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 complete 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 the VMC850E machine; the results show that the SEC in the X and Y cutting directions is 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 the improved SEC model could reach 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 much energy and consequently has to adopt energy-saving techniques such as optimization of workshop schedule, machine tools structure, machining process, and process path [1]. The effective implementation of manifold measures for increasing energy efficiency has a positive effect on reducing electricity consumption from workshop to machining process. Additionally, the improvement of the machining process plays more important role in the condition of fixed machine tools, especially the cutting parameters, tool path, process route, and so on [2]. Computer numerical control (CNC) machining plays a significant role in manufacturing activities with the advantage of the 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 the energy efficiency of specific part machining. Due to the complexity of operating principle and activities in each axis direction for different CNC machines, it can be challenging to establish an elaboration energy requirements model under the complexity of cutting parameters and tool path.

The current research on machining energy consumption focus on the material removal 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 the establishment of an 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 modelling energy usage in machining, 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 an 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 for 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 the above models considering MRR and \( n \) as an aggregate function of the 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 few 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 considers 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 Behrendt’ results [12], we found that spindle power follows a linear relationship with spindle speed for turning machine. Altına et al. [13] (2016) developed a different spindle power model in a 5-axis vertical machining center finding 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 is not always linear proportional constants in each speed space. Thus, the air cut power should be modelled accurately based on spindle running characteristic for a 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 the Internet of Things technology, intelligent methods are being studied in recent years to monitor and manage energy consumption in machining workshop.

### Table 1 A summary of major energy consumption models

| Literature                        | Model                                                                 |
|-----------------------------------|-----------------------------------------------------------------------|
| Gutowski et al. 2006 [3]          | \( E = (P_o + K \cdot MRR) \cdot t \)                                 |
|                                   | \( P_o \) 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 [4]; Kara and Li, 2011 [5] | \( E_{cut} = \text{SEC} \cdot V_{cut} = \left( C_0 + \frac{C_1 \cdot MRR}{C_2} \right) \cdot V_{cut} \) |
|                                   | \( C_0 \) and \( C_1 \) are the coefficients related to the specific machine tool |
| Li et al., 2013 [6]               | \( E_{cut} = \text{SEC} \cdot V_{cut} = (k_0 + k_1 \cdot \frac{MRR}{C_0} + k_2 \cdot \frac{1}{C_2}) \cdot V_{cut} \) |
|                                   | \( n \) is the spindle speed; \( k_0, k_1, \) and \( k_2 \) are the coefficients related to the machine tool |
| Diaz et al. 2011 [4]              | \( E = (P_{cut} + P_{air}) \cdot t \)                                |
|                                   | \( P_{cut} \) represents the power of cutting process, \( P_{air} \) represents the power of air process |
| Mori et al. 2011 [9]             | \( E = P_1 \cdot T_1 + P_2 \cdot T_2 + P_3 \cdot t_{tc} \) |
|                                   | \( P_1 \) 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, \( T_{tc} \) is the time for spindle rotation |
| He et al. 2012 [11]              | \( E = \int_{t_{cut}} P_{sp} \cdot dt + \int_{t_{cut}} P_{cool} \cdot dt + \sum_{i=1}^{m} \int_{t_{i}} P_{i} \cdot dt + P_{cool} \cdot t_{cool} + P_{tc} \cdot t_{tc} + (P_{pass} + P_{fan}) \cdot t \) |
|                                   | \( P_{sp} \) is the power of spindle with corresponding \( t_{cut} \), \( P_{cool} \) is the cutting power with time \( t_{cool} \), \( i \) 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 \( t_{cool} \), \( P_{tc} \) is the power of tool-change with time \( t_{tc} \), \( P_{pass} \) and \( P_{fan} \) are the power of servos systems and fan motors separately with time \( t \) |
| Balogun and Mativenga, 2013 [8]   | \( E = E_{0} + E_{r} + P_{c} \cdot t_{cut} [\text{INT} \left( \frac{t}{T} \right) + 1] + P_{air} \cdot t_{air} + (P_{cool} + k \cdot MRR) \cdot t_{cool} \) |
|                                   | \( E_{0} \) is the basic energy, \( E_{r} \) is the ready state energy, \( P_{c} \) is the tool change power with time \( t_{cut} \), \( T \) is the tool life, \( P_{air} \) is the air cutting power with the time \( t_{air} \), \( P_{cool} \) and \( k \cdot MRR \) are the power of spindle and coolant system respectively, \( t_{cool} \) is the cutting time, \( k \cdot MRR \) represents energy required for material removal proportional to the MRR |
Shin et al. [16] established an online optimization model adopting a dynamic composition approach and divide-and-conquer technique based on component. Chen et al. [17] proposed the framework of the Internet of Things to monitor and manage energy, contributing to identifying 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 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 has 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 a machined component. At the same time, 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 that the existing energy models have not studied the influence of spindle power characteristic under non-load on all cutting power model.

Although the existing energy models have improved prediction precision, there is 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 uniform in all cutting directions (X, Y, Z, and another axis for 5-axis machine). At the same time, practicing 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 literature [13, 20].

(3) One NC code could describe a whole machining process, and hence, the energy consumption could be predicted based on the correlation coefficient of the selected machine. Some model, such as SEC, could not directly calculate the energy consumption of each activity 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 the energy consumption model for the 3-axis CNC machining process through the experiment test. The proposed energy model is based on selected CNC machines, individual process parameter, and cutting directions in 3-axis machining. We also find that spindle power is not always a 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 is affected when reaching the rated power of the spindle. Therefore, it is necessary for improving the existing energy model in a piecewise way according to spindle speed. Another contribution of this paper is to develop an 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 the CNC machine is presented in Section 2. Section 3 gives the experiment design and results from 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.

$$E_{NC-block} = E_{constant} + E_{variable} \quad (1)$$

where $E_{NC-block}$ 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, and $E_{variable}$ is the consume energy at a variable rate decided by cutting parameters, tool path, and movement directions.

$$E_{NC-block} = E_{standby} + E_{coolant} + E_{tool\_change} + E_{rapid} + E_{spindle} + E_{feed} + E_{cut} \quad (2)$$

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

\[
P = P_{\text{standby}} + P_{\text{coolant}} + P_{\text{tool change}} + P_{\text{rapid}} + P_{\text{feed}} + P_{\text{spindle}} + P_{\text{cut}}
\]

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

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

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 \( P_{\text{rapid}}^x, P_{\text{rapid}}^y, \) and \( P_{\text{rapid}}^z. \) The air feed power is different on different axis affected by feed rate, which is the proportional to the feed rate \([14]\). They are expressed as:

\[
\begin{align*}
P_{\text{feed}}^x &= k_1^x \cdot f + k_2^x \cdot f^2 \\
P_{\text{feed}}^y &= k_1^y \cdot f + k_2^y \cdot f^2 \\
P_{\text{feed}}^z &= k_1^z \cdot f + k_2^z \cdot f^2
\end{align*}
\]

where \( k_1^x, k_2^x \) are the coefficients of \( x \) axis feed movement, and \( f \) is the feed rate. The feed distance in different axis is different, and hence, it assists in calculating energy consumption accurately due to different axis movement with different mass.

The 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 step-less 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 [12, 14]. 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:

\[
P_{\text{spindle}} = \begin{cases} \frac{k_1}{s_0} + \frac{k_2}{s_1} \cdot n & 0 < n < n_1 \\ \frac{k_3}{s_0} + \frac{k_4}{s_1} \cdot n & n_1 < n < n_2 \\ \frac{k_5}{s_0} + \frac{k_6}{s_1} \cdot n & n_2 < n < n_3 \\ k_7 + k_8 \cdot n & n_3 < n < n_4 \end{cases}
\]  

(6)

where \( n \) is the spindle speed; \( k_1 \) and \( k_2 \) are the coefficient on the corresponding \( n \) interval.

Specific energy consumption for the cutting process is proportional to MRR and \( n \). At the same time, MRR is calculated through integrating cutting parameters of feed rate, the width of cut and depth of cut. The correlated coefficient is determined by specific machine as well as cutting direction [6]. Specific energy consumption of cutting operation is expressed as:

\[
\begin{align*}
SEC_x &= k_0 + k_1 \cdot \frac{n}{\text{MRR}} + k_2 \frac{\text{MRR}}{k_3} \\
SEC_y &= k_0 + k_1 \cdot \frac{n}{\text{MRR}} + k_2 \frac{\text{MRR}}{k_3} \\
SEC_z &= k_0 + k_1 \cdot \frac{n}{\text{MRR}} + k_2 \frac{\text{MRR}}{k_3}
\end{align*}
\]

(7)

\( SEC_x, SEC_y, \) and \( SEC_z \) are functions of MRR and \( n \), 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 the Z axis direction. The energy required in one cutting direction (like X axis) is calculated as:

\[
E_{\text{cut},x} = SEC_x \cdot V_{\text{cut}}
\]

(8)

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

\[
E = P_{\text{standby}} \cdot t_{\text{standby}} + P_{\text{coolant}} \cdot t_{\text{coolant}} + P_{\text{rapid}} \cdot t_{\text{rapid}} + \sum (P_{\text{tool change}} \cdot t_{\text{tool change}}) + P_{\text{spindle}} \cdot t_{\text{spindle}} + \sum x, y, z (P_{\text{feed}} \cdot t_{\text{feed}}) + \sum (SEC_x \cdot V_{\text{cut}})
\]  

(9)

3 Experimental method and results

3.1 Experiments setup

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 setup 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 a tool with 8-mm diameter.

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 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, and 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. The sampling rate of measuring was 200Hz (the VMC850E is 50Hz).

3.2 Design of experiments

The standby power is obtained through 20 times measurement when machine tools are opened with the display screen. The final numerical value is the average power of 20 times. The rapid power in the X, Y, and Z axis are obtained through G00 rode in the corresponding axis movement. Meanwhile, the spindle power at different speed is measured from 500 to 5100 rpm. The feed power for the X, Y, Z+ and Z− axis is obtained at different feed rates. The orthogonal experiment is designed by 27 trial in the X direction and Y direction cutting

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

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               |

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             |

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       | \( P_{x-feed} = 327.00 + 0.22 f \) | 97.58%                  |
| 150 X direction    | 358       | \( P_{x-feed} = 319.33 + 0.38 f \) | 99.91%                  |
| 200 X direction    | 372       | \( P_{x-feed} = 319.33 + 0.38 f \) |                       |
| 100 Y direction    | 357       | \( P_{y-feed} = 319.33 + 0.38 f \) |                       |
| 150 Y direction    | 372       |                       |                       |
| 200 Y direction    | 385       |                       |                       |
| 100 Z+ direction   | 354       | \( P_{z-feed} = 350 + 0.04 f \) | 100%                   |
| 150 Z+ direction   | 356       | \( P_{z-feed} = 350 + 0.04 f \) | 100%                   |
| 200 Z+ direction   | 358       | \( P_{z-feed} = 350 + 0.04 f \) | 100%                   |
| 100 Z− direction   | 345       | \( P_{z-feed} = 337 + 0.08 f \) | 100%                   |
| 150 Z− direction   | 349       | \( P_{z-feed} = 337 + 0.08 f \) | 100%                   |
| 200 Z− direction   | 353       | \( P_{z-feed} = 337 + 0.08 f \) | 100%                   |
process separately for identifying their differences for energy consumption. Toolpath strategies are shown in Fig. 3. 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 are shown in Table 3. The same experiment is carried out in the same machining parameters, while the cutting direction is different with X and Y cutting direction separately.

### 3.3 Experiment results analysis

The standby power is obtained through 20 times measurement when machine tools are opened with a display screen as shown in Table 4. The average standby power is 342.4 W. The rapid powers in axis are measured using the 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 the regression equation.

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

The spindle air running power is measured at a different speed from 500 to 5100 rpm. Each time keeps operating above 5 min. The power load is shown in Table 7 with regression equation in different speed square. The overall trend chart is shown in Fig. 4. From the chart of Fig. 4, we can see that the power is divided into four parts formed due to load and frictional loss using Eq. (6).

According to the data in Table 7, it was observed that the spindle exhibits four different characteristics in the 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:
The machined workpiece in Y direction cutting and X direction cutting is 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 (mm³/s) | SEC (J/mm³) | 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   |
According to Table 8, the regression equation of \( \text{SEC}_y \) 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 \( \text{SEC} \) is below 98%, while the correlation coefficient of cutting power is just 24%. Similarly, the SEC and power are obtained using Eq. (7) in \( X \) direction cutting, as shown in Table 9.

\[
\text{SEC}_y = \begin{cases} 
11.781 + 0.11771 \cdot \frac{n}{\text{MRR}} + 659.65 \cdot \frac{n}{\text{MRR}} & 0 < n \leq 1500 \\
8.548 - 0.22121 \cdot \frac{n}{\text{MRR}} + 1178.3 \cdot \frac{n}{\text{MRR}} & 1500 < n \leq 2000 
\end{cases}
\]

According to the data of Table 9, the regression equation of \( \text{SEC}_x \) in \( X \) cutting direction is obtained using Eq. (7) by fragments based on spindle speed.

| Trial | \( n(\text{r/min}) \) | \( f(\text{mm/min}) \) | \( a_y(\text{mm}) \) | \( a_x(\text{mm}) \) | \( \text{MRR}(\text{mm}^3/\text{s}) \) | \( \text{SEC}(\text{J/mm}^3) \) | \( P(\text{W}) \) |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|--------|
| 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 Table 8, the regression equation of \( \text{SEC}_y \) 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 \( \text{SEC} \) is below 98%, while the correlation coefficient of cutting power is just 24%. Similarly, the SEC and power are obtained using Eq. (7) in \( X \) direction cutting, as shown in Table 9.

![Fig. 5](image-url)  
**Fig. 5**  
(a) Toolpath strategies \( Y \) direction cutting.  
(b) Toolpath strategies \( X \) direction cutting.
3.4 Sensitivity analysis of machining parameter values

According to the results of 27 sets of experiments, as shown in Table 9, sensitivity analysis of machining parameters is performed to obtain the effects of parameters on surface roughness, unit cutting energy consumption, and power, as shown in Fig. 6 and Fig. 7.

It can be seen from Fig. 6 that within the experimental range, the unit cutting energy consumption will decrease with the increase of the spindle speed, and the decrease of the speed in the range of 1000–1500r/min is smaller than the process of 1500–2000r/min. The amount of knife, the amount of side-grabbing, and the unit cutting energy consumption are also inversely proportional. With the increase of processing parameters, the unit cutting energy consumption gradually decreases. It can be seen that the influence on the unit cutting energy consumption is feed rate > back tool engagement > side tool engagement > spindle speed.

Similarly, it can be seen from Fig. 7 that the power of the machine tool increases with the increase of the spindle speed in the range of 1000–1500r/min, and the power of the machine tool decreases with the increase of the spindle speed in the range of 1500–2000r/min. In the range of 1000–2000r/min, the feed speed, back-grab amount, and side-grab amount are roughly positively correlated with the machine power. With the increase of processing parameters, the machine power
gradually increases. From Fig. 7, it can be seen that in the influence on the machine tool power, spindle speed > side cutting amount > feed speed > back cutting amount.

4 Discussion

From the above data, we can see that the cutting specific energy consumption is different in the X and Y direction. The comparison of power in each time machining is shown in Fig. 8. We can see that the cutting power of X direction is lower than the Y direction at the same cutting parameters. The reason is mainly that the Y direction needs to support the bigger load when Y-axis moves. When feeding in the X direction, it is only necessary to drive the upper rail to move in the X direction. However, when feeding in the Y direction, it is necessary to drive the upper rail and the lower rail to move in the Y direction at the same time. Therefore, the Y direction needs to support a larger load when the Y axis moves. Therefore, the energy consumption should be calculated individually for improving the accuracy of energy prediction. Similarly, the SEC in Y is also bigger than the X direction shown in Fig. 9.

For validating the proposed method, the correlation coefficient summary in the different model is analyzed 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 shown 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 it has the same results. However, an issue emerges for R-square values of the relationship between cutting power and $n$ and MRR, just having 25.45% and 36.65% in Y and X direction, respectively. On this basis, the regression mathematical model of cutting power will lead to a mistake in the following calculation. This result is inconsistent with the facts leading to cause puzzle for users and researchers who will understand they have no relationship.

The source of this issue must be found in order to increase robust of the 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 that the R-square value of the relationship between spindle power and speed just has 49.18% without segmented, while the values are exceeded 95.27% with segmented. The above analysis indicates 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 a specific CNC machine should be carried out to observe the variable characteristics, which do not consume too much time. Meanwhile, the total cutting energy calculated by SEC and material removal volumes will reduce the error rate compared with the cutting power and cutting time approach.
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 the whole machining process. The different machines have different standby power, and hence, it should be considered one of the energy evaluation indicators.

(2) The mass increase of the 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 guideway of the Y-axis needs to support the mass of the X axis leading to the power increasing.

(3) After determining the machine tools, the 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 increases the cutting force and cutting power studied in the literature [22].

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

### 5 Conclusions and future work

This paper proposed an improved energy model for predicting the energy consumption of machined part in the CNC milling machine. In order to better apply the proposed model in NC nodes of CNC control system, rapid feed and feed power in the X, Y, and Z axis are considered separately. Furthermore, the relationship of spindle power and speed is deep analysis through the experiment in CNC milling machine, which is not always the linear proportion due to the difference between constant torque speed regulation and constant power speed regulation. On that basis, the energy model of cutting material is also improved through the segmented form for spindle speed to enhance the accuracy of predicting the energy consumption of workpiece. They are not 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 a specific part. Apart from that, the users just need to determine the correlation coefficient of their CNC machines’ current state without considering and searching for other factors or handbook.

From the experiment results, we also could find that it is very necessary to build powerful models of different moving axes separately. On the same machining parameters, the feed power of Y-axis movement is higher than X-axis. Additionally, cutting power in the Y direction is also higher than the X direction, which leads to SEC in the Y cutting direction more than the X cutting direction. This means Y cutting direction will consume more energy than X cutting direction for the same material remove volume.

| 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%   |
Additionally, the total cutting energy calculated by SEC and material removal volumes will reduce the error rate compared with the cutting power and cutting time approach. Therefore, the machining process could be optimized by selecting cutting direction under meeting the requirements of machining surface accuracy.

The CNC vertical machining center is used as a research object with the X-, Y-, and Z-axis. In the 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 sustainable manufacturing in the industry.

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

Declarations

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