Research on Multi-source Energy Consumption Characteristics of CNC Machine Tool Processing System

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Abstract. CNC machine tools are a complex and variable system with a large number of energy-consuming components and the energy consumption type covers the field of electromechanical liquid. Therefore, it is of great significance to study the energy consumption of CNC machine tools in order to find energy conservation and emission reduction, improve resource utilization, reduce environmental pollution, and promote green manufacturing. This paper analyzes the energy consumption form and characteristics of a typical machine tool, combines the machining status of the machine tool, and studies the various energy-consuming components of the machine tool, establishes the power balance equations of each state, and the specific energy consumption and energy efficiency model of the machine tool. The model combines the energy consumption characteristics and machining status of the machine tool, and lays a theoretical foundation for the research of the energy of the CNC machine tool.

1. Introduction

With the advancement of socio-economic development and science and technology, while the material needs of human beings have been greatly satisfied, the problems of energy, resources and the environment on a global scale have become increasingly prominent [1]. Relevant research shows that manufacturing is not only the main creator of material wealth but also the main influencer of current environmental problems. While maintaining the continuous development of the manufacturing industry, it is of great significance to increase production efficiency, energy efficiency, technological level and product quality, reduce the consumption of energy resources, and realize the intelligent and green development of the manufacturing process.

The energy consumption of CNC machine tools is one of the important indicators for evaluating the environmental performance of machine tools. The energy consumption of machine tools as "energy flow" runs through the whole process of machining. According to the definition of the International Standards Committee (ISO) 14955-1, the following functions (see Figure 1) of a machine tool are closely related to energy consumption. The results of various studies have shown that 99% of the impact of the manufacturing and processing industries (cars, milling, grinding, planing, etc.) on the environment is caused by the consumption of electrical energy [2]. Therefore, reducing the energy consumption during the use of the machine tool is a key measure to improve the environmental performance of the machine tool. To solve the problem of difficult to uniformly model the energy consumption of CNC machine tools,
this paper proposes a unified model of machine energy consumption. By establishing the power balance equations of each state of the machine tool, it is possible to effectively relate the various operating states and energy consumption characteristics of the machine tool. This lays the foundation for further quantification of machine tool energy consumption.

2 Multi-source energy consumption characteristics of CNC machine tools

2.1. Machine energy consumption category
From the aspect of energy consumption, the machining process of CNC machine tools is analyzed. The total energy consumption of machine tool equipment is composed of the energy consumption of many individual components on the machine tool[3], such as the main drive system, feed transmission system, hydraulic system, and auxiliary system, lubrication and cooling systems, lighting systems, cleaning systems, tool change systems, etc. The main drive system is mainly responsible for providing grinding force to remove metal materials. The feed drive system is mainly responsible for driving the table or tool to do the feed movement; the hydraulic system, auxiliary system, cooling system, etc. mainly provide auxiliary functions for the machine running, such as tool change, Lubrication, etc. Table 1 shows the description of energy consumption, functions, and energy loss of CNC machine tools.

It can be seen from Table 1 that the energy consumption components of a CNC machine are mainly composed of motors or pumps of the main transmission system, feed transmission system, and other systems. From the perspective of energy, CNC machine tools can be regarded as consisting of several energy-consuming units that interact and interdependent and have specific functions. The dynamic balance is established through the mathematical relationship between input, consumption, output, feedback, and control in the energy consumption unit. The entire machine tool work process is accompanied by material flow, energy flow, and information flow [4]. Table 2 lists the main energy consumption units of the XK713 CNC milling machine. The complexity of the CNC milling machine XK713 is general, but it can be seen from Table 2 that the energy-consumption motor of the CNC milling machine XK713 has reached seven, plus other electrical components such as lights and drivers love you, and the total energy-consuming components reach 10 or more.

2.2. CNC machine tool energy form
The machining process of CNC machine tools is always accompanied by the flow of material flow, information flow, energy flow and environmental emission flow. The energy flow of machine tools has many sources, many energy flow links, and the energy flow movement and loss law is complex, and energy efficiency is low [5]. Any machine tool energy consumption system is a flow of energy from the input to the output. The machine takes electrical energy from an external input and converts it into mechanical energy via an internal motor [6].

The total energy of the machine tool system is stored in the energy storage of the internal components of the machine tool to maintain its own operation, which is called generalized energy storage. The other
part is the consumption of motor loss, mechanical loss, and hydraulic system loss caused by the operation of the motor and the mechanical transmission system during the machining of the machine tool. The remaining part of the mechanical energy is converted into the cutting grinding energy required by the tool to cut the metal material, which is the effective energy. The energy flow of the CNC machining process can be shown in Figure 2.

| System name                  | Energy source             | Function                                                                 |
|------------------------------|---------------------------|--------------------------------------------------------------------------|
| Spindle drive system         | Spindle motor             | The tool revolves at a high speed and provides the grinding force to remove the material |
| Feed drive system            | Feed drive motor          | Straight line feed motion along the X axis or Y axis                      |
| Hydraulic system             | Hydraulic pump            | Provide clamping force                                                    |
| Auxiliary system             | Computer and its display  | Display processing numerical control program                              |
| Cooling and lubrication system | Lubricating pump motor, cooling pump | Lubrication and cooling                                                  |
| Lighting system              | Floodlight                | lighting                                                                  |
| Chip removal system          | Chip motor                | Chip                                                                      |
| Knife exchange system        | Cutter base motor         | Change the knife                                                          |

**Table 2. CNC milling machine XK713 main energy-consuming motor**

| Name                          | Motor type                  | Model                | Rated power/kW |
|-------------------------------|----------------------------|----------------------|----------------|
| Spindle motor                 | Inverter motor              | YPNGC-50-5.5-A       | 5.5            |
| X-axis motor                  | AC servo                    | GK6061-6AC31-FE      | 1              |
| Y-axis motor                  | AC servo                    | GK6061-6AC31-FE      | 1              |
| Z-axis motor                  | AC servo                    | GK6061-6AC31-FB      | 1              |
| Cooling motor                 | Three-phase asynchronous    | DB-12B               | 0.04           |
| Hydraulic motor               | Three-phase asynchronous    | Y90L-4-B3            | 1.5            |
| Lubrication pump/chip removal device | Manually                | /                    | 0              |
| Ventilation fan               | Single-phase asynchronous   | 125FZY2-S            | 0.025          |
| Others (lighting lamps, etc.) | /                          | JC38-C               | 0.05           |
3. Machine power balance formula characteristics

According to the energy consumption form and energy flow of machine tool, the state of machine tool production process is divided into basic starting state, standby running state, no-load running state and grinding state[7]-[8]. Because CNC machine tool system includes a main transmission system, transmission system, hydraulic system, control system, cooling system, lubricating system, lighting system, cleaning system, machine tool changing system, the total energy consumption is mainly composed of many individual components of energy consumption of the machine tool components.

According to the energy consumption of the CNC machine tool CNC machine tool chart to establish the power balance equation, the total power is divided into basic starting power, power, standby operation power, no-load operation of cutting and grinding processing power [9], the basic starting power is the basic power of machine maintenance after open operation of the machine tool, the power to maintain the basic stability. The standby power is the power of the other auxiliary system after maintaining the basic starting power, and the power value is a constant value. No load operation power is based on standby power, and the power after spindle motor and feed drive motor is opened. The power value of this part is related to the variables of machine speed and feed speed. The power of cutting and grinding is to process the power of workpiece material on the basis of no load running power, and the power value of this part is related to the technological parameters of machine tool processing [10][11]. The power flow diagram of the machine tool is shown in 3.

![Energy flow chart of CNC machining process](image-url)
Therefore, the power balance equation of machine tool can be divided into basic starting power, standby power, no-load power and cutting power.

(1) Basic starting power \(P_1(t)\)

The basic starting power is the basic power to maintain the machine running after opening the machine, including CNC system, hydraulic system and cooling system, so the basic starting power is equal to the sum of the power of each system:

\[
P_1(t) = \Delta p_a = p_{a1} + p_{a2} + p_{a3}
\]

Where, \(\Delta p_a\) is the increment of power when the machine starts to enter the basic starting state. \(p_{a1}\), \(p_{a2}\) and \(p_{a3}\) are the inherent power of CNC system, hydraulic system and cooling system respectively.

(2) Standby power \(P_2(t)\)

Standby power is maintained at start-up rate, and the other auxiliary systems open to achieve stable power. Standby power is equal to the sum of the power of each system component:

\[
P_2(t) = P_1(t) + \Delta p_\beta = p_{\beta1} + p_{\beta2} + p_{\beta3} + p_{\beta4}
\]

Where, \(\Delta p_\beta\) is the increment of power when the machine tool enters the standby operation state from the basic startup state. \(p_{\beta1}\), \(p_{\beta2}\), \(p_{\beta3}\) and \(p_{\beta4}\) are the inherent power of the lubrication system, tool changing feeding system, lighting system and cleaning system, respectively.

(3) No load operation power \(P_3(t)\)

No load operation power is based on standby power, and then the power after spindle motor and feed drive motor is opened, which is the sum of power between main drive system and feed drive system.

\[
P_3(t) = P_2(t) + \Delta p_\chi = p_{\chi1} + p_{\chi2}
\]

Where, \(\Delta p_\chi\) is the increment of machine power from the stand-by operation state to the no load running state. \(p_{\chi1}\) and \(p_{\chi2}\) are the main power of drive system and feed drive system respectively.

(4) Cutting grinding power \(P_4(t)\)

The power of cutting and grinding is to process the power of work piece material on the basis of no

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![Figure 3. Theoretical power flow diagram of CNC machine tools](image-url)
load operation power, which is the sum of effective power and additional load loss power of CNC machine tools [12].

\[ P(t) = P_3(t) + \Delta P_\delta = P_a(t) \]  
\[ \Delta P_\delta = p_a + p_b \]  
(3-7)  
(3-8)

Where, \( \Delta P_\delta \) is the increment of power when the machine tool enters the processing state from the no load running state; \( P(t) \) is the total input power of the machine tool; \( p_a \) is the effective machining power of the machine tool; \( p_b \) is the additional load and power consumption of the machine tool when machining.

The effective power of machine tool \( p_a \) is the effective output power of the machine tool, and it is the effective power used to remove the metal material. The effective machining power of machine tool is composed of main cutting and grinding power and feed motion power, but the power consumed by feed motion is negligible relative to the main cutting and grinding power. Therefore, the effective cutting grinding power can be expressed as:

\[ p_c = \frac{F_c.v_c + F_s.n.f}{60} \]  
(3-9)

In the form, \( F_c \) is the main cutting force of machine tool processing; \( F_s \) is the feed force of machine tool processing; \( v_c \) is the main cutting speed; \( n \) is the spindle speed; \( f \) is the feed speed. Among them, the cutting speed can be calculated by the formula (3-10).

\[ v_c = \frac{\pi.Dn}{1000 \times 60} \]  
(3-10)

In the form, \( D \) is the surface diameter of the work piece to be processed in turning, which is also the diameter of the cutter grinding wheel in the grinding and milling.

The additional load loss power refers to the machine in the load condition, the total loss of power machine motor and transmission system based on the original no-load loss on additional power loss and mechanical loss, because the measurement is very complex and can not be directly measured accurately, it is well documented that additional load loss is proportional to the power and cutting power therefore, it can be expressed as:

\[ p_\alpha = \alpha.p_a \]  
(3-11)

In the formula, \( \alpha \) is an additional load loss coefficient.

Combined with the power balance equation established above and figure 3, the whole power balance equation of the machine tool can be expressed as:

\[ P_n(t) = P(t) = \Delta P_a + \Delta P_\beta + \Delta P_x + \Delta P_\delta \]  
(3-12)

4. Analysis of Machine Energy Ratio and Energy Efficiency Model

CNC system is the input of energy consumption from the outside to the flow of the process output, in the process of energy conversion and transfer always follows the law of conservation of energy [13], so the energy consumption and energy efficiency ratio of machine tool for the exploration of energy saving and emission reduction has important significance in the machining process.

(1) Machining ratio of machine tool to energy consumption \( A_s \)

The specific energy consumption of machine tool refers to the total energy consumption of machine tools when processing the unit volume. The specific energy consumption reflects the energy consumption of the machine to remove the unit volume material, and the smaller the specific energy consumption, the more energy saving the machine tool.

According to the power balance equation of the machine tool set up above, the following energy consumption model is established:
In the formula, \( E_{\phi} \) is the total input energy of the machine tool. \( t_1 \) and \( t_2 \) are the beginning and end time of the machine tool.

(2) Effective processing energy efficiency of machine tools \( \eta_c \)

The energy efficiency of machine tools refers to the ratio between the energy consumption and the total energy consumed during the processing of machine tools when machining. The greater the energy efficiency of machine tools, the higher the energy utilization rate of machine tools.

The effective processing energy efficiency of the machine tool \( \eta_c \) can be expressed as:

\[
\eta_c = \frac{E_u}{E_{\phi}} = \frac{\int_{t_1}^{t_2} P_s(t) \, dt}{\int_{t_1}^{t_2} P_{\phi}(t) \, dt} = \frac{P_s(t)}{P_{\phi}(t)}
\]  

(4-2)

In the formula, \( E_u \) is the energy consumption when machine tool is used to remove material, \( E_{\phi} \) is the total energy consumption when machine tool is processed, \( t_1 \) and \( t_2 \) are the starting time and ending time of machine tool processing.

5. Conclusion

This paper analyzes the energy consumption form and characteristics of CNC machine tools, combined with the machine state, the processing state of the machine tools are divided into basic start state, the standby operation state, no-load running state and cutting grinding state energy components and for each state were studied. The machine tool was set up in each state of the power balance equation and the energy consumption and energy efficiency than the machine model, the model combines the characteristics of energy consumption and processing state machine, grinding machine for cutting specific energy consumption, energy efficiency calculation and analysis of cutting and grinding ratio can provides a theoretical basis for modeling and prediction.

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