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Evaluation method for cutting energy efficiency of high-speed milling cutter

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Abstract. Based on the analysis of the energy flow configuration in the machine tool spindle system, the energy efficiency model of the high-speed milling cutter is put forward. Through the high-speed milling experiment, the relation among the cutter vibration, the cutter wear, the maximum machined surface scallop height and the additional energy consumption of the machine tool spindle system are researched to establish the energy effect ratio models of the cutting layer thickness and machined surface scallop height. And then the evaluation method for the cutting energy efficiency of the high-speed milling cutter is proposed and verified by the energy efficiency comparison experiments.

Key words. High-speedmillingcutter, vibration, cutting energy, machined surface scallop height, energyeffectratio.

1. Introduction

The cutting energy efficiency of milling cutter is an important indicator that reflects the relation between the cutting energy efficiency and the process object.To achieve the high energy efficiency cutting, the principal problem is to establish the energy efficiency evaluation model. It is well known that the energy efficiency is the ratio of the effective cutting energy consumption power to the spindle system input power[1], which only represents the energy utilization efficiency and cannot reflect the influence of the tool, the process and other external factors on the cutting capacity and the cutting efficiency. Thus, it is necessary to conduct a deep study.

Gutowski[2], Schudeleit [3] and Zhou [4] studied energy models. The existing energy models of the machine tool system have revealed the energy efficiency of electromechanical main drive system in the machine service process, but failed to completely reveal the composition of the cutting energy consumption and the rela-

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tion between the milling cutter energy consumption and the process design object. Likewise, with the difficulty in calculating the effective cutting energy consumption of the milling cutter, there is a lager error in solving the energy efficiency, and the energy efficiency can't be characterized accurately. Therefore, there areunclear and uncertainproblems in the energy efficiency evaluation for the high-speed milling cutter.

During the high-speed milling process, the cutter vibration and the cutter wear increase the proportion of friction energy consumption in the cutting energy[5],but Sealy[6], Liu [7], and HugoM [8]discovered that cutter's vibration and wearalso reduce the machined surface quality, the tool service life and the cutting efficiency. Therefore, it's necessary to establish an evaluation model on the basis of energy consumption, which can reflect the cutting ability and the machining effect. Liu, Ma, Meng Liu and Li studied the relation among the energy efficiency and the cutting efficiencythe production cost, the surface roughness and the energy consumption, but haven't combined the energy with the machining target effectively. Therefore, the cutting energy efficiency model and the evaluation method for milling cutter are acquired to the further research.

Based on the input and output energy characteristics of spindle system, the cutting energy efficiency model of high-speed milling cutter is established. Through the experiment, the influence of the additional cutting energy efficiency on the cutting energy efficiency is analyzed. The energy efficiency ratio models of the cutting layer thickness and the machined surface scallop height are established. The relation among the input power of the machine tool spindle system, the cutting energy consumption, the cutting layer thickness and the machined surface scallop height is revealed and the evaluation method of the cutting energy efficiency is proposed and verified by the energy efficiency comparison experiments.

2. Energy efficiency of spindle system in high-speed milling process

During high-speed milling process, the energy flow configuration of the machine tool spindle system is shown in Figure1. The relation between the input and output energy of the machine tool spindle system is shown in Eq. (1).

$$P_i(t) = P_L(t) + P_a(t) + P_s(t) + P_c(t) + \Delta P_f(t) \tag{1}$$

Where $P_i(t)$ is the input power of the spindle system at time t, $P_L(t)$ is the transmission energy consumption power of spindle feed system at time t, $Pa(t)$ is the additional loss power of the spindle feed system at time t, $Ps(t)$ is the generalized energy storage power of the spindle feed system at time t, $Pc(t)$ is the cutting consumption power of milling cutter at time t, $\Delta P_f(t)$ is the additional loss power of the cutter wear at time t.

Herein, $P_s(t)$ is the generalized energy storage power of spindle feed system, as

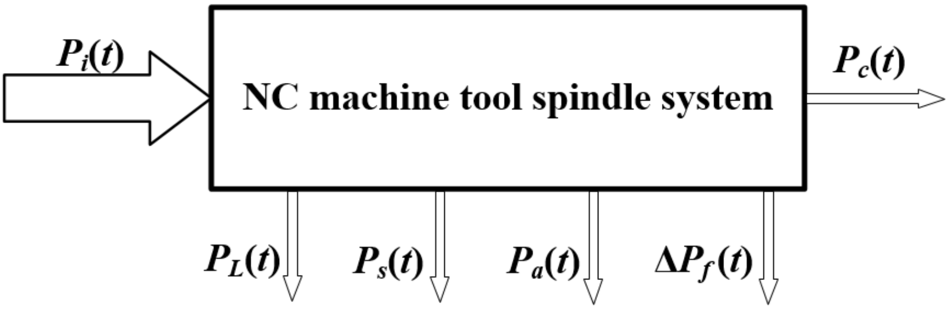


Fig. 1. Input and output energy of machine tool spindle system

shown in Eq.(2).

$$P_s(t) = \frac{dE_s(t)}{dt}, E_s(t) = \frac{1}{2}kA(t)^2 \tag{2}$$

Where $E_s(t)$ is the generalized energy storage of machine tool spindle system at time t, $A(t)$ is the vibration amplitude of spindle system at time t, k is the vibration coefficient of NC machine tool spindle system.

According to Kienzle-Vector formulationMustafa [14],the cutting energy consumption power of milling cutter Pc is shown in Eq.(3).

$$P_c = A_D k_c h_D^{-\mu} v_c \tag{3}$$

Where A_D is the cutting area, k_c is the cutting force per unit cutting area that the nominal thickness and nominal width are 1mm, h_D is the nominal thickness of cutting layer, ν_c is the cutting velocity and μ is the fixed coefficient.

The spindle system energy efficiency ψ is the ratio of effective cutting consumption power to the input power of the spindle system at a certain moment, as shown in Eq. (4).

$$\psi = \frac{P_c(t)}{P_c(t) + P_a(t) + P_s(t) + P_L(t) + \Delta P_f(t)} \tag{4}$$

When the spindle system is unloaded, the total input power of spindle system is called spindle system no-load power which is represented by P_u. It includes the generalized energy storage power of spindle feed system and the transmission energy consumption power of unloaded machine spindle feed system, as shown in Eq.(5).

$$P_u(t) = P_s(t) + P_L(t) \tag{5}$$

When the spindle system is loaded, the transmission resistance and motor magnetic field are all changed, thus, the total power loss of spindle feed drive system and spindle motor increases on the basis of original unload energy loss, and the increase is referred to as the additional power loss of spindle feed system Pa(t). And with the increase of cutting stroke, the milling cutter wear will inevitably cause the energy consumption $\Delta P_f(t)$. Meanwhile, the cutting of milling cutter will cause the vibration energy consumption $\Delta P_s(t)$.

The input power difference of loaded and unloaded spindle system of NC machine is the sum of cutting energy consumption of milling cutter and additional power loss caused by the cutting, as shown in Eq. (6).

$$\Delta P_i(t) = P_c(t) + P_a(t) + \Delta P_s(t) + \Delta P_f(t) \tag{6}$$

As known from Eq. (4)to Eq. (6), with increasing the cutting stroke, the cutter vibration and the cutter wear will increase the additional energy consumption power and reduce the energy efficiency of spindle system.

3. Influence of additional energy consumption on cutting energy consumption of cutting energy efficiency for high-speed milling cutter

The machine tool DMTGVML-1000E is used in this experiment. The milling cutter is assembled cemented carbide blade with five teeth and 45 cutting edge angle, which diameter is 63mm. The size of workpiece HT300 is 300×150×100mm. *ap* is the cutting depth of 0.4mm, *ae* is the cutting width of 30mm, *fz* is the per tooth feed of 0.4mm/z, νc is the cutting velocity of 395m/min and the maximum cutting stroke is 8700mm.

During the initial stage of milling process, the cutter vibration and the cutter wear are in an unstable stage. In order to ensure experimental data accurately, the cutter vibration, the cutter wear, the machined surface quality and the spindle system power are measured from the cutting stroke of 5100mm. In order to analyze the above parameters under the longer cutting stroke, the experimental data are conducted to comparison analysis when the cutting strokes reach to 5100mm and 8700mm, as shown in Table 1.

Table 1.Experimental data of milling cutter

L(mm)	A_x(m/s^2)	f_x(Hz)	A_y(m/s^2)	f_y(Hz)	A_z(m/s^2)	f_z(Hz)	h_{max}(μm)
5100	3.12	950	1.14	8175	1.16	8000	10.9
8700	4.11	950	2.01	8250	1.96	8375	12.8

Where A_x denotes the vibration amplitude in the row spacing direction of the spindle, f_x denotes the vibration frequency in the row spacing direction of the spindle, Ay denotes the vibration amplitude in the axial direction of the spindle, $f_y$denotes the vibration frequency in the axial direction of the spindle, A_z denotes the vibration amplitude in the feed direction of the spindle, f_z denotes the vibration frequency in the feed direction of the spindle, h_{max} denotes the maximum machined surface scallop height, P_{i1} denotes the input power of no-load spindle system, P_{i2} denotes the input power of spindle system under load.

As known from the wear detection results of the rake face and the flank face of milling cutter, when the cutting stroke reaches to 5100mm, the cutter wear is not distinct.But when the cutting stroke increases to 8700mm, there are obvious wears on the rake face and flank face of milling cutter. The wear depth on the rake face $W_h$is 2.74μm and the wear width on the flank face W_e is 9.07μm.

According to the above experimental results, the cutting energy efficiency of milling cutter in this experiment is calculated with the energy efficiency model. From Table 1 and Eq. (2), the vibration energy consumption is 22.27W and 44.57W respectively, when the cutting strokesare 5100mm and 8700mm respectively.

Based onexperimental data in Table 1, the input powers of the spindle system are 200W and 240Wrespectively when the cutting stroke is 5100mm and 8700mm respectively. From Eq. (3), the effective cutting energy consumption power is 126.54W, and then from Eq.(4), the spindle system energy efficiency are 0.521 and 0.342 respectively under the above two cutting strokes.

According to the experimental results, when the cutting stroke increases from5100mm to 8700mm, the vibration amplitude, the vibration frequency, the wear depth on the rake face, and the wear width on the flank face are all changed.The energy consumption caused by the cutter vibration and the cutter wear is increased obviously and the energy efficiency of the spindle system is reduced from 0.521 to 0.342, meanwhile, the machined surface scallopheight is increased, and the cutting capacity and the machining quality of milling cutter are reduced. The energy efficiency model of milling cutter can only reflect the change of energy consumption, but cannot completely reflect the change of the cutting ability and the machining quality, so it is necessary to establish a model which can reflect the relationship between cutting energy consumption and machining efficiency on the basis of the energy efficiency model of spindle system.

4. Energy effect ratio model of cutting thickness and energy effect ratio model of machined surface scallop height

The energy consumption and conversion process also canbe regarded as the formation process of machined surface. Cutting layer parameters are important characteristic factors in the formation process of machined surface and have considerable influence on the cutting force, the cutter wear, the machined surface quality and the cutting efficiency. Therefore, the cutting ability is measured by the cutting thickness under the per unit cutting power. Based on the cutting input power and the cutting layer thickness, the energy effect ratio model represented by K_h(t) is established, as shown in Eq. (7).

$$K_h(t) = \frac{f_z \sin \kappa_\gamma}{P_c(t) + \Delta P_s(t) + \Delta P_f(t)} \tag{7}$$

From the Eq. (7), if the energy effect ratio $K_h(t)$ is constant, the relationship between the cutting layer thickness and the cutting input energy power will be stable. If the energy effect ratio$K_h(t)$changes frequently, this relation will be unstable. The energy effect ratio of the cutting layer thickness are effectively controlled by the cutting edge angle and the per tooth feed. Thus, the energy effect ratio of the cutting layer thickness cannot only evaluate the cutting ability, but also judge and control the cutting process stability of high-speed milling cutter.

The input power of spindle system and the maximum machined surface scallop height h_{max} are adopted to establish the energy effect ratio model of the machined surface scallop height represented by $K_V(t)$, as shown in the Eq.(8).

$$K_V(t) = \frac{1}{[P_c(t) + \Delta P_s(t) + \Delta P_f(t)]h_{\max}} \tag{8}$$

From the above equations, if the machined surface scallop height and the input power are smaller, the energy effect ratio of the machined surface scallop heightwill be greater and the cutting effect will be better. The Eq. (8)can effectively reflect the relation between the cutting energy consumption and the machining quality of milling cutter.

Based on the relationship between the machined surface scallop height and the cutting layer thickness, another expression of the energy efficiency ratio of the machined surface scallop height is obtained, as shown in Eq.(9).

$$K_V(t) = \frac{(\cot \kappa_\gamma + \cot\kappa_\gamma^{'}) \sin \kappa_\gamma}{[P_c(t) + \Delta P_s(t) + \Delta P_f(t)]h_D} \tag{9}$$

Where κ_γ ' is the minor cutting edge angle.

From the Eq. (9), during the milling process, the energy effect ratio of the machined surface scallop height can reflect the change state of the machined surface scallop height and the cutting input power. Combined with the Eq.(7) and the Eq.(9), the cutting capacity and the cutting process can be evaluated.

5. Cutting energy efficiency experiment of high-speed milling cutter

The NC machine tool DMTGVML-1000E is used in the experiment and the size of workpiece HT300 is 300×150×100mm. Two milling cutters are used in this experiment. Their diameters are both 63mm and the feed per tooth and the cutting speed are both same. In order to change the cutter vibration characteristics, the tooth number and the linear velocityof two milling cutters are different. The specific tool parameters and cutting parameters are shown in Table 2.

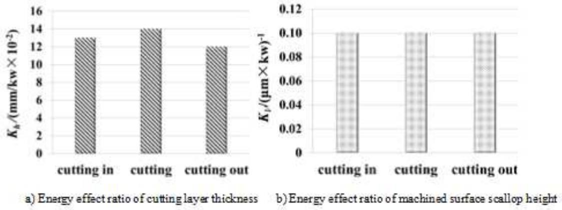
Table 2. Milling experiment scheme

experiment scheme	z	a_p (mm)	a_e (mm)	f_z(mm/z)	v_c(m/min)
scheme 1	5	0.3	30	0.08	356
scheme 2	6	0.3	30	0.08	475

Adopting above experiment schemes, hmaxis the maximum machined surface scallop height, which values are 12.88μm and 10.25μm respectively inthe experimental scheme 1 and the experimental scheme 2. As known from above experimental results, the machined quality of experimental scheme 2 is better. The energy efficiency ratio data of two experiment schemes under different cutting stages are shown in Figure 2 and Figure 3 respectively.

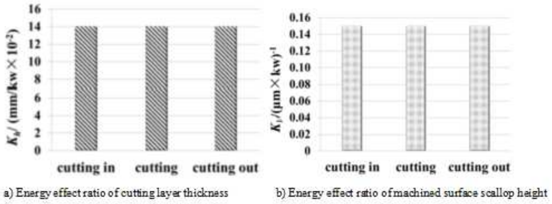
Comparing energy effect ratio data of the cutting layer thickness and the machined surface scallop height in Figure 2 and Figure 3, the energy effect ratio of the cutting thickness and machined surface scallop height of experimental scheme 2 remain unchanged in different cutting stages. The cutting stability of experimental scheme 2 is better. According to the cutting energy efficiency model, the cutting energy efficiency of the milling cutter ψ are 0.725 and 0.798 respectively in the experiment scheme 1 and the scheme 2. Therefore, the cutting energy efficiency of milling cutter in scheme 2 is higher than that in scheme 1.

In summary, under above experimental condition that the machine tool is DMTGVML-1000E, the milling cutter has six teeth, the per tooth feed *fz* is 0.15 mm/z, and the cutting speed v_c is 475m/min, if the stable energy is inputted in the cutting process, the energy will be effectively utilized and obtain better machining quality.



a) Energy effect ratio of cutting layer thickness b) Energy effect ratio of machined surface scallop height

Fig. 2. The milling cutter energy efficiency ratio of experiment scheme 1



a) Energy effect ratio of cutting layer thickness b) Energy effect ratio of machined surface scallop height

Fig. 3. The milling cutter energy efficiency ratio of experiment scheme 2

6. Conclusions

The cutting energy efficiency model of high-speed milling cutter is constructed and the proportion relation between the cutting energy and input energy of spindle system can be revealed at any time.The verification experimental results of the cutting energy efficiency model show that with the increasing of the cutting stroke, the milling cutter vibration and wear will increase the additional energy consumption power, thereby reduce the effective energy efficiency and the cutting energy efficiency of the milling cutter. Finally, the cutting ability of the milling cutter and the machining quality are reduced.

The energy effect ratio model of the cutting layer thickness is established to reflect the relation between the cutting capacity and the energy consumption. The energy effect ratio model of the machined surfacescallop height is established to reflect the relation between the machining quality and the cutting energy consumption. Adopting above models, the energy efficiency and energy effect of the milling cutter can be evaluated. The experimental results show that the evaluation model can effectively estimate the energy utilization efficiency, the cutting capacity, the machining quality of the milling cutter and can be used for the process scheme optimization.

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