Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería

Efficiency assessment of the complex process of variable cutting parameters

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Abstract

Saving energy and low carbon strategy has becoming the future trend of manufacturing industry. Cutting process in mechanical manufacturing has the characteristics of heavy energy consumption and complex process. The estimation and evaluation of energy consumption and energy efficiency of cutting process are hot topics in research groups and industry. The energy consumption of cutting process is determined by the load, which is related to the cutting parameters under fixed cutting systems, while the cutting parameter might change with the cutting process and material. Based on the relationship between energy consumption and cutting characteristics and the quality requirements, the cutting specific energy u(t) = P(t)/M(t), which is varies with time is proposed to evaluate the energy consumption of various cutting parameters under complex machining processes. The influence of cutting parameters on cutting energy consumption is studied by experiments and a calculation method is proposed to calculate cutting energy consumption. Finally, a case study of complex curve machining in mold manufacturing is illustrated to prove the effectiveness of the proposed evaluation method.

OPEN ACCESS

Published: 05/04/2022

Accepted: 24/03/2022

DOI:
10.23967/j.rimni.2022.03.014

Keywords:
variable cutting parameters
complex process
cutting specific energy
energy consumption

1. Introduction

The energy yearbook published by the U.S. energy information administration in 2012 showed that industrial electricity consumption accounted for 31% of the total electricity consumption, manufacturing electricity consumption accounted for 90% of the industrial electricity consumption, and machine tools electricity consumption occupied 75% of manufacturing electricity consumption [1]. For the reason, the energy consumption of the manufacturing industry has been widely concerned by the industry and academia. The United States Department of Energy has launched an Industrial Assessment Center program to improve the energy efficiency of manufacturing processes. Gutowski et al. at the Massachusetts Institute of Technology studied the energy consumption of various manufacturing processes on the job shop from a thermodynamic point and proposed a generalized energy flow of manufacturing system, in which machinery manufacturing is one of the important contents [2]. Peng analyzed the composition of cutting energy consumption from the perspective of mechanical mechanics, and analyzed the influence of cutting parameters on cutting power from the deduced cutting power formula [3]. Wang et al. collect experimental data of surface roughness, cutting force and power through instruments, performs multi-objective optimization based on weighted gray correlation and least squares fitting methods, and establishes a multi-objective prediction model [4]. Xie et al. analyze the energy consumption characteristics at different periods of the machining process, and obtains the coefficients of the energy consumptioncutting parameter model; then constructs the univariate influence characteristic curve and multivariate influence characteristic surface of each cutting parameter according to the cutting processing conditions; finally, the processing conditions Lower cutting parameters for energy saving decisions [5-6]. Mori et al. proposed to improve some functions of machine tools, which can reduce the energy consumption of machine tool in cutting process [7]. Qiu analyzed the cutting energy consumption and proposed a cutting energy consumption prediction model based on the exponential model and the specific cutting force model [8]. Gu and Xu established a machine tool energy consumption prediction model based on improved fruit fly algorithm and neural network integration with processing parameters as input, which can more accurately and stably predict the energy consumption of machine tools during machining [9]. Sun et al. proposed a plunge milling tool path generation method which could control the radial depth to improve the cutting efficiency and cutter life [10]. Li et al. proposed cutting tools energy consumption base on material extraction, manufacturing, use, and recycling [11]. Winter et al. proposed a method for reducing cutting fluid and energy consumption [12]. Study the energy consumption of the machine tool spindle during startup and operation [13]. The International Organization drafted the standard “environmental evaluation of machine tools” in 2010 (ISO 14955-1:2014), and the International Organization for Standardization had revised the standard “environmental evaluation of machine tools” in 2017 (ISO 14955-1:2017) [14]. The energy consumption of manufacturing system or flexible manufacturing system is further studied [15-18].

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Scholars naturally study energy efficiency while investigating energy consumption. In the aspect of energy efficiency evaluation, the scholars use the physical concept “specific energy” to scale the energy efficiency of the machine, that is, specific energy consumption (SEC). It represents the power consumed for removing unit volume material. Patrik et al. apply an interdisciplinary perspective to study industrial system energy efficiency [19]. Liu et al. put forward the development trend of energy efficiency of mechanical processing system [20]. Zhang analyzed energy efficiency techniques in the domain of discrete part manufacturing by reviewing [21]. Production decisions consider energy efficiency [22]. The energy efficiency of machine tool and production system was discussed hierarchically [23]. Real time power consumption monitoring to improve energy efficiency was presented [24]. Effects of tool geometry and cutting parameters on energy efficiency during turning of ANSI 4140 steel were investigated [25]. Through the study of effects of the sawing parameters on sawing force and energy consumption, Huang et al. proved that increasing the grain depth of cutting is conducive to improve the ratio of volume crushing, thus reduce the sawing specific energy [26]. Rodrigues and Coelho studied the relationship between the SEC and cutting speed and tool geometry angle in the condition of high speed cutting [27]. On the basis of a large amount of collected data, Gutowski et al. established averaged SEC diagrams based on the materials for a variety of technology [28].

The SEC mentioned above can be a factor on its impact or the average value of the whole cutting energy consumption divided by removed material. The change of SEC caused by the change of cutting parameters to guarantee the quality in the complex process is not considered. That is to say, the time characteristic of energy consumption is not considered in the cutting process. Energy consumption is a function of time in the cutting process. For the reason, in this paper, based on the change of cutting parameters with time, the energy efficiency evaluation method of cutting technology of variable cutting parameters is proposed. Based on the experimental study of the influence of the cutting parameters on the energy consumption and the cutting quality, a method for evaluating the energy consumption of complex machining is proposed.

2. Energy consumption analysis of cutting process

2.1 Energy consumption of cutting process

The energy consumption of the cutting process is mainly composed of three parts.

1. P_1 is the power required for spindle and servo axis when the machine tool is smooth running with no-load as well as the power required for the cooling liquid(cutting fluid), air compressor, spindle cooling equipment, chip conveyor and peripheral devices such as the controller unit, etc.
2. P_2 is the power consumed by the spindle and servo axis to overcome the load in the cutting process.
3. P_3 is the power required by positioning of machine tool and acceleration/deceleration of spindle.

So the energy consumption of the cutting process E can be calculated by the Eq.(1)

$$E = P_1X(T_1 + T_2) + P_2XT_2 + P_3XT_3 \tag{1}$$

where T_1 is the no-load running time of machine tool, T_2 is the cutting time, T_3 is the time of positioning of machine tool and acceleration/deceleration of spindle, P_1 and P_3 are determined by the characteristics of the machine itself and is not affected by the cutting process. They are only related to the use time of the machine tool. Cutting power P_2 changes with the cutting load, so it is important and difficult for cutting energy consumption evaluation.

2.2. Factors affecting P_2 of cutting power2.2. Factors affecting P 2 {\displaystyle P {2}} of cutting power

Cutting power is the power consumed in the cutting process, the product of the cutting force and cutting speed on the basic point of cutting edge point at the same moment. The power consumption of the feed motion is negligible compared with the power consumption of the main cutting force F_c. Thus, cutting power $P_2 = F_c \times V_s$. Namely, the cutting power is determined by the main cutting force Fc and the cutting speed V_s. The main cutting force is determined by the cutting parameters. Taking the milling process as an example, the empirical formula for calculating the main cutting force is as follows:

$$F_c = K_{Fc} a_p^{b1} V_s^{b2} f_z^{b3} a_e^{b4} \tag{2}$$

where K_{Fc} is the influence factor related to the workpiece material and tool material, and its value is related to the experimental conditions, b_1 is the influence index of the milling depth ap on the cutting force, b_2 is the influence index of cutting speed V_s on the cutting force, b_3 is the influence index of the feed per tooth F_z(mm/z) on the cutting force,

b_4 is the influence index of the milling width ae on the cutting force. From the Eq.(2) can be known, main cutting force F_c is determined by cutting parameters (cutting speed V_s, milling depth a_p, feed per tooth F_z, milling width a_e). So, the cutting power is affected by the cutting parameters. However, the choice of cutting parameters is usually determined by the machining process and the quality. Taking the surface roughness as an example, it is not only related to the cutting parameters but also to the shape of the machining surface. Under normal conditions, increasing the cutting speed can reduce the surface roughness value. The cutting depth has little influence on the surface roughness. The feed rate which has a direct relation with the residual area has a great influence on the surface roughness. The relationship between the shape of the machining surface and the surface roughness is shown in Figure 1.

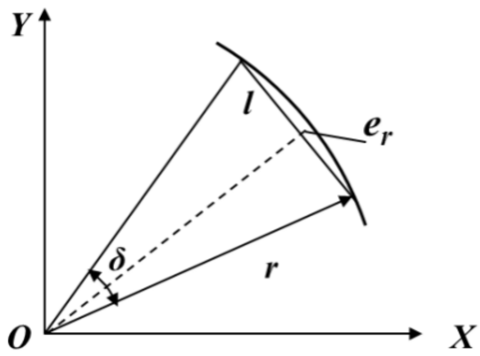

Figure 1. The relationship between residual height, feed rate and curvature

The curvature of approximating arc is directly related to the residual height. The smaller the radius of curvature is, the greater the residual height is. The relationship between the residual heighter, the feed rate and the curvature is shown in Figure 1 and Eq. (3). For example, for the complex machining surfaces shown in Figure 2, the processing parameters must be different to ensure the four different curvature surface AB, BC, CD, CE have the same surface roughness. So the process is very complex

$$e_r = l^2/8r = (fT)^2/8r \tag{3}$$

where f (mm/min）is the feed rate, T is the interpolation period, r is the radius of curvature, and l is the $\cdot_{l=fT}$.

In summary, evaluating consumption is an evaluation of the complex process. In the process of A to E, the cutting parameters should be changed with the processing track. The change of cutting parameters will affect the cutting power P_2. Obviously, this cutting power $P(t)$ is a function of cutting time. And the material removal rate (MRR) $M(t)$ determined by the cutting parameters is also a function of the time. So, the evaluation of cutting energy consumption under the condition of complex process should be the evaluation of energy consumption due to the change of cutting parameters with time. In the process of cutting energy consumption evaluation under complex conditions, the dynamic change of energy consumption due to the change of cutting parameters with time should be taken into full consideration.

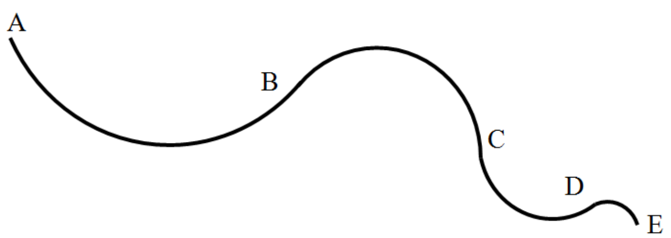

Figure 2. Illustration of processing of different curvature

2.3 Energy consumption evaluation function of complex process of variable cutting parameter

The analysis 2.2 shows that the cutting power and the MRR are the function of the processing time. The traditional SEC is the power consumed by removing the unit volume material. It is difficult to use it to describe the dynamic energy efficiency of cutting process. Therefore, combined with the process requirements of the cutting, this paper proposes to use power consumption by removing the unit volume material in the unit time to describe the energy efficiency. Namely:

$$u(t) = p(t)/M(t) \tag{4}$$

Considering the influence of the processing quality, the specific energy of the variable cutting parameters can be expressed by Eq.(5)

$$minu(t) = p(t)/M(t)c_{\min} \leq st,\ Q \leq c_{\max} \tag{5}$$

where $P(t)$ is the time-varying cutting power, $M(t)$ (mm3/min)is the time-varying material removal per unit time, $u(t)$ is the time-varying cutting special energy, Q is a quality function, $Q_{\min}$ is the lower limit of the processing quality allowed and $Q_{\max}$ is the upper limit of the processing quality allowed.

With the Eq.(5), integral $u(t)M(t)$ in temporal domains and the energy consumption function of the complex process of variable cutting parameter is obtained

$$\begin{cases} E(t) = \int_0^t u(t)M(t) \\ c_{\min} \leq s\,.\,t,\ Q \leq c_{\max} \end{cases} \tag{6}$$

3. Effects of different cutting parameters on the SEC

Known from 2.2, because of different cutting parameters, energy consumption MRR and surface roughness in the cutting process are changed, then cutting power and MRR can be obtained by experiments, and the corresponding cutting specific energy can be calculated.

3.1. Experimental apparatus and method

Milling experiments were conducted on a DMG DMU60 5-axes machining center (maximal spindle speed, 25000rpm; maximal feed speed, 7.6m/min). The cutters were tungsten carbide 2-flute straight end mills with TiN coating. They had a diameter of 16mm, a helix angle of 35° and a rake angle of 0°. The workpiece material used for milling was a typical S136 die steel. Figure 3 shows the schematic diagram for milling experiment setup. The workpiece was mounted on a piezoelectric platform dynamometer (Kistler 9257B), with which the cutting forces (F_x, F_y, F_z) were measured during the milling process.

For the selection of milling parameters, considering machine tools, such as machine tool does not produce vibration, using recommended parameters, the orthogonal experiment of four factors was designed. In the respect of experimental design, considering the characteristics of machine tools such as stiffness and vibration of machine tool, and milling parameters allowed or recommended, the orthogonal text of four factors was designed. The experimental factors are milling speed V_s (m/min), milling depth a_p (mm) and feed rate f_r(mm/r). The milling width a_e (mm) is unchanged and every factor has four levels. The experimental parameters and results are shown in Table 1.

Table 1. Experimental parameters and results

No.	V_s (m/min)	f_r (mm/r)	a_p (mm)	a_e (mm)	R_a (μm)	Cutting force $F_c(N)$	Milling power $P_c(w)$	Material removal rate MRR(cm^3/min)	Cutting specific energy u(J/mm^3)
1	150	0.05	0.2	12	0.53	34.46	86.15	0.36	14.358
2	150	0.1	0.5	12	0.76	117.00	292.51	1.79	9.805
3	150	0.15	0.8	12	1.08	216.33	540.82	4.30	7.546
4	150	0.2	1	12	1.23	295.68	739.21	7.16	6.194
5	200	0.05	0.5	12	0.42	80.64	268.82	1.19	13.554
6	200	0.1	0.2	12	0.67	47.04	156.82	0.95	9.904
7	200	0.15	1	12	1.45	259.29	864.31	7.16	7.243
8	200	0.2	0.8	12	1.66	254.86	849.55	7.64	6.672

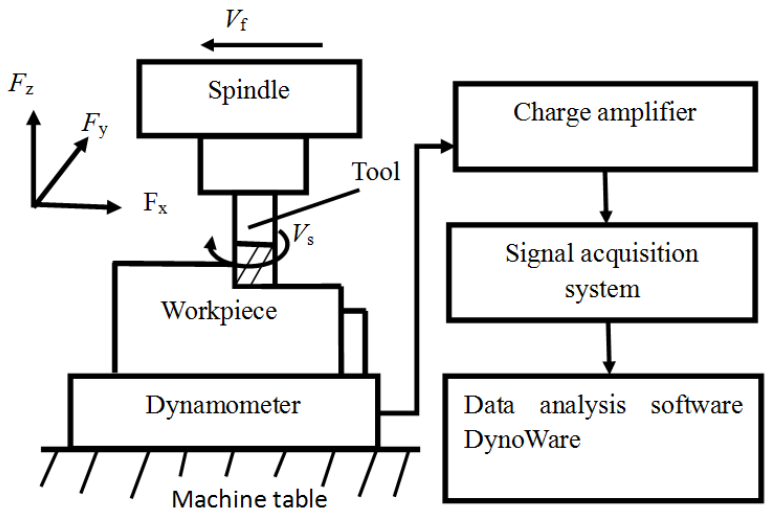

Figure 3. Illustration of processing of different curvature

9	250	0.05	0.8	12	0.507	120.03	500.13	2.39	12.556
10	250	0.1	1	12	1.12	235.15	979.78	5.97	9.847
11	250	0.15	0.2	12	0.828	61.90	257.91	1.79	8.645
12	250	0.2	0.5	12	1.11	179.28	747.00	5.97	7.508
13	300	0.05	1	12	0.66	166.75	833.73	3.58	13.973
14	300	0.1	0.8	12	0.51	171.82	859.10	5.73	8.996
15	300	0.15	0.5	12	0.68	141.46	707.32	5.37	7.903
16	300	0.2	0.2	12	0.88	114.61	573.07	2.86	12.022

3.2 Effects of different cutting parameters on the SEC

The experimental results show that the milling power range under different cutting parameters from 86.15 to 979.78W. The material removal rate varied from 0.36 to 7.64 cm^3/min. The surface roughness varied from 0.42 to 1.66μm. The cutting specific energy ranging from 6.194 to 14.358 J/mm^3. From the point of reducing the energy consumption, in the premise of ensuring the quality of processing, it is hoped to consume less energy to remove the materials, that is, the SEC can be small.

The influence of the cutting parameters on the cutting specific energy can be analyzed by the Taguchi method to obtain the cutting parameters that have the minimum effect. The quality loss (signal-to-noise ratio (S/N)) of $u(t)$ is calculated

$$S/N = -10\log\frac{\sum_{i=1}^{n} u_i^2}{n} \qquad (7)$$

To minimize the squared deviation of $u(t)$ (or minimize the quality loss), the larger the S/N is, the better. Figures 4 to 6 show the impact of speed V_s, milling depth a_p and feed per revolution f_r on $u(t)$.

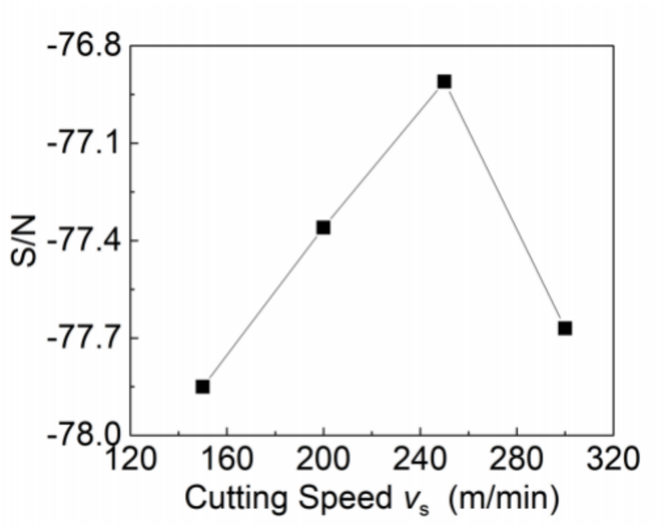

Figure 4. Effect of V_S on quality loss

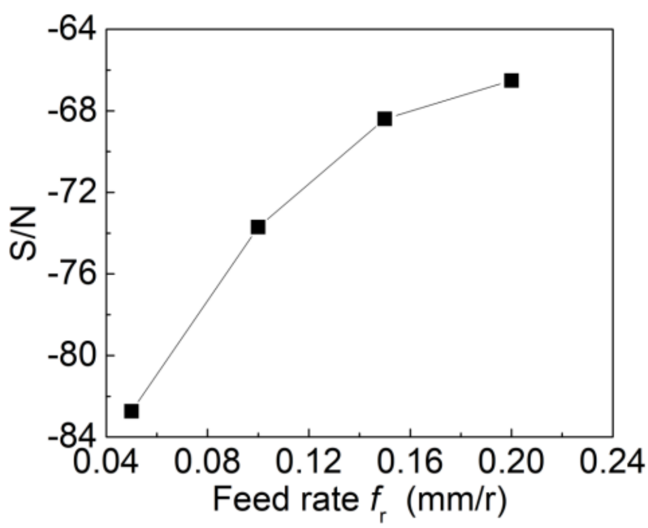

Figure 5. Effect of f_r on quality loss

Ultimately, the effect of cutting parameters on the cutting power is the influence on the cutting force. As shown in Figure 7. The total cutting force F produced by milling on the workpiece can be decomposed into the F_c along the cutting speed direction, the vertical cutting force F_{cN} along the radial direction of the milling cutter and the back force Fp along the milling tool axis. The power consumed by F_c is called cutting power P_c. The F_p does not consumed power. In the real measurement, the force F is decompose into the feed force F_x and F_y in the vertical and back force Fp

$$\angle ADG = 90 - \tan^{-1}(F_y/F_x) - \angle BDC \tag{8}$$

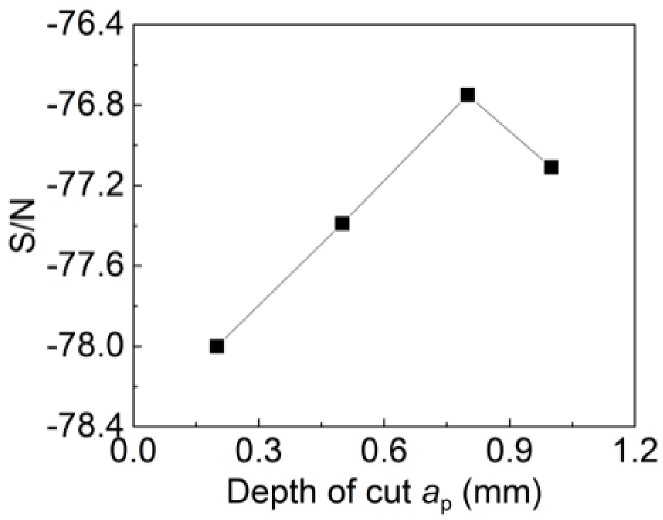

Figure 6. Effect of a_p on quality loss

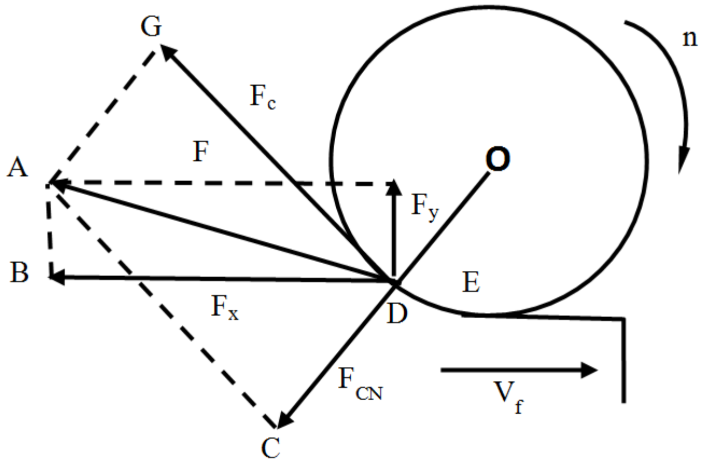

Figure 7. Milling force and decomposition

Because the $\angle BDC$ is determined, the $\angle ADG$ is related to $\tan^{-1}(F_y/F_x)$. The larger F_y/F_x is, the smaller the $\angle ADG$, then the larger F_c is, the larger the cutting power at the same cutting speed. So the factors that cause the increase of the F_c will cause the increase of F_c, and P_c will increase. The relationship between the cutting parameters and the cutting force is shown in Figures 8 to 10.

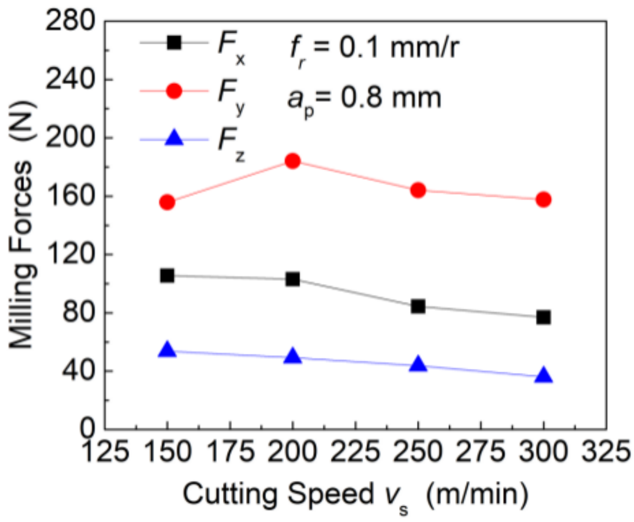

Figure 8. Effect of milling speed on the milling force

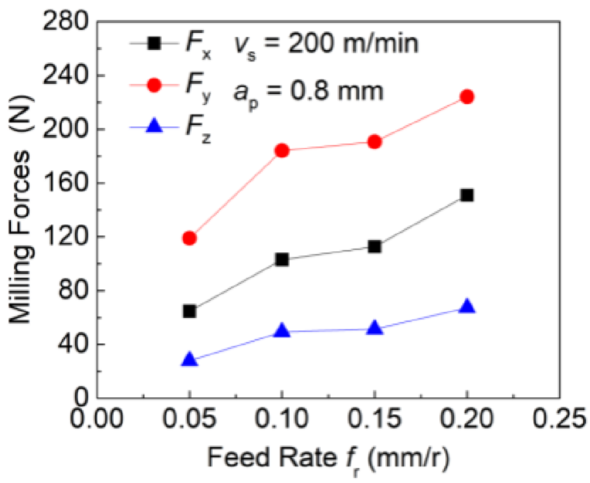

Figure 9. Effect of the amount of feed on the milling force

The influence of the cutting parameters on the cutting forces can explain the influence of the cutting parameters on the S/N. In the Figure 4, S/N increase with the increase of V_s. But when V_s > 250m/min, the S/N began to decrease. The influence of V_s on the cutting force is shown in Figure 8. F_x decrease with the increase of V_s. But the slop of the curve become smaller when V_s > 250m/min, that means the decrease of F_x is not obvious. The milling force F_y almost does not change when the cutting speed increase from 150m/min to 200m/min, but in the process of 200m/min to 300m/min, it decreases with the increase of the cutting speed, and the slope of the curve become smaller when V_s > 250m/min，that is, the F_y decrease of is not obvious. Because of $P_c = F_c \cdot V_s$, when F_y < 250m/min, the impact on S/N by decrease of F_y and F_x is larger than by increase of V_s. When the thickness of the cutting layer increases, the average deformation decreases, and the cutting force is increased, as shown in Figure 10. In Figure 6, when the milling depth increases, the S/N increases and then decrease. When the milling depth increases, the cutting depth does not change and the cutting layer width increases, then the cutting load on the cutting edge, that is, the deformation resistance of cutting and friction force on the rake face is proportional to the increase. From Figure 10, with the

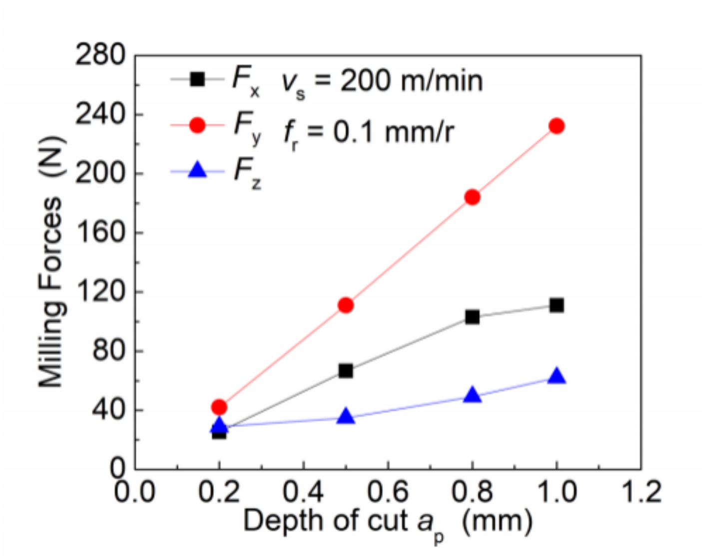

Figure 10. Effect of milling depth ap on milling force

increase of a_p, the F_y increases proportionally and the F_x increases almost proportionally in the beginning, but when a_p > 0.8mm, the slope of F_x decreases, $\tan^{-1}(F_y/F_x)$ and F_c increase, so the P_c increases. In a word, the S/N reduces when the a_p increases, but S/N increases when the a_p is larger than a certain value as shown in Figure 6.

From the above analysis and experimental results show that the cutting power and material removal rate are not same with the different cutting parameters. From the point of view of energy consumption, in the premise of satisfying the processing quality, the energy efficiency can be evaluated by the Eq.(5), and the energy consumption of the cutting process can be evaluated by the Eq.(6).

4. Energy consumption evaluation and example of complex process

As shown in Figure 11 of the processing hemisphere, the material is the same as the 2.1 experimental materials. Smooth surface with no sharp corners and pits is required. With the increase of the arc radius in the process, the cutting parameter, the unit power and the material removal amount in unit time will change with the change of the trajectory. The energy consumption of the whole process can be obtained from the Eq.(6). Considering the cutting force, tool life, surface quality and stability, according to the above experimental results, the value of V_s is equal to 250m/min. The every radial width of milling is equal.

According to the above experiments, the different cutting parameters correspond to the different cutting energy. Therefore, in the process of design, the cutting parameters can be used to determine the SEC and material removal, and then the energy consumption can be estimated. That is, under condition of known the SEC, based on the Eq.(5), integrated $u(t)M(t)$ in the time domain to obtain the energy consumption evaluation function of variable cutting parameters under the constraint of quality, as shown in Eq.(7).

By Eq.(6):

$$\begin{cases} E(t) = \int_0^t u(t)M(t) \\ 0 \leq s.t,\ Q(t) \leq 3.2 \end{cases} \tag{10}$$

Total energy of processing semicircle:

$$\begin{cases} E(t) = \int_{t_A}^{t_B} u(t)M(t) = \sum_{i=1}^{i=n} u(t_i)M(t_i) \\ 0 \leq s.t,\ Q(t) \leq 3.2 \end{cases} \tag{11}$$

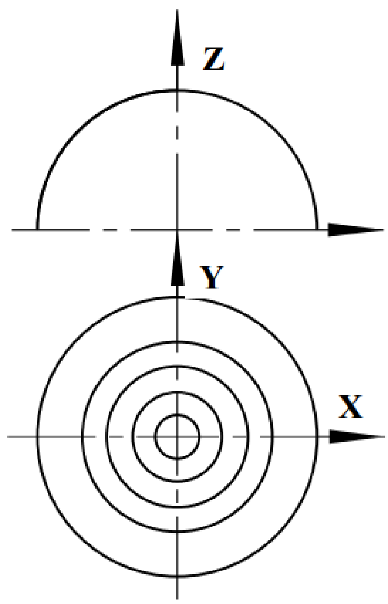

Figure 11. Illustration of complex process

where n is the total number of processing steps, $u(t_i)$ is a better specific energy of processing different radius circles and $M(t_i)$ is the material removal rate of processing different radius circle.

Make the angle increment between processing point and Z axis 1 degree. The machine tool is ¢10 ball cutter. Then the Eq.(10) can be written:

$$\begin{cases} E(t) = \int_{t_A}^{t_B} u(t)M(t) = \sum_{i=1}^{i=90} u(t_i)M(t_i) \\ 0 \leq s.t,\ Q(t) \leq 3.2 \end{cases} \tag{12}$$

As shown in Figure 11 of the hemisphere, when the machining allowance is 1mm, surface roughness $Ra \leq 3.2$ and the degree between processing point and the Z axis is in 0□10°,10°□20°,20°□30° ,30□40°,40°□60°,60°□90°, different feed speed is used to ensure the processing quality. The energy consumption calculated by Eq.(10) is about 7,500 kilojoule.

5. Conclusions

At present, the research on cutting process of energy still remain in the concept of static macro, such as the energy flow of manufacturing system, the proportion of the cutting energy consumption in the entire system and the composition of energy consumption of machine tool. Cutting process is a complicated process because the cutting power is determined by the load, the load is determined by the cutting parameters in the machining process system. During the cutting process, cutting parameters will change with the change of processing elements. In order to guarantee the machining quality, selection of cutting parameters should change with process and processing factors. In the process of cutting energy consumption under complex conditions, the dynamic change of energy consumption due to the change of cutting parameters with time should be taken into full consideration. Studying on machining efficiency is to seek the minimum energy consumption or the maximum material removal per unit time under the condition of quality assurance. So it is proposed to evaluate the energy consumption of the complex machining process with the specific energy $u(t) = P(t)/M(t)$. Because the evaluation index considers the actual situation during the cutting process, it can reflect the energy consumption of complex process of variable cutting parameters which makes it possible that energy consumption becomes a factor to be considered in computer aided process design. It also provides the basis for the energy consumption to be one of the conditions for choosing the cutting parameters in the design of adaptive system for cutting machine tools.

Acknowledgments

The authors would like to gratefully acknowledge the financial support of the National Natural Science Foundation of

China (Grant No. 51775113).

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