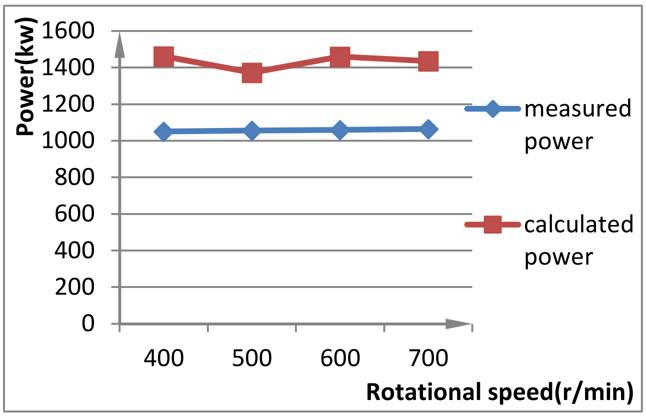


Fig.5 Power relationship under different rotational speeds Fig.6Power relationship under different cutting depths

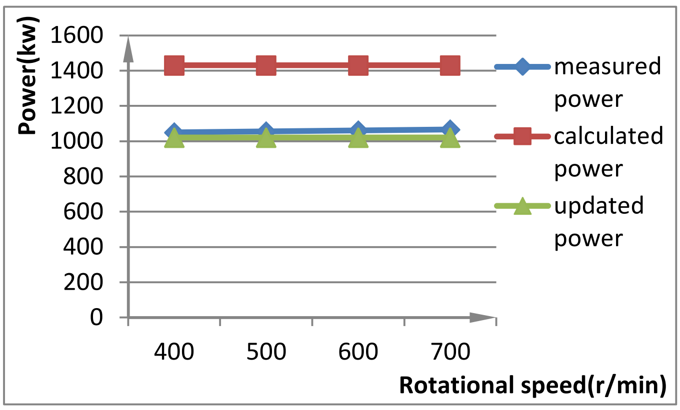


Fig.7Power relationship under different feed rates

Fig.5 and Fig.6 show the relationship between measured spindle power and calculated cutting power. It is found that the measured spindle power is a multiple of calculated cutting power. As can be seen from Fig. 5, for the same cutting depth and feed rate, each of the four conditions (rotational speed n=400,500,600,700r/min) achieved the same trend. For the same rotational speed and feed rate, each of the four conditions (cutting depth a_p=1, 1.2, 1.4, 1.6mm) achieved similar trend in Fig. 6.It can be assumed that theoretical cutting power is 1.4 times higher than experimental spindle power and the theory model is therefore updated. Updated power is used to express the multiple of measured power. For this purpose, another replication experiment was conducted to determine multiple relationships, and Fig.7 shows the results. For the same rotational speed and cutting depth, each of the four conditions (feed rate F=20, 30, 40, 50 mm/min) shows the same tendency. Consequently, the previous hypothesis is experimentally confirmed.

It can be concluded that consumed power increases with the increase of rotational speed. As can be seen from Figs.5-6, the relative error of the actual measured spindle power and the updated calculation power is rather small; the cutting power model of CNC milling machine proposed in this paper can reflect the trend of actual spindle power consumption well.

Conclusions

A cutting power model for end milling operation has been developed in this research. It was found through experiment that rotational speed affects cutting power visibly when compared with feed rate and depth of cut. Experiments were performed to verify this modeling method and promising results were achieved. However, feed shaft power needs to be verified in the near future.This paperonly aimed at end milling process; other types of cutting processes need to be studied. The suggested strategy is for more types of cutting models to be developed to predict the energy consumption for cutting in the near future.

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