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A generalized analysis of energy saving strategies through experiment for CNC milling machine tools

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Abstract

This paper proposes the elaboration model of energy requirement prediction taking into account the power of standby, spindle rotation in non-load, feeding and rapid movement in X, Y, Z+ and Z- axially, and specific energy consumption (SEC) in the X and Y cutting directions respectively, which could not be considered completely in other models. Each part energy of specific machine tools could be obtained through little experiments for identifying the relationship between energy and tool path with cutting parameters. The method is validated by 27 trial cutting experiment in X and Y cutting directions in VMC850E machine, the results show that the SEC in the X and Y cutting directions are exactly different. Moreover, it is found that spindle power should be piecewise linear representation according to spindle speed characteristic, due to the correlation coefficient of power model only has 25.45% without segmented. Additionally, the correlation coefficient of improved SEC model could reach to more than 99.98% in each segment. The contribution of this paper is mainly the elaboration energy consumption model considering the cutting direction, which is an efficient approach for predicting energy consumption through tool path to achieve sustainable production in manufacturing sectors.

Keywords: energy predict model; energy-saving strategy; CNC milling process; tool path

1. Introduction

The manufacturing industry consumes a lot of energy and consequently has to adopt energy-saving techniques such as optimization of workshop scheduling, machine tools structure, machining process, and process path [1]. The effective implementation of manifold measures for increasing energy efficiency has had a positive effect on reducing electricity consumption from workshop to machining process. Additionally, the improvement of machining process play more important role on the condition of fixed machine tools, especially the cutting parameters, tool path, process route, and so on [2]. Computer numerical control (CNC) machining play a significant role in manufacturing activities with the advantage of highly automated control system. For CNC equipment, it executes the NC notes step by step through tool activities based on workpiece geometry. Therefore, it is indispensable to establish the elaboration energy consumption model for CNC machining considering NC nodes implementation activities to evaluate energy efficiency of specific part machining. Due to the complexity of operating principle and activities in each axis direction for different kinds of CNC machine, it can be challenging to establish elaboration energy requirements model under complexity of cutting parameters and tool path.

The current research on machining energy consumption focus on material remove process, auxiliary system, and whole energy calculation. The methods could be classified into general methods and intelligent methods according to whether or not using big data information and artificial intelligence approach.

The general methods mainly concentrate on establishment of energy efficiency model for excavating the interrelation of unit energy consumption and machining parameters. A generalized representation of most existing energy models is from Gutowski et al. [3] using material removal rate (MRR) as the norm when modeling energy usage in machining, which is widely adopted and improved by many researchers. Following observation of MRR and specific energy consumption, Diaz et al. [4] validated the MRR's effect on energy consumption through experiment in a 3-axis machining center. Similarly, Kara and Li [5] verified the SEC model of Gutowski et al. [3] to characterize the correlation with MRR through five turning machines and three milling machines. Except MRR, it is noted that the spindle speed also has an important effect on the total cutting energy. Thus, Li et al. [6] proposed the improved SEC model for expressing correlation with n and MRR proved through orthogonal experiment. Unlike above models considering MRR and n as an aggregate function of cutting process, Newman et al. [7] partially considered the contribution of individual process parameters (depth of cut) to cutting power for selecting energy efficiency process planning. Meanwhile, Balogun and Mativenga [8] researched the influence of toolpaths (including tool life) on energy requirements, and first proposed the speed power segmented characteristic based on speed. However, the MRR-based methods only take into account partly toolpaths influence, and little experiments are carried out focusing on cutting directions differences for turning or milling machining.

Additionally, in practical energy consumption calculation, the entire energy consumption requirements for machining a workpiece should also be obtained for understanding machine tools' characteristic. The power mainly takes into account of standby, feed axis movement, air cut, and cutting process occupying the main position. Diaz et al. [4] calculated the energy consumption through divided power into cutting and air cutting states. Similarly, Mori et al. [9] and Balogun et al. [10] identified the power into constant power, cutting, and air cutting to calculate energy requirements and carbon emission with corresponding running time. He et al. [11] proposed the practical calculation method of NC machining through decomposing subsystems of CNC machines. For better identifying the energy state of machines, Behrendt et al. [12] developed the monitoring system for machine tools, which research the energy constitutes all of the nine machine tools. From the results, we found that spindle power follow a linear relationship with spindle speed for turning machine. Altıntaş et al. [13] (2016) developed a different spindle power model in 5-axis vertical machining center founding that the power load of the spindle changes with the speed. Similarly, Moradnazhad and Unver [14] analyzed the energy characteristics of turn-mill machining in feed movement in X, Y, Z+ and Z- as well as main spindle and sub-spindle. That means that the relationship trend between the spindle power of different kinds of machine tools and speed are not always a linear proportional constants in each speed space. Thus, the air cut power should be modeled accurately based on spindle running characteristic for specific machine. Hu et al. [15] calculated energy considering cutting and non-cutting state for optimizing the cutting parameters according to theoretical power model and time relationship with process parameters. The major existing models are collected as shown in Table 1.

With the development of Internet of Things technology, intelligent methods are being studied in recently years to monitor and manage energy consumption in machining workshop. Shin et al. [16] established an online optimization model adopting dynamic composition approach and divide-and-conquer technique based on component. Chen et al. [17] proposed the framework of Internet of Things to monitor and management energy contributing to identify the strategies of reducing energy. The deep learning algorithms are used to establish a generic energy prediction model in [18] for identifying energy consumption characteristics among different machine tools under the condition of big machinery data. Xu et al. [19] proposed a novel intelligent reasoning system to assess energy consumption and optimize cutting parameters through black-box theory. Intelligent methods for energy consumption prediction are still under development, which still have many problems to be solved such as how to let users understand the specific meaning of energy consumption in black-box and how to calculate the energy consumption for machined component. While intelligent design methods are mainly deep learning, neural networks, etc. The key is the accuracy of a large amount of data processing, which is a black box structure. It is effective in the management of the energy consumption of the workshop and the machine tools, but it is difficult to understand the energy construction for a single component. From the above analysis, we observe the existing energy models have not studied the influence of spindle power characteristic under non-load on all cutting power model.

Table 1 A summary of major energy consumption models

Literature	Model
Gutowski et al. 2006	$E = (P_0 + K \cdot MRR) \cdot t$ P_0 represents the portion of total energy consumed at a constant rate, while $K \cdot MRR$ represents energy required for material removal proportional to the *MRR*.
Diaz et al., 2011; Kara and Li, 2011	$\mathrm{E_{cut}} = \mathrm{SEC} \cdot V_{cut} = (C_0 + \frac{C_1}{MRR}) \cdot V_{cut}$ C_0 and C_1 are the coefficients related to the specific machine tool.
Li et al., 2013	$\mathrm{E_{cut}} = \mathrm{SEC} \cdot V_{cut} = (k_0 + k_1 \frac{n}{MRR} + k_2 \frac{1}{MRR}) \cdot V_{cut}$ *n* is the spindle speed; k_0, k_1, and k_2 are the coefficients related to the machine tool.
Diaz et al. 2011	$\mathrm{E} = (P_{cut} + P_{air}) \cdot t$ P_{cut} represents the power of cutting process, P_{air} represents the power of air process.
Mori et al. 2011	$E=P_1 \times (T_1+T_2)+P_2 \times T_2+ P_3 \times T_3$ P_1 is the constant power during the machine operation, T_1 is the cycle time during non-cutting stage, T_2 is the cycle time during cutting state, P_2 is the power for cutting by the spindle and servo motor, P_3 is the power to position the work and to accelerate/decelerate the spindle to the specified speed, T_3 is the time for spindle rotation.
He et al. 2012	$\mathrm{E} = \int_{t_{sp}} P_{sp} dt + \int_{t_{cut}} P_{cut} dt + \sum_{i=1}^{m} \int_{t_f} P_i dt + P_{cool} t_{cool} + P_{tc} t_{tc} + (P_{servo} + P_{fan}) t$ P_{sp} is the power of spindle with corresponding time t_{sp}, P_{cut} is the cutting power with time t_{cut}, *i* is the *i*th axis, m is the number of axis, P_i is the feed power for *i*th axis, P_{cool} is the power of cooling system with time t_{tool}, P_{tc} is the power of tool-change with time t_{tc}, P_{serve} and P_{fan} are the power of servos systems and fan motors separately with time *t*.
Balogun and Mativenga, 2013	$\mathrm{E} = E_b + E_r + P_{tc} \cdot t_{tc}[INT\left(\frac{t_2}{T}\right) + 1] + P_{air} \cdot t_{air} + (P_s + P_{cool} + k \cdot MRR) \cdot t_c$ E_b is the basic energy, E_r is the ready state energy, P_{tc} is the tool change power with time t_{tc}, *T* is the tool life, P_{air} is the air cutting power with the time t_{air}, P_s and P_{cool} are the power of spindle and coolant system respectively, t_c is the cutting time, $k \cdot MRR$ represents energy required for material removal proportional to the MRR.

Although the existing energy models have improved prediction precision, there are still some problem requiring in-depth study.

(1) Most existing models assumed the cutting power is the same in X and Y cutting direction without considering cutting direction, while we found that it is different in our experiment. Additionally, we also found that the spindle power is not always linear proportional increasing relation because of the different principle of constant torque speed regulation and constant power speed regulation. The different trend of spindle power directly affects the accuracy of cutting power prediction due to the spindle support most of the load during the material cutting process. This issue is also be found in some research review [12, 13], while did not conduct in-depth research. Therefore, it is necessary to improve the spindle power model.

(2) Additionally, the existing SEC model assumed that the energy required to remove the same material is also the uniform in all cutting directions (X, Y, Z and other axis for 5-axis machine), while practically this assumption is defective due to different axis undertake different loads depending on the direction of motion. This phenomenon has been verified in our experiment and some research literatures [13, 20].

(3) One NC code could describe a whole machining process, and hence, the energy consumption could be

predicted based on correlation coefficient of selected machine. Some model such as SEC could not directly calculate energy consumption of each activities during the executive process of NC nodes [21]. Thus, the energy prediction for the spindle axis, feed axis, and cutting axis should be established based on the tool paths from NC codes.

Based on the above analysis, the aim of this paper is to study energy consumption model for 3-axis CNC machining process through experiment test. The proposed energy model is based on selected CNC machines, individual process parameter, cutting directions in 3-axis machining. We also find that spindle power is not always be linear proportional increasing trend with spindle speed due to the different speed control methods (constant torque speed regulation and constant power speed regulation). That directly affects the accuracy of energy consumption calculation in the air cutting process. Especially, specific energy consumption model also be affected when reaching the rated power of the spindle. Therefore, it is necessary for improving the existing energy model through piecewise way according to spindle speed. Another contribution of this paper is to develop energy model for CNC milling considering each activity of tool path and machine movement.

The rest of this paper is arranged as follows. The improved energy model for CNC machine is presented in Section 2. Section 3 gives the experiment design and results analysis. Finally, the conclusion and future work are drawn in Section 4.

2. The elaboration model analysis of energy consumption

Energy consumed of running an NC block for machining component on CNC equipment could be divided into two parts---consume energy at a constant rate, and consume energy at a variable rate.

$$E_{NC\text{-}block} = E_{constant} + E_{variable} \tag{1}$$

where $E_{NC\text{-}block}$ is the energy consumed by a component, $E_{constant}$ is the consume energy at a constant rate (like standby, coolant fluid, and tool change) without relation with cutting parameters, $E_{variable}$ is the consume energy at a variable rate decided by cutting parameters, tool path, and movement directions.

$$E_{NC\text{-}block} = E_{standby} + E_{coolant} + E_{tool\_change} + E_{rapid} + E_{spindle} + E_{feed} + E_{cut} \tag{2}$$

Since the energy required in different components machining operation, the total energy consumption is calculated through identifying energy need of each activity in its NC program. Due to NC codes reflect the used manufacturing method including energy requirements of all activities, it is better method to calculate energy demand based on G code. Meanwhile, each activity machining time can be also calculated according to cutting parameters and tool information. Additionally, the power of each activity is obtained by little experiment on CNC equipment. It is key step to establish power model of specific CNC machine for predicting energy consumption, which is be expressed as

$$P = P_{standby} + P_{coolant} + P_{tool\_change} + P_{rapid} + P_{feed} + P_{spindle} + P_{cut} \tag{3}$$

where $P_{standby}$ constitutes the controller, lights, etc. $P_{coolant}$ is the coolant fluid power depending on the state of the machine. The tool generally need rapid feed to the workpiece coordinate point, which also need power ignored in other power model. P_{tool_change} is the power of changing tool. P_{rapid} is the power of the rapid movement of axis. P_{feed} is the power of feed in different axis (X, Y and Z) used in air feed movement between two points. $P_{spindle}$ is the power of spindle rotation related to spindle speed. P_{cut} is power drawn from removing material. Considering the corresponding time of each acidity, the energy of one NC-block is expressed as

$$E_{NC\text{-}block} = P_{standby} \cdot t_{standby} + P_{coolant} \cdot t_{coolant} + P_{tool\_change} \cdot t_{tool\_change} + P_{rapid} \cdot t_{rapid} + P_{spindle} \cdot t_{spindle} + P_{feed} \cdot t_{feed} + P_{cut} \cdot t_{cut} \tag{4}$$

The feed power includes rapid power and air feed power according to movement rate. The rapid feed rate is constant decided by machine tool design structure, and hence, it is constant obtained by experiment on different axis expressed as P^{x}_{rapid}, P^{y}_{rapid}, P^{z}_{rapid}. The air feed power is different on different axis affected by feed rate, which is the proportional to the feed rate. They are expressed as

$$\left.\begin{aligned} P^{x}_{feed} &= k^{1}_{x\_feed} + k^{2}_{x\_feed} \cdot f \\ P^{y}_{feed} &= k^{1}_{y\_feed} + k^{2}_{y\_feed} \cdot f \\ P^{z+}_{feed} &= k^{1}_{z+_{feed}} + k^{2}_{z+_{feed}} \cdot f \\ P^{z-}_{feed} &= k^{1}_{z-_{feed}} + k^{2}_{z-_{feed}} \cdot f \end{aligned}\right\} \tag{5}$$

Where $k^{1}_{x\_feed}$ and $k^{2}_{x\_feed}$ is the coefficient of *x* axis feed movement, and *f* is the feed rate. The feed distance in different axis is different, and hence, it assists to calculate accurately energy consumption due to different axis movement with different mass.

Non-cutting state includes standby, spindle and axis movement activity. From our experiment observations, it can be drawn that the energy need of each axis movement is the linear relation with feed rate. Similarly, the energy need of spindle rotation is the linear or quadratic linear relation with spindle speed in different speed space. The spindle motor has stepless speed regulation and frequency conversion speed regulation, so the linear relationship between direct power and motor speed is sometimes invalid. For the spindle motor that usually adopts frequency conversion speed regulation, when it runs above the reference frequency, the loss of the motor itself will remain unchanged, and even slightly decrease with the increase of the speed. This is the same as the spindle rotation power in the linear equation. The assumption of linear increase is contradictory. It is found through experiments that it can generally be divided into three or four sections. According to the structure of different machine tools, the relationship between spindle speed and power can even be divided into four or five sections. This situation will affect the prediction of the overall energy consumption of the processed parts, as follows:

$$P_{spindle} = \left.\begin{matrix} k^{1}_{s0} + k^{2}_{s0} \cdot n & 0 < n < n_1 \\ k^{1}_{s1} + k^{2}_{s1} \cdot n & n_1 < n < n_2 \\ k^{1}_{s2} + k^{2}_{s2} \cdot n & n_2 < n < n_3 \\ k^{1}_{s3} + k^{2}_{s3} \cdot n & n_3 < n < n_4 \end{matrix}\right\} \tag{6}$$

Where *n* is the spindle speed, k^{1}_{s} and k^{2}_{s} is the coefficient on corresponding *n* interval.

Specific energy consumption for cutting process is the proportional to MRR and *n*, while MRR is calculated through integrating cutting parameters of feed rate, width of cut and depth of cut. The correlated coefficient is determined by specific machine as well as cutting direction. Specific energy consumption of cutting operation is expressed as

$$\left.\begin{aligned} SEC_x &= k^{x}_{0} + k^{x}_{1} \cdot \frac{n}{MRR} + \frac{k^{x}_{2}}{MRR} \\ SEC_y &= k^{y}_{0} + k^{y}_{1} \cdot \frac{n}{MRR} + \frac{k^{y}_{2}}{MRR} \\ SEC_z &= k^{z}_{0} + k^{z}_{1} \cdot \frac{n}{MRR} + \frac{k^{z}_{2}}{MRR} \end{aligned}\right\} \tag{7}$$

SEC_x, SEC_y and SEC_z is a function of MRR and *n* in corresponding axial cutting direction. Where k_0, k_1, and k_2 are the coefficients related to the machine tool. SEC_x and SEC_y are the specific energy consumption in X axis cutting and Y axis direction separately during the milling machining. SEC_z represents the drilling machining in Z axis direction. The energy required in one cutting direction (like *x* axis) is calculated as

$$E_{cut\_x} = SEC_x \cdot V_{\mathrm{cut}} \tag{8}$$

Similarly, the energy required of other axis could be calculated through the same equation. Using of our proposed model, the users just determine the customization constants for their machine under current state. Meanwhile, each coefficient is determined by little experiments for specific machine without requiring more sensors and handbooks.

$$E = P_{standby} \cdot t_{standby} + P_{coolant} \cdot t_{coolant} + P_{rapid} \cdot t_{rapid} + \Sigma\,(P_{tool\_change} \cdot t_{tool\_change}) + P_{spindle} \cdot t_{spindle} + \Sigma_{x,y,z}\,(P_{feed} \cdot t_{feed}) + \Sigma_{x,y,z}\,(SEC_x \cdot V_{\mathrm{cut}}) \tag{9}$$

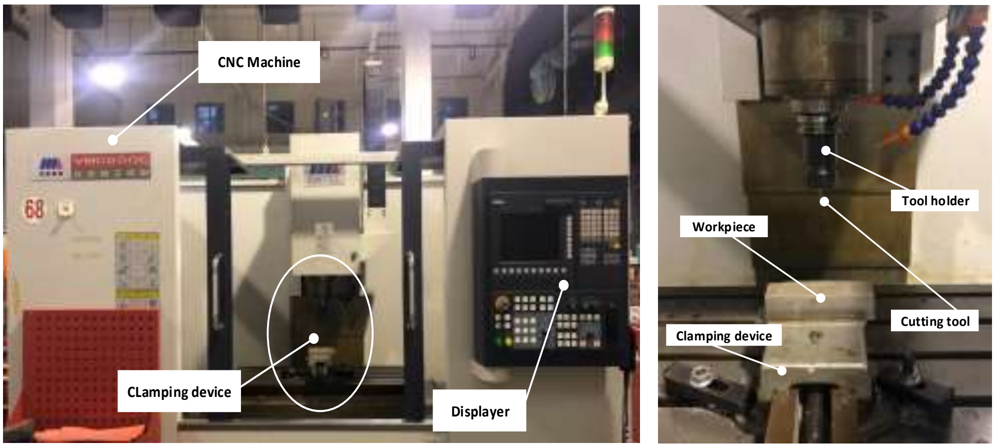
3. Experimental method and results

3.1 Experiments set-up

The power of each part is obtained in a 3-axis VMC850E milling center with 7.5 KW rated power, 8000 rpm maximum spindle speed and 380 V voltage. The other information and equipment set-up are shown in Table 2 and Fig.1. The aluminum alloy material is used as the machined workpiece for experimental trials. Additionally, the machining is proceeded in dry conditions using tool with 8mm diameter.

Table 2 Technical specifications of vertical machining center used in the study

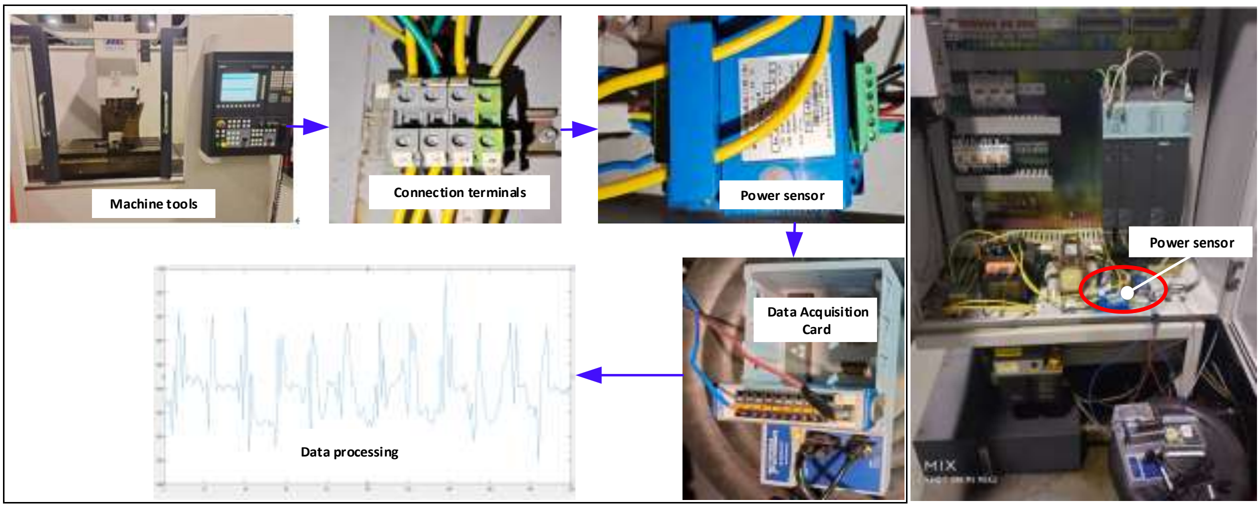
Shenyang VMC850E	Parameters
Power supply	380（1±10%）V 50HZ
Table travel (mm) XYZ	850/500/540
Spindle speed	0-8000RPM
Maximum weight on table	450Kg
Spindle motor power	7.5KW
Feed motor power (X、Y and Z)	3KW
Rapid feed rate (X and Y)	24m/min
Rapid feed rate (Z)	15m/min
Tool diameter (D)	8mm
No. of teeth (N)	3



(a) (b)

Fig.1. (a) VMC850E machine (b) Machined workpiece and cutting tool

The power was monitored by a WB9128-1 three-phase power sensor, which comprised of AC voltage wiring input and AC current through the heart input mounted on both sides of the input voltage terminal of the machine tool. The connection method is shown in the Fig.2. The power sensor adopts a three-phase three-wire wiring method. The entire data acquisition module includes a signal acquisition block, a signal conditioning block, a computer display block and a power supply block. The signal acquisition module with NI-9201 collects the corresponding physical signal, the sensor collects the physical signal, and converts it into an analog or digital signal. Then it transmits the signal to the signal conditioning module, which is processed by the signal conditioning block and directly transmitted to the acquisition card, and then converted from the acquisition card to the USB interface signal transmitted to the computer. Sampling rate of measuring was 200Hz (the VMC850E is 50Hz).

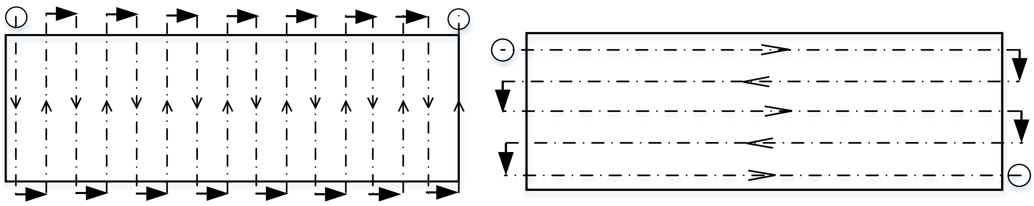


(a) (b)

Fig.2 (a) A diagram for the power data acquisition (b) Connection diagram

3.2 Design of experiments

The standby power is obtained through 20 times measurement when machine tools is opened with display screen. The final numerical value is the average power of 20 times. The rapid power in X, Y and Z axis are obtained through G00 rode in corresponding axis movement. Meanwhile, the spindle power at different speed is measured from 500rpm to 5100 rpm. The feed power for X, Y, Z- and Z+ axis are obtained in different feed rates. Orthogonal experiment is designed by 27 trial in X direction and Y direction cutting process separately for identifying their differences for energy consumption. Toolpath strategies are shown in **Fig.3**.



(a) (b)

Fig.3 (a) Toolpath strategies in Y cutting direction (b) Toolpath strategies in X cutting direction

In order to better understand the correlation between SEC and MRR (feed rate, width of cut and depth) as well as spindle speed, four factors and three levels are used for roughing machining shown in Table 3. Machining parameters for the experiments in VMC850E is shown in Table 3. The same experiment is carried out in the same machining parameters, while cutting direction is different with X and Y cutting direction separately.

Table 3 Machining parameters for the experiments

Levels	Spindle speed (RPM)	Feed rate(mm/min)	Width of cut (mm)	Deepen of cut (mm)
Level 1	1000	100	4	0.2
Level 2	1500	150	6	0.3
Level 3	2000	200	8	0.4

3.3 Experiment results analysis

The standby power is obtained through 20 times measurement when machine tools is opened with display screen as shown in Table 4. The average standby power is 342.4 W. The rapid powers axis are measured using G00 node in X, Y and Z individually, as shown in Table 5. Feed power in X, Y, Z+, and Z- direction are shown in Table 6 with regression equation.

Table 4 The standby power in 20 times

Number	Standby power (W)	Number	Standby power (W)	**Average power (W)**
1	347	11	343	
2	345	12	341	
3	345	13	339	
4	341	14	342	
5	348	15	338	
6	340	16	344	
7	339	17	343	
8	340	18	342	
9	346	19	338	
10	344	20	343	**342.4**

Table 5 The rapid power in X, Y and Z axis

Axis	Rapid feed rates (m/min)	Rapid power (W)
X	24	377
Y	24	389
Z	15	370

The feed power are measured using G01 node in X,Y, Z+, and Z- directions in three levels feed rate. Using Eq. (5) and the measured data, regression equation could be obtained as shown in Table 6. The correlation coefficient can reach to more than 97.58%.

Table 6 Feed power in X, Y, Z+, and Z- direction

Feed rate (mm/min)	**Power (W)**	**Regression equation**	**Correlation coefficient**
100 X direction	350	$P_{x\text{-feed}}$=327.00 + 0.22 f	97.58%
150 X direction	358		
200 X direction	372		
100 Y direction	357	$P_{y\text{-feed}}$=319.33 + 0.38 f	99.91%
150 Y direction	377		
200 Y direction	395		
100 Z+ direction	354	$P_{Z+\text{feed}}$=350 + 0.04 f	100%
150 Z+ direction	356		
200 Z+ direction	358		
100 Z- direction	345	$P_{Z\text{-feed}}$=337 + 0.08 f	100%
150 Z- direction	349		
200 Z- direction	353		

The spindle air running power is measured at different speed from 500 RPM to 5100 RPM. Each time keep operating above 5 minutes. The power load is shown in Table 7 with regression equation in different speed square. Overall trend chart is shown in Fig.4. From the chart, we can see that the power is divided into four part form due to load and frictional loss.

Table 7 Average power load at various spindle rates

Spindle speed (RPM)	Average power (W)	Regression equation
500	559	$P_{spindle} = 453.6 + 0.2704 \cdot n$ $500 < n \leq 1500$
600	617	
800	667	
900	730	
1100	769	
1200	796	
1400	816	
1500	838	
1700	783	$P_{spindle} = 1459 - 0.6184n + 0.000129n^2$ $1500 < n \leq 2400$
1800	761	
2000	742	
2100	729	
2300	720	
2400	719	
2600	720	$P_{spindle} = 680.61 + 0.01493 \cdot n$ $2400 < n \leq 3300$
2700	721	
2900	723	
3000	725	
3200	729	
3300	730	
3500	756	$P_{spindle} = 308.0 + 0.12963 \cdot n$ $3300 < n \leq 5100$
3600	762	
3800	810	
3900	813	
4100	850	
4200	851	
4500	900	
4800	937	
5100	954	

According to the data in the **Table 7**, it was observed that the spindle exhibits four different characteristics in non-load state, whose zone was divided into A, B, C and D. The relationship between spindle power and speed are fitted using linear or quadratic formula expressed as

$$P_{spindle} = \left.\begin{matrix} 453.6 + 0.2704 \cdot n & 500 < n \leq 1500 \\ 1459 - 0.6184 \cdot n + 0.000129 \cdot n^2 & 1500 < n \leq 2400 \\ 680.61 + 0.01493 \cdot n & 2400 < n \leq 3300 \\ 308.0 + 0.12963 \cdot n & 3300 < n \leq 5100 \end{matrix}\right\}$$

The machined workpiece in Y direction cutting and X direction cutting are shown in **Fig.5**. Experimental results for milling in Y direction cutting and Y direction cutting are shown in **Tables 8 and 9**.

Table 8 Experimental results for milling in Y direction cutting

Trial	N(r/min)	f(mm/min)	a_p(mm)	a_e(mm)	MRR(mm^3/s)	SEC(J/mm^3)	P(W)
1	1000	100	0.2	4	1.33	593.25	791
2	1000	100	0.3	6	3	270.67	812
3	1000	100	0.4	8	5.33	159.34	850
4	1000	150	0.2	4	2	402	804
5	1000	150	0.3	6	4.5	187.33	843
6	1000	150	0.4	8	8	108	864
7	1000	200	0.2	4	2.67	303	808
8	1000	200	0.3	6	6	143	858
9	1000	200	0.4	8	10.67	81.94	874
10	1500	100	0.2	6	2	429.5	859
11	1500	100	0.3	8	4	221	884
12	1500	100	0.4	4	2.67	325.5	868
13	1500	150	0.2	6	3	291.67	875
14	1500	150	0.3	8	6	151.33	908
15	1500	150	0.4	4	4	220.75	883
16	1500	200	0.2	6	4	221.5	886
17	1500	200	0.3	8	8	114.13	913
18	1500	200	0.4	4	5.33	167.63	894
19	2000	100	0.2	8	2.67	285	760
20	2000	100	0.3	4	2	378	756
21	2000	100	0.4	6	4	191.5	766
22	2000	150	0.2	8	4	191.75	767
23	2000	150	0.3	4	3	254.33	763
24	2000	150	0.4	6	6	130.5	783
25	2000	200	0.2	8	5.33	144.94	773
26	2000	200	0.3	4	4	191.75	767
27	2000	200	0.4	6	8	100.13	801

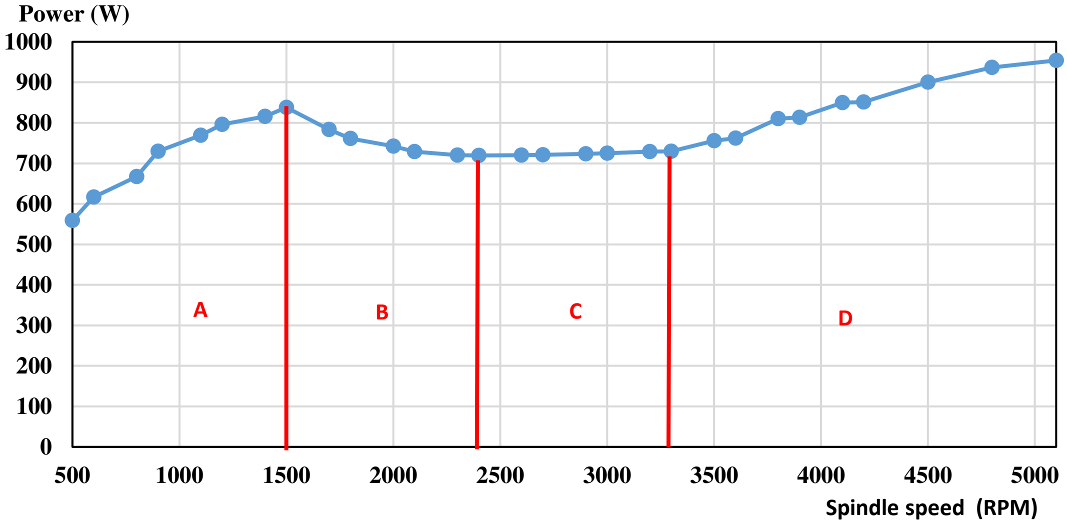


Fig. 4 Average power of spindle at various spindle rates

(a) (b)

Fig. 5 (a) Toolpath strategies Y direction cutting (b) Toolpath strategies X direction cutting

According to the data of Table 8, the regression equation of SEC_y in Y cutting direction is obtained by fragments based on spindle speed. The correlation coefficient in each part could also reach 99.99%, which explains the necessity of segmentation. If it is not segmented, the correlation coefficient of SEC is below 98%, while correlation coefficient of cutting power is just 24%. Similarly, the SEC and power are obtained in X direction cutting as shown in Table 9.

$$SEC_y = \begin{cases} 11.781 + 0.11771 \cdot \dfrac{n}{MRR} + \dfrac{659.65}{MRR} & 0 < n \leq 1500 \\ 8.548 - 0.22121 \cdot \dfrac{n}{MRR} + \dfrac{1178.3}{MRR} & 1500 < n \leq 2000 \end{cases}$$

Table 9 Experimental results for milling in X direction cutting

Trial	N(r/min)	f(mm/min)	a_p(mm)	a_e(mm)	MRR(mm^3/s)	SEC(J/mm^3)	P(W)
1	1000	100	0.2	4	1.33	558	744
2	1000	100	0.3	6	3	252	756
3	1000	100	0.4	8	5.33	143.43	765
4	1000	150	0.2	4	2	376	752
5	1000	150	0.3	6	4.5	168.89	760
6	1000	150	0.4	8	8	96.25	770
7	1000	200	0.2	4	2.67	282.75	754
8	1000	200	0.3	6	6	127.67	766
9	1000	200	0.4	8	10.67	72.94	778
10	1500	100	0.2	6	2	416.5	833
11	1500	100	0.3	8	4	211.25	845
12	1500	100	0.4	4	2.67	313.885	837
13	1500	150	0.2	6	3	283.33	850
14	1500	150	0.3	8	6	142.33	854
15	1500	150	0.4	4	4	210.75	843
16	1500	200	0.2	6	4	211	844
17	1500	200	0.3	8	8	107.25	858
18	1500	200	0.4	4	5.33	159	848
19	2000	100	0.2	8	2.67	273.56	729.5
20	2000	100	0.3	4	2	362.25	724.5
21	2000	100	0.4	6	4	180	720
22	2000	150	0.2	8	4	182.5	730
23	2000	150	0.3	4	3	242.33	727
24	2000	150	0.4	6	6	123.33	740
25	2000	200	0.2	8	5.33	138.08	736.4
26	2000	200	0.3	4	4	182.4	729.6
27	2000	200	0.4	6	8	93.13	745

According to the data of Table 9, the regression equation of SEC_x in X cutting direction is obtained by fragments based on spindle speed.

$$SEC_x = \left. \begin{array}{ll} 4.487 + 0.17312 \cdot \frac{n}{MRR} + \frac{566.9}{MRR} & 0 < n \leq 1500 \\ 3.698 - 0.22607 \cdot \frac{n}{MRR} + \frac{1168.21}{MRR} & 1500 < n \leq 2000 \end{array} \right\}$$

3.4 Discussion

From the above data, we can see that the cutting specific energy consumption is different in X and Y direction. The compare of power in each time machining is shown in Fig.6. We can see that the cutting power of X direction is lower than Y direction at the same cutting parameters. The reason is mainly that Y direction need support the bigger load when Y axis movement. Therefore, the energy consumption should be calculated individually for improving accuracy of energy prediction. Similarly, the SEC in Y is also bigger than X direction shown in Fig.7.

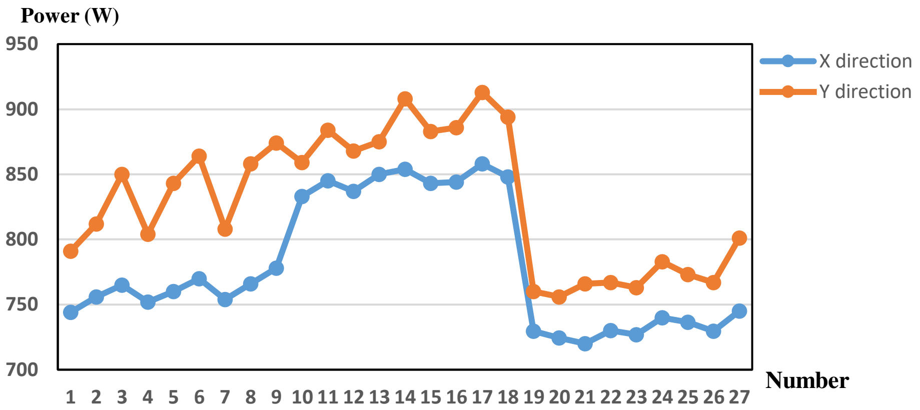


Fig. 6 The power compare of X and Y direction cutting in the same parameters

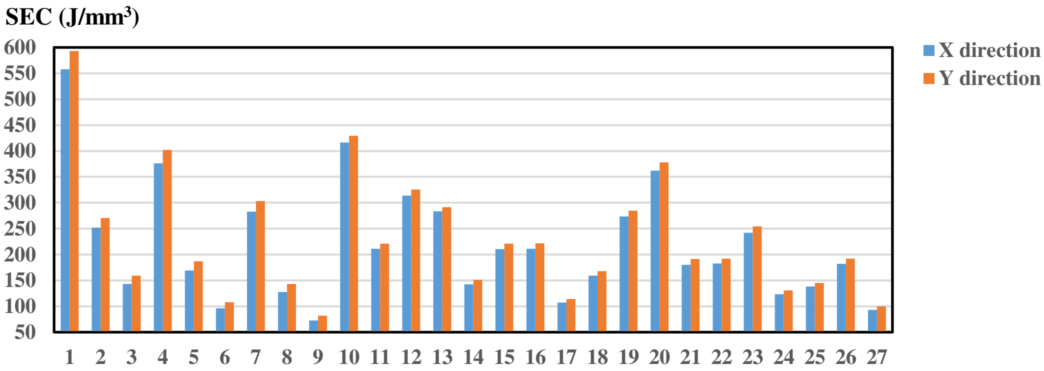


Fig. 7 The SEC compare of X and Y direction cutting in the same parameters

For validating the proposed method, the correlation coefficient summary in different model is analyzes in Table 10, which explains the necessity of segmentation. When the SEC as a whole without segmented, the coefficient R-square of models in Y and X cutting direction is 98.95% and 98.41% separately. Nevertheless, the R-square values could reach 99.98% and 99.99% if the *SEC* model is established based on the spindle speed n space. It is clearly shows that there is a direct correlation between *SEC* and n and *MRR*. The difference of *SEC* without segmented and segmented is not particularly obvious due to measurement and data handling error inevitability. Then, we analyze the cutting power whether or not has the same results. However, it emerges an issue for R-square values of relationship between cutting power and n and *MRR*, just having 25.45% and 36.65% in Y and X direction respectively. In this basis, the regression mathematic model of cutting power will lead to a mistake in following calculation. This result is inconsistent with the facts leading to cause puzzle for users and research who will understand they have no relationship.

The source of this issue must be found in order to increase robust of SEC model and cutting power model. Since the MRR is invariable for the same cutting parameters, the issue should be the spindle rotation power under different speed. Hence, we analyzed the R-square value of relationship between spindle power and speed just has 49.18% without segmented, while the values are exceed 95.27% with segmented. The above analysis indicate that piecewise representation is necessary for cutting energy prediction model according to the spindle rotation power characteristics in non-load. Therefore, the experiment of spindle rotation power in non-load for specific CNC machine should be carried out to observe the variable characteristics, which not consume too much time. Meanwhile, the total cutting energy calculated by SEC and material removal volumes will reduce the error rate compared with cutting power and cutting time approach.

Table 10 Different model summary results

Model	S	R-square
SEC without segmented in Y cutting direction	12.8025	98.95%
SEC in Y cutting direction (n<1500)	1.52747	99.99%
SEC in Y cutting direction(n>1500)	0.77535	99.99%
SEC without segmented in X cutting direction	15.1233	98.41%
SEC in X cutting direction (n<1500)	1.22346	99.99%
SEC in X cutting direction(n>1500)	1.2659	99.98%
Cutting power without segmented in Y direction	43.2568	36.65%
Cutting power in Y cutting direction (n<1500)	8.04992	95.55%
Cutting power in Y cutting direction (n>1500)	4.05947	99.61%
Cutting power without segmented in X direction	45.099	25.45%
Cutting power in X cutting direction (n<1500)	5.90827	98.46%
Cutting power in X cutting direction (n>1500)	4.09465	99.58%
Spindle power without segmented	61.775	49.18%
Spindle power (n<=1500)	23.6075	95.27%
Spindle power (1500<n<=2400) using linear equation	8.15926	91.74%
Spindle power (1500<n<=2400) using quadratic equation	2.94637	99.19%
Spindle power (2400<n<=3300)	0.99932	95.58%
Spindle power (3300<n<=5100)	10.3088	98.16%

From the above analysis, we can obtain the following energy saving strategies:

(1) The selection of machine tools will directly affect the standby energy, which is the basic energy consumption in whole machining process. The different machines have different standby power, and hence, it should be considered as one of energy evaluation indicators.

(2) The mass increase of spindle structure system will lead the power increase in the Z+ direction, which need overcome major obstacles. Similarly, the feed powers in X and Y directions are also different due to the mass difference. The guide way of Y axis need support the mass of X axis leading to the power increasing.

(3) After determining the machine tools, tool path will also affect the total energy consumption due to air cutting distance and time. Therefore, the efforts for reducing distance of air cutting through optimizing tool path and process route planning are coming.

(4) The cutting direction also affect the energy consumption in X and Y directions due to the cutting vibration intensity, which increase the cutting force and cutting power studied in literature [22].

(5) The cutting parameters (spindle speed, depth of cutting, width of cutting and feed rate) lead to the difference of the material remove rate and specific energy consumption. In the same cutting condition, specific energy consumption represents energy efficiency of cutting process.

4. Conclusions and future work

This paper proposed improved energy model for predicting energy consumption of machined part in CNC milling machine. In order to better apply the proposed model in NC nodes of CNC control system, rapid feed and feed power in X, Y and Z axis are considered separately. Furthermore, the relationship of spindle power and speed is deeply analysis through experiment in CNC milling machine, which is not always the linear proportion due to the different of constant torque speed regulation and constant power speed regulation. On that basis, energy model of cutting material is also be improved through segmented form for spindle speed to enhance the accuracy of predicting energy consumption of workpiece. They are not be considered in existing energy models. The contribution of this paper is mainly to make energy consumption prediction of CNC machining process easier to achieve based on NC nodes of specific a part. Apart from that, the users just need to determine correlation coefficient of their CNC machines' current state without considering and searching other factors or handbook.

From the experiment results, we also could find that it is very necessary to build power models of different moving axes separately. On the same machining parameters, feed power of Y axis movement is higher than X axis. Additionally, cutting power in Y direction is also higher than X direction, which leads to SEC in Y cutting direction more than X cutting direction. This means Y cutting direction will consume more energy than X cutting direction for the same material remove volume. Additionally, the total cutting energy calculated by SEC and material removal volumes will reduce the error rate compared with cutting power and cutting time approach. Therefore, the machining process could be optimized through selecting cutting direction under meeting the requirements of machining surface accuracy.

The CNC vertical machining center is used as a research object with X, Y and Z axis. In future, more kinds of machine tools should be studied for expanding the use of energy consumption models. Additionally, intelligent methods such as deep learning and digital Twin technology will be integrated into energy prediction software to accelerate the development of sustainable manufacturing in industry.

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Authors' contributions

Chunhua Feng: Conceptualization, Methodology, Software, Validation, Writing-Original Draft, Funding acquisition. Xiang Chen: Investigation, Data Curation, Software. Jingyang Zhang: Investigation, Data Curation, Resources. Yugui Huang: Investigation, Data Curation, Resources.

Data availability: All the data have been presented in the manuscript.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval: Not applicable.

Consent to participate: The authors declare that they all consent to participate this research.

Consent to publish: The authors declare that they all consent to publish the manuscript.

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Figures

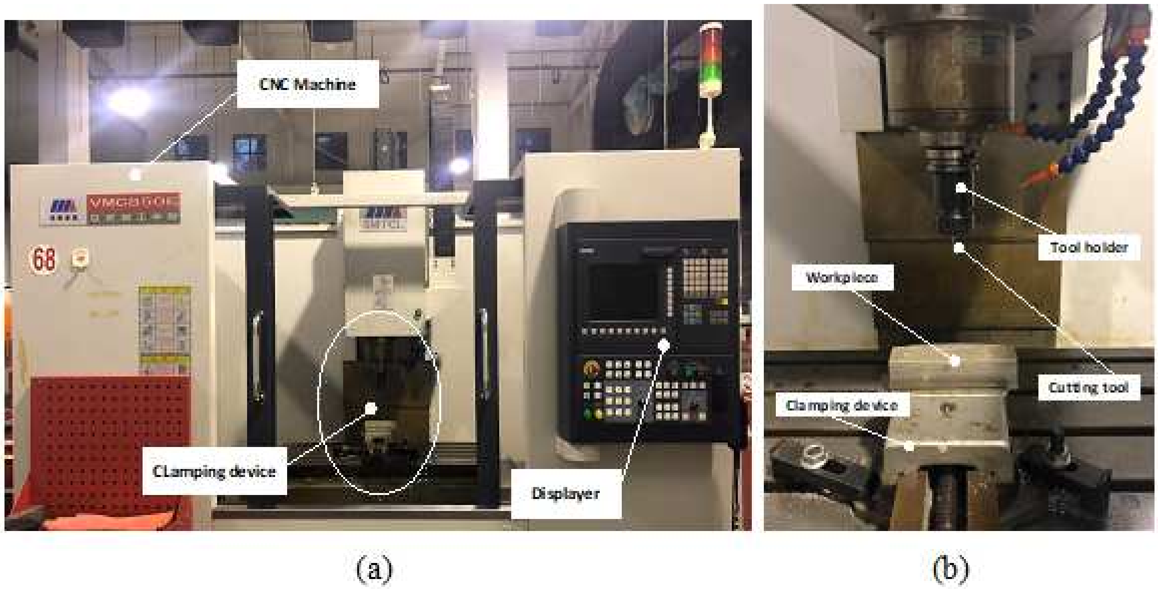

Figure 1

(a) VMC850E machine (b) Machined workpiece and cutting tool

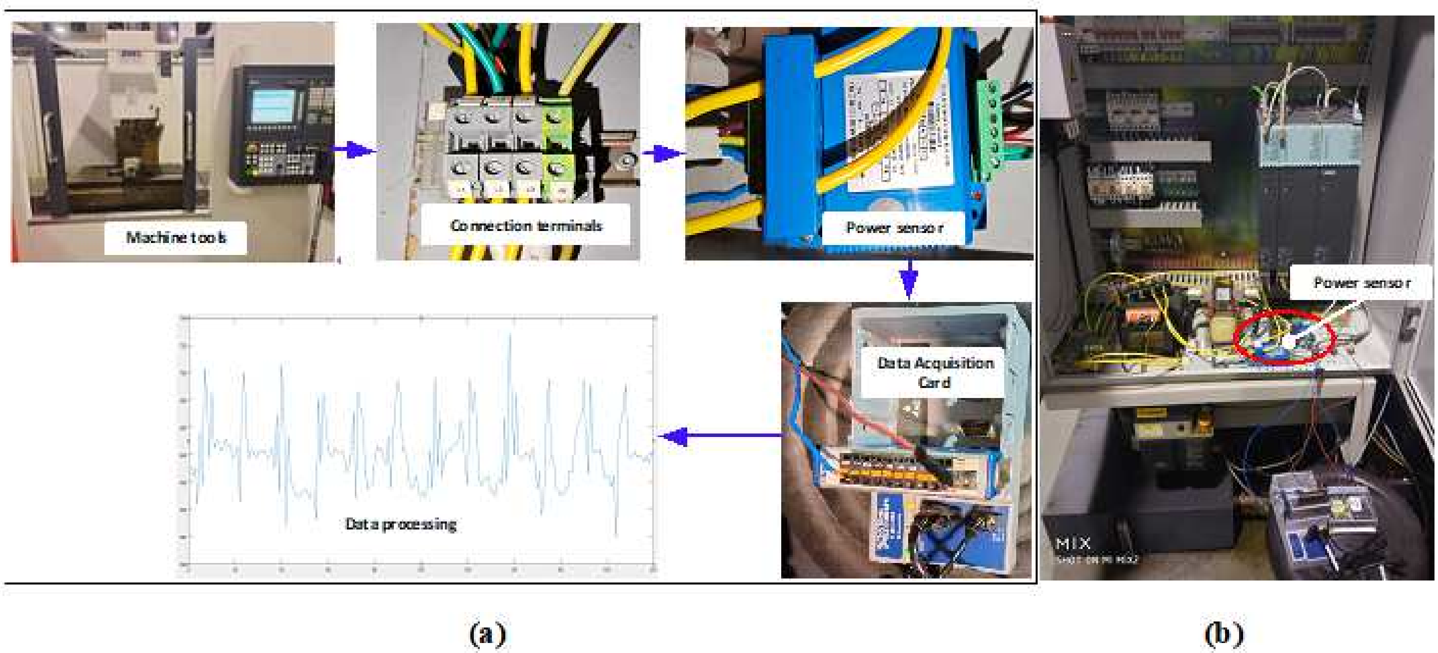

Figure 2

(a) A diagram for the power data acquisition (b) Connection diagram

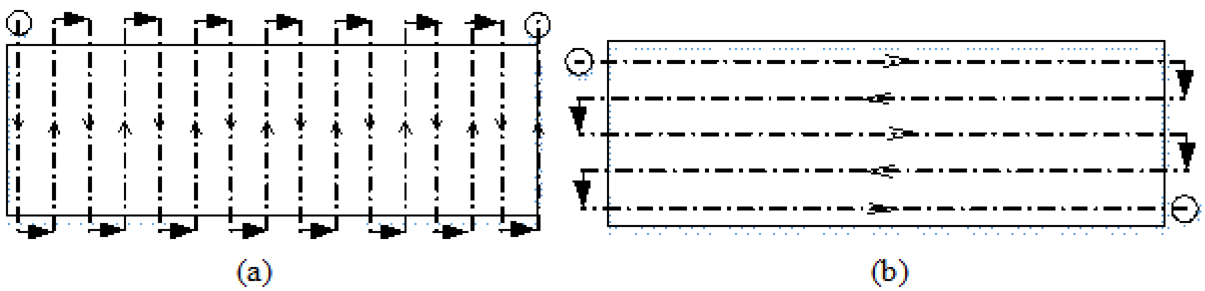

Figure 3

(a) Toolpath strategies in Y cutting direction (b) Toolpath strategies in X cutting direction

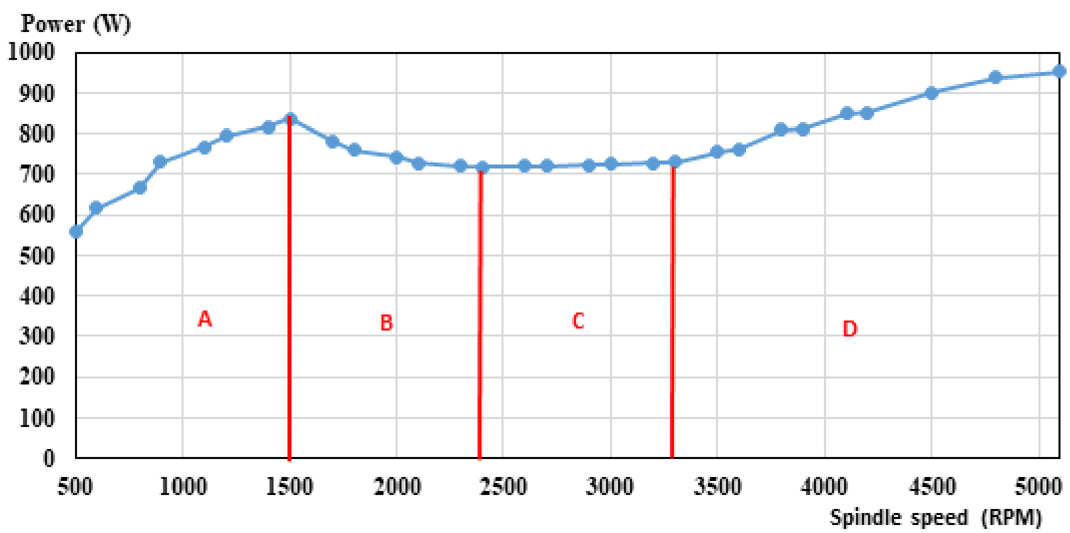

Figure 4

Average power of spindle at various spindle rates

Figure 5

(a) Toolpath strategies Y direction cutting (b) Toolpath strategies X direction cutting

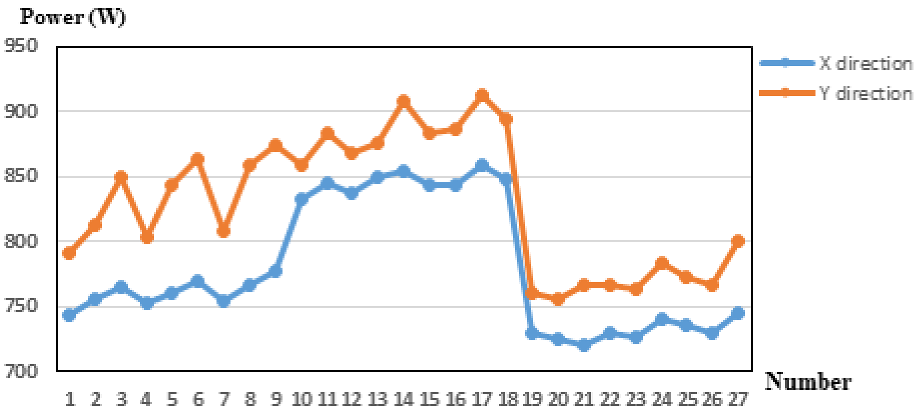

Figure 6

The power compare of X and Y direction cutting in the same parameters

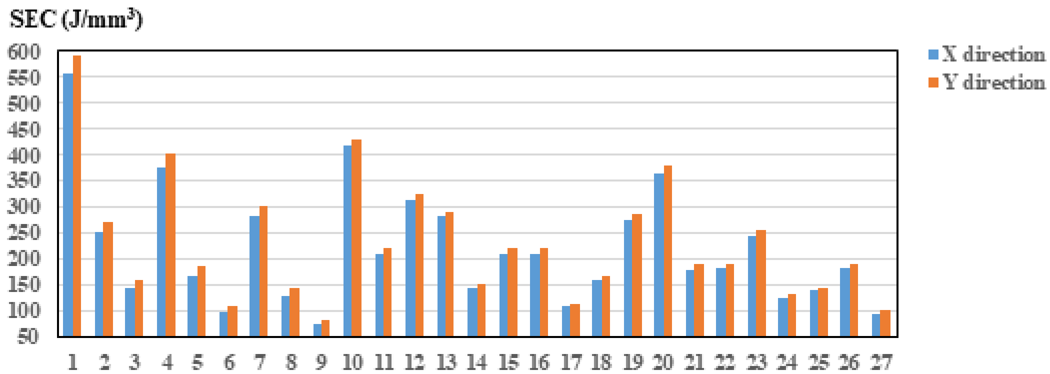

Figure 7

The SEC compare of X and Y direction cutting in the same parameters