

Review

Energy consumption model and energy efficiency of machine tools: a comprehensive literature review



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ABSTRACT

To cope with the serious situations such as rising energy price, the global resource depletion and climate warming, improving energy efficiency in manufacturing becomes an inevitable trend for energy conservation, emissions reduction and sustainability. As the basis energy consumed device in manufacturing system, machine tools' energy consumption modeling and energy efficiency evaluation are the prerequisite for energy-saving in manufacturing. A comprehensive literature review is needed because some related concepts are not clear and the precision of models still need to be promoted in this field. Firstly, the connotation of energy efficiency for machine tools was discussed. It was pointed out that specific energy consumption referred to the mapping relationship between energy consumption and the processing parameters, which reflected the energy efficiency of machine tools from the perspective of effective input and output. Secondly, design, scheduling management, optimization and environment assessment of machine tools were introduced based on energy efficiency. Thirdly, the existing energy consumption models were classified into three categories in this work: 1) the linear type of cutting energy consumption model based on material remove rate, 2) detailed parameter type of cutting energy consumption correlation models and 3) process oriented machining energy consumption model. Finally, conclusions were drawn for the future study in two major points: 1) the accuracy of current energy consumption models could be improved through introducing the correlation analysis of machine tools, parts, tools and processing condition, 2) more scientific evaluation index system is required for the assessment and test of machining tools' energy efficiency.

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1. Introduction

The energy yearbook published by the U.S. energy information administration in 2012 showed that industrial electricity consumption accounted for 31% of the total electricity consumption, manufacturing electricity consumption accounted for 90% of the industrial electricity consumption, and machine tools electricity consumption occupied 75% of manufacturing electricity consumption (EIA, 2011), as shown in Fig. 1. As an important part of national industry, manufacturing consumes a large amount of energy and resources in product manufacturing process and leads to serious environmental emissions (Zhai et al., 2014; Du et al., 2015).

Machine tools are the basic energy consumption devices in manufacturing (Liu et al., 2013). The emission caused by machine tools using electricity can not be neglected. Gutowski (2013) pointed out that the CO₂ emissions of a numerical control machine tool with main shaft power in 22 kW operating one year was equivalent to the emissions of 61 SUV cars. Machine tools have been regarded as one of the regulatory priority categories in the European Union's Eco-design Directive2009/125/E (EPTA, 2007). That puts the pressure on manufacturer to make the machine meeting the eco-design directive and carbon emission standard.

The International Organization for Standardization drafted the standard "environmental evaluation of machine tools" in 2010 (ISO14955-1, 2014). It focused on energy consumption test procedure of metal cutting and design methodology for energy-efficient machine tools. Predictably, the energy consumption index will be one of the machine tools product indexes in the future. Growing energy demand and rising energy prices force manufacturing to seek for high energy efficiency and low cost solutions. Meanwhile,

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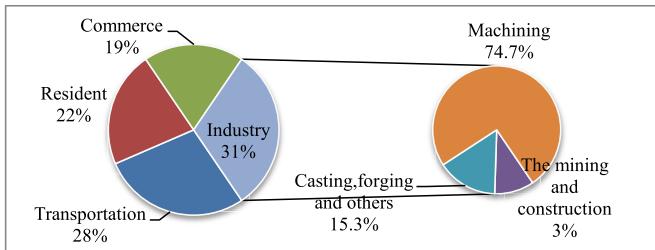


Fig. 1. Electricity consumption proportion of various fields in the United States.

serious environmental pollutions and severe environmental legislations drive both academia and enterprises to attach great importance to energy efficiency problems of manufacturing process and machine tools (Anderberg et al., 2009; Enrico and Andrea, 2013; Trianni et al., 2014). For seldom seeing comprehensive review in this field, this research was written to discuss connotation of energy efficiency and characteristics of the existing energy consumption models of machine tools. In addition, design, scheduling and assessment methods to optimize energy efficiency and study trends of this field were also discussed.

2. Methods

This comprehensive literature review was to reveal the current state of academic insight into the energy consumption model and energy efficiency of machine tools, carried out with methods like meta-analysis and meta-ethnography. Meta-analysis refers to summarizing the results of quantitative studies and finding the effect of a particular variable through various analytical tests, while meta-ethnography is to obtain interpretative synthesis of qualitative research (Bryman and Bell, 2011).

The comprehensive review process included three main steps. Firstly, research theme or question was specified, meanwhile a large number of relevant literature data and appropriate search strategies were selected. Secondly, after reading and critical analysis, the current topics and issues were refined. Thirdly, the findings were synthesized.

2.1. Specifying research question and searching literature data

In the past, compared to high energy consumption of metal smelting and casting industry, attention to energy consumption of machine tools was not enough. Nowadays, as the surge in the number of machine tool equipments and increasingly serious environmental problems, in addition studies find that machining system showed a great potential for energy saving, thus problems of energy efficiency of machine tools have been received the widespread attention at home and abroad (Santos et al., 2011; Shrouf et al., 2014; Camposeco-Negrete et al., 2013; Wang et al., 2015). As a result, the energy efficiency of machine tools was determined as one of the research questions. The initial, the research questions for the systematic review were rather broad: "What is the energy efficiency?" or "How to evaluate the energy efficiency of machine tools, machining system or manufacturing?" or "How to improve the energy efficiency of machine tools?". The search term ("energy efficiency" and "machine tool*" or "machining") was used, where "machine tool*" included "machine tools". Because the machine tool was part of the manufacturing system, the term ("energy efficiency" and "manufactur*") was used, where "manufactur*" included "manufacturing" as well as "manufacture". Then "energy efficiency" was changed to "energy-efficient", "efficient", "energy consumption", and the above search

was repeated. Considering energy saving implied energy efficiency, the search term ("energy*saving" and "machine tool*" or "machining") was also used, where "energy*saving" included "energy-saving". Then "energy saving" was changed to "energy conservation" to repeat again.

After reading some literatures, it was found that energy consumption model of machine tool was the key to solve the problem of energy efficiency, and some studies used the specific energy consumption to evaluating energy efficiency (Wang et al., 2013; Bhushan, 2013; Peng and Xu, 2014; Duflou et al., 2012). Therefore, the energy consumption model of machine tools was determined as the other research question. The search term (("machine tool*" or "machining") and ("energy consumption model*")) was used. Then "energy consumption model*" was changed to "specific energy consumption" and "specific cutting energy". Because some studies would use words such as "cutting force", "power or electricity demand" to express the energy consumption, then these words were used to repeat the search. This step broadened the scope of knowledge about energy efficiency and energy consumption model of machine tools. Literature search was carried out in the Engineering Village, the Web of Science, Elsevier ScienceDirect and Springer Link. Because some researches could not be accessed, Google Scholar was also used to identify conference proceedings and unpublished studies. And some national statistics websites were used for industry statistics information.

2.2. Applying screening criteria and refining the current topics and issues

It is easy to bog into the mire of literature for lacking the screening criteria, although as widely as possible to collect literature data is the responsible attitude of the study. The first criterion applied was to target the mainstream. Literature in famous journals, classics, research reports of full-time department were reading carefully to catch the mainstream direction of this field, and their references needed much attention. The second was to narrow the search range after organizing the literature. In order to accumulate the knowledge, it is necessary to take good reading notes for the important literature. Then the literature researches were classified roughly according to the content through comparing them in common and differences. On the one hand it was found that improving energy efficiency mainly depended on the design and use. Beside the theory, some technologies were also need to evaluate the energy efficiency. On the other hand, it was found that energy consumption models were different in form and application characteristics. In order to further observes, problems were extracted, the search was narrowed and a new round of search was done. For example, the search term ("lightweighting design" and "machine tool*" and "energy efficiency"), ("energy consumption data" and "machine tool*" and "monitoring"), ("energy-saving operation" and "machine tool*"), ("scheduling" and "energy efficiency"), ("energy consumption simulation software") was used and so on.

2.3. Synthesized our findings

It was found that many universities and research institutions including the University of New South Wales, Brunswick Industrial University, University of Stuttgart, the University of California, Seoul national University, Chongqing University, etc. carried out a lot energy efficiency researches on different levels of machining system (such as single/multiple machine system, the workshop/factory, the enterprise/supply chain). However, machine tool, as the basis energy consumed device in manufacturing system, energy efficiency definition of it has not been very clear so far. Therefore,

the connotation of machine tool energy efficiency was discussed in this paper. Then methods to improving the energy efficiency were summarized from the aspects of machine tool design, scheduling management, used and evaluation implementing. It was found that the energy consumption models were established based on cutting force, cutting parameters, the tool wear and so on. So these models were classified and summarized according to their application characteristics. In the following sections, these will be introduced one by one.

3. Energy efficiency of machine tools

In this section, the connotation energy efficiency of machine tools was discussed. Then some methods and strategies to improving the energy efficiency from the aspects of machine tool design, scheduling management and used were introduced. Finally, some technical researches for implementing the energy efficiency evaluation were presented.

3.1. The connotation of the machine tools energy efficiency

The International Energy Agency regards energy efficiency as the goal to reduce the energy demand of products and services, or to obtain the same quality and the same end-use energy under a less energy input (Konstantinos and Peter, 2013). The Chinese national standard defines the energy efficiency as the ratio or other quantitative relationship between output of products, energy, services, or performance and energy input. For example, conversion efficiency, theoretical energy demand/energy actually used (The Energy Management System Requirements, GB/T 23331-2012). As can be seen, the word term energy efficiency is very universal, and thus it has a specific application definition at different occasions. Someone in technical field will define energy efficiency from the perspective of thermodynamics (Patterson, 1996), which is the ratio of input energy and the output so as to assess the level of energy conversion, such as the conversion between heating value of the fuel combustion and the steam heat. In the manufacturing, energy efficiency from viewpoint of physical thermodynamics is often used, which means the ratio of the product output and total input energy (Quadriguasi et al., 2009), also known as input–output efficiency.

For a machine tool, both the intrinsic characteristics and processing conditions affect its energy efficiency. Intrinsic characteristics mainly affect the energy efficiency for the energy losses such as motor loss, mechanical loss and hydraulic system loss etc. Motor loss contains stator iron loss, friction loss, the wind loss, the copper loss and stray loss, which is closely related to the power factor, resistance and current of the motor. Mechanical loss including coulomb friction loss and viscous friction loss is caused by friction between the driving part, which depends on running speed, damping coefficient and lubrication situation of transmission parts. Hydraulic system loss mainly includes volumetric leakage loss, hydraulic loss and mechanical loss, which are closely related to structure of the hydraulic oil pump, tubing cross section, the oil properties. From the perspective of the machining process of machine tools, reactive power losses affect the energy efficiency mainly for no real output, such as standby energy consumption, air-cutting energy consumption reactive power consumption of acceleration and deceleration etc., which are related to inertia force caused by the components quality, operations of machine tools, production strategy and so on. Due to the complexity of function of machine tools, energy efficiency definition of it has not been very clear so far, and some overall evaluation indicators for energy efficiency of machine tools can be seen more form the viewpoint of input–output efficiency.

Sebastian (2012) proposed an energy efficiency definition of machine tools based on power demand.

$$\eta_{energy} = \frac{\text{produced pieces}}{\text{electrical power demand} \cdot \text{time}} \quad (1)$$

Liu et al. (2013) divided the machine tools energy efficiency into instantaneous energy efficiency and process energy efficiency. Machine instantaneous energy efficiency $\eta_{energy}(t)$ was the ratio of material removal cutting power $P_{cut}(t)$ and the machine input power $P(t)$. Process energy efficiency η_{energy} expressed the ratio of the effective energy and energy consumed by the system in a processing time T in the integral form.

$$\eta_{energy}(t) = \frac{P_{cut}(t)}{P(t)} \quad (2)$$

$$\eta_{energy} = \frac{E_{cut}}{E} = \frac{\int_0^T P_{cut}(t)dt}{\int_0^T P(t)dt} \quad (3)$$

At present, most studies use Specific Energy Consumption (SEC) to express the machining process or machine energy efficiency, and the definition of SEC is the energy required to remove material per unit volume or mass. Some studies also call it as energy intensity, or specific cutting energy.

$$SEC = \frac{E}{V_{material}} \quad (4)$$

$$SEC = \frac{P \cdot T}{MRR \cdot T} = \frac{P}{MRR} \quad (5)$$

$$SEC = \frac{F}{a_e \cdot h} \quad (6)$$

Where $V_{material}$ represents the total volume of removed material, T is the processing time, the Material Removal Rate (MRR) refers to the volume or quality of removed material per unit time. F is the cutting force, a_e is the cutting width, h is the thickness of the chip. It is worth noting that Eq. (5) and Eq. (6) only expressed the energy efficiency of the machine under the cutting condition, while Eq. (4) expresses the energy efficiency of the entire machining process, because it also contains the energy consumption when the machine started, or was in standby mode and other non-cutting status. Obviously, SEC is a way to express the energy efficiency level from the perspective of the machine effective input and output, and its value is used to estimate the energy consumption of the machining process, so the SEC is also a model of energy consumption from a certain perspective. Since the SEC covers the mapping relationship between energy consumption and MRR, and its value can not only compare the energy efficiency differences of the same machining process under different processing parameters, but also can reflect the energy intensity and the productivity differences in different machining processes. So, although some SEC models are not enough accurate and the relevant parameters are complex, the concept of it is easy to understand and calculate. Therefore its application is very common.

Some studies definite the machine efficiency η as the ratio of output power P_{out} and input power P of the machine (Peters, 1975).

$$\eta = \frac{P_{out}}{P} = \frac{1}{1 + (P_{loss}/P_{out})} \quad (7)$$

Where P_{loss} is caused by friction of mechanical drive and motor electromagnetic losses in the power transfer of the machine.

Notably, both η and η_{energy} reflect the relationship of the input and output energy, and their values are affected by the machine load. But the connotation of energy efficiency is more widely than that of mechanical efficiency, in another word η is included in η_{energy} . η implies the mechanical energy loss and electrical loss, while η_{energy} including all kinds of the energy loss needs to be combined with production and reflects the relationship between the energy input and product output. η can not indicate how power or energy is used to cut exactly. For example, in the air-cutting status, keeping the speed of the spindle reach the same as the cutting status, the torque can be obtained by the braking the spindle, then the machine tool can be under load in the maximum efficiency (Draganescu et al., 2003), but this energy is not used for metal cutting, and there is not any actual output. However the way using the SEC to express energy efficiency of the machine can reflect how the machining energy is distributed and used to remove material in detail.

3.2. Design and optimization for energy-efficient

The demand of high productivity, high quality and low energy consumption fundamentally affect the future machine design, and this trend comes from the promotion of attention to resource saving and conservation (Neugebauer et al., 2011; Strano et al., 2013). The draft standard ISO14955-1 “Machine tools—Environmental evaluation of machine tool—Part 1: Design methodology for energy-efficient machine tools” pointed out that the corresponding functional modules of machine tool should be considered when an energy efficiency design was planning. The draft standard mentioned that energy consumption in phases of material production and use was dominated in a machine tool’s life cycle, which indicated the direction for energy-efficient optimization (Jiao et al., 2012). Lightweight design and selecting energy-saving components are common design method for energy-efficient of machine tools (Dietmair et al., 2011). Kroll et al. (2011) pointed out that lightweight design could be taken as the pursuit for a higher lightweight factor—the ratio of the elastic modulus and density of the material, or the ratio of quality and hardness.

$$\text{lightweight factor} = \frac{\text{elasticity modulus}}{\rho} \quad \text{or} \quad = \frac{c}{m} \quad (8)$$

For a higher lightweight factor, let the $m \downarrow$ while $c = \text{constant}$, or $c \uparrow$ while $m = \text{constant}$ are the two main design aim. On the one hand, Machine components in movement will produce gravity and inertia force. Reducing the quality of acceleration components can decrease the influence of inertial force on the necessary engine torque. The accelerated motions of machine tool spindle lead a power loss for no output, so reducing the quality of spindle will decrease the reactive energy. In addition, due to the lighter weight, the time to acceleration will get short, thereby the overall processing time reduces and energy consumption per unit of output reduces. Moreover, loss in energy transferring will reduce with less friction losses due to less gravity in bearings and guides. On the other hand, when the stiffness increases, the stability of machine tool in processing will be improved, thereby improving the productivity of machine tools, thus indirectly improving the energy efficiency of machine tools.

Machine tool structure lightweight (topology optimization), material selection optimization (such as titanium alloy, carbon-fiber composite materials), integration and module design (the mechanical and electrical integration to reduce redundant drive process), etc. are lightweight design strategies commonly used (Wanner, 2010; Zhao et al., 2010). For different types of machine tools, the energy saving design strategy will be different. Grinding machine, for example, it is not obviously to see the energy

efficiency improvement through reducing quality of its components, because its main driving power is used to process workpiece rather than accelerate. However, for a 5 axis milling machining center, due to complex motion path and frequent acceleration and deceleration, lightweight design for its energy saving is relatively effective (Kroll et al., 2011).

The premise for energy-saving design is sorting out energy flow in the transmission path and the energy loss situation of the machine tools. Energy consumption or power modeling can provide theoretical basis for energy-saving design and optimization. For example, a power model of a machine tool feed servo motor could be set up as follows (Hu, 2012; Saidur, 2010):

$$P_{ax} = 3RI_s^2 + \frac{\omega_e^2(\psi_d^2 + \psi_q^2)}{R_i} + \omega_e K_e i_q \quad (9)$$

Where $R(\Omega)$ was the stator winding resistance, $I_s(A)$ was the effective current value, $\omega_e(\text{rad/s})$ was angular velocity of the motor electromagnetic field, $\psi_d(Wb)$ and $\psi_q(Wb)$ was magnetic flux component of the motor, K_e was the electromagnetic torque coefficient, $i_q(A)$ was the stator current component, $3RI_s^2$ was motor stator copper loss, $\frac{\omega_e^2(\psi_d^2 + \psi_q^2)}{R_i}$ was iron loss of motor, $\omega_e K_e i_q$ was electromagnetic power including the mechanical loss stray loss and output power of the motor. In this formula, R_i , ψ_d , ψ_q and i_q could not be measured directly, but could be transformed into force or torque. Through the analysis of power model, the motor can be more efficient through using new materials to reduce iron loss, copper loss, and using lubrication to reduce motor mechanical friction loss, and redesigning the structure and shape to reduce the wind resistance. Selecting energy-saving components also is a design method to improve the machine tool energy efficiency, such as using motor and frequency converter which can match the machine load, using the direct drive pump controlled servo hydraulic press and so on (Triet and Ahn, 2011), and here is no longer described in detail.

3.3. Scheduling management and use for energy-efficient

The energy-saving strategies of using new materials and new technologies may require enterprises to transform the existing manufacturing system and invest heavily, thus the enterprises usually prefer to carry on energy saving scheduling and management (Bi and Wang, 2012). Energy efficiency can be improved through matching the production task with machine tools scientifically, reducing machine idle time, choosing start and stop time reasonably and reducing reactive power operation (Zeng et al., 2009).

Scheduling problem based on energy efficiency of machining system is a multi-objective constraint and complex NP problem, because the enterprises also need to consider the quality, cost, time and other issues in addition to energy consumption. For example, the energy consumption objective of the machining system scheduling problem could be represented as Eq. (10) (Wang, 2011):

$$\begin{aligned} \min E_{\text{system}} = & \sum_{k=1}^m \sum_{i=1}^n PE(j_i, k) + \sum_{k=1}^m WE_k + \sum_{k=1}^m TE(k-1, k) \\ & + \sum_{k=1}^m AE_k + CE \end{aligned} \quad (10)$$

Where n was workpiece number, m was machine number, $PE(j_i, k)$ was energy consumption of processing the i_{th} workpiece in the k_{th} machine tool, WE_k was standby energy consumption of the k_{th}

machine. $TE(k-1,k)$ was transport energy consumption from the $(k-1)_{th}$ machine to the k_{th} machine tool, AE_k was the adopting energy of the k_{th} machine tool(such as tool change energy), CE was energy consumption of other auxiliary equipment in the workshop. After completing all the goals and constraints in the scheduling model, it usually could be solved by using ant-colony algorithm, genetic algorithm, tabu search, simulated annealing, hierarchical scheduling based on Petri net and decomposition tree etc. (Kan et al., 2011; He,Y. et al., 2012a; Bruzzone et al., 2012; Dai et al., 2013; Tuo et al., 2014).

Following several common strategies of energy efficiency in scheduling management and use of machine tools are introduced:

- (1) Standby energy consumption optimization: machine tools generally keep on standby to wait jobs. This part of the energy can be saved about 10%–25% (European Communities Information Society and Media, 2009). Controlling the shutdown of machine tool reasonably can save energy effectively. But start–stop operations need to consider the average arrival time interval of workpiece, the production batch and whether start–stop energy consumption is less than the no-load power consumption in the standby process or not, because the frequent start–stop will extend the maximum completion time even the stability of machine tools (Mouzon et al., 2007).
- (2) Process sequence optimization: how the workpiece machining features are allocated to machining process has an important influence on energy consumption (Bähre et al., 2012). The maximum workshop capacity depends on the bottleneck process. Bottleneck processes make the production line lose balance, causing the downstream equipments of bottleneck process to wait for long and increasing the standby energy consumption. While dividing part of the jobs to other process and increasing the number of devices appropriately can improve this situation. For the non-bottleneck process, more than 50% of the energy consumption of the machine tool is consumed in indirect production, and utilization rate of machines is low, through batch production will reduce waiting time and total time of task processing and can improve energy efficiency correspondingly.
- (3) Machine tools selection optimization: in general, when the machine is running, proportion of energy consumption used to dealing with the material is small and the background components consume a large amount of electricity. Sometimes the same working procedure can be processed in different machine tools and get the same satisfied quality, but the energy consumption is quite different due to their different characteristics of energy consumption. Gutowski et al. (2006) machined the same material with a machining center and automatic milling machine and found that the processing energy consumption was affected by machine type and energy consumption differed obviously. So choosing machine tool equipment and arranging processing routes reasonably is a way to improve energy efficiency.
- (4) Other use optimization: Mori et al. (2011) pointed out that the time-consuming of spindle process was long, and that of feed system positioning process was short during high-speed cutting. Therefore he proposed a control method to make the feed system movement synchronized with the spindle speeding up, which allowed the machine to reduce energy consumption. Some research presents methods to reduce the energy consumption of machining process in recovering energy from the spindle inertia kinetic, repairing and maintaining energy component, improving tool path to reduce empty cutting stroke (Vincent et al., 2013), changing

the lubricating condition of cutting process (Fratila, 2009), optimizing cutting parameters and so on. For example, the energy consumption of material removal could be established as $E_{cut} = k \cdot a_e \cdot a_p \cdot z^b \cdot v_f^{1-b} \cdot n^b$ (Diaz et al., 2010), through optimizing cutting parameters then E_{cut} can be reduced.

3.4. Energy efficiency and environmental impact assessment

Correct energy saving strategies depend on energy efficiency and environmental impact assessment. Avram et al. (2011) evaluated the energy efficiency and environmental impact in machining process, using the analytic hierarchy process to weigh the criteria in three areas of technical, economic and environmental. Cao et al. (2012) proposed a carbon efficiency evaluation method to quantify the life cycle carbon emissions of machine tools. Le Bourhis et al. (2013) did the environmental impact assessment of a machine tool based on global sustainable perspective taking the materials, liquid substance, power consumption of processing into consideration. Ma et al. (2014) did comprehensive energy efficiency evaluation of metal cutting process using finite element numerical simulation experiments. In a nutshell, some researches assess the energy efficiency of machine tools with a single energy indicator, such as specific energy consumption, energy utilization and the others do the integrated assessment considering energy efficiency, environmental impact, economic, technical and other properties. Currently, the challenge is how to establish a more scientific and practical energy efficiency evaluation index system and form the machine energy efficiency test standard.

In order to help the enterprises to carry out the evaluation of energy efficiency, researches have been carried out accordingly from the aspects of technology, such as monitoring the energy consumption data, developing software to simulate process energy consumption and implement energy efficiency evaluation.

- (1) Monitor and application energy consumption data: whether it is technical energy-saving or management energy-saving, they all require the support of energy consumption data to get the proper evaluation and analysis. Studies have shown that energy consumption data provide valuable feedback information for supervising machine tool operation, monitoring tool condition, improving workpiece quality and productivity (Peng and Xu, 2014). It is important to use automatic technology to monitor and analyze energy consumption in manufacturing systems due to system complexity and numerous data sources (Vijayaraghavan and Dornfeld, 2010). Hu et al. (2012) proposed an on-line approach to monitor the energy efficiency of machine tools without using any torque sensor or dynamometer. Zhao et al. (2013) introduced how to use computer and sensors to build machine tool energy efficiency monitoring system in detail. Lee and Tarn (1999), Zhang et al. (2014), Kim et al. (2002) pointed out that decomposing spindle current and power signals could predict the failure or wear of tools during machining process.

It is difficult to provide adequate support for decision-making due to many studies often using historical or experimental data (Taisch et al., 2011). So, current challenges are the lack of reliable real-time energy consumption data and how to implement data transfer and sharing. Technologies similar to MTConnect using Internet to monitor energy data from different plants affect the energy consumption data collecting method of plants in the future. Establishing enterprise energy consumption foundation database

including all kinds of processing technique and device state data will be the trends in order to optimizing energy efficiency and management (Niggeschmidt et al., 2010).

(2) Energy consumption simulation and related softwares: simulation is a kind of method that can capture interaction among a variety of dynamic energy flows and resource flows in the machining process (Larek et al., 2011). Traditional manufacturing system simulation may pay more attention to output, production time, man power and equipment resources, but new simulation study taking manufacture system energy consumption into account is rising gradually. Shao et al. (2010) established a CNC machining simulation model which used the parameters such as spindle speed, cutting depth to calculate the energy consumption and discussed environmental impact assessment method of machining process energy consumption and emission. Herrmann et al. (2011) proposed a simulation framework for production process chain which used the rated power of equipment and production lot size to prediction energy consumption. Hibino et al. (2012) and Muroyama et al. (2011) established comprehensive evaluation model of manufacturing systems using WITNESS and AUTOMOD respectively. The simulation result included material utilization, output, and energy consumption and so on.

Currently, there are some commercially software for energy simulation. Some LCA software such as SimaPro7.0 (Pré Consultants, 2011), Gabi4.0 (PE International GmbH, 2007) etc. can simulate the energy consumption for a product of every stage of life cycle, but the final evaluation result of LCA software is shown as the overall environmental impact instead of energy decomposition in detail. Besides, Some energy management simulation software such as Energy Lens (BizEE, 2011), EnergyCAP (EnergyCAP Inc, 2011), Optima (Optima Energy Management, 2011), DOE-TIP (US DOE, 2011) etc. can simulate the energy flows of plant, workshop and equipment unit. More details about the energy simulation software can be seen in the reference research by Seow et al. (2013). Simulation for machine tools not only can observe the real-time running status and change of energy flows but also can detect whether there is a collision or interference in the machining process (Heisel and Braun, 2014). But the professional simulation software is less currently. Therefore, it is difficult to evaluate the energy consumption change caused by a series of processing parameters and machine configurations changes.

4. Energy consumption model of machine tools

Improving energy efficiency is based on estimating energy consumption accurately. The following sections will focus on the

energy consumption model of machine tools, before that, energy consumption composition and factors need to be introduced.

4.1. Energy decomposition and energy consumption factors of a machine tool

The use of the machine tools mainly depends on electricity. Energy consumption is equal to power multiplied by time, namely the area between machine tool power load curve and time axis, as shown in Fig. 2. Calculating the energy consumption is to divide the surface area into several parts and then to accumulate them. The different segmentation methods of area correspond to different ways of energy consumption division of a machine tool. According to research needs, machine tool energy consumption can be divided by the function, composition system, components, operation status and energy consumption attributes. Sometimes, energy consumption of some components or processes can be ignored and some assumptions will be taken. For example, some researches ignored the energy consumption of feed unit or tool change process and some assumed that spindle speed was constant in the machining process. (How detailed the energy be divided affects the calculation accuracy and complexity of energy consumption model). Fig. 3 shows the typical division ways of machine tools energy consumption.

The energy consumption of machine tool is usually divided into constant part and variable part, as shown in Fig. 4. Fixed energy consumption including energy consumption of chip removal device, cooling and lubrication device, computer control system, tool change device energy, tool monitoring device and so on, often referred as the standby energy consumption. In addition, it is regarded as fixed energy when the spindle or feed shaft is at constant speed and in air-cutting status. In general, the higher the degree of automation of machine tools, the more fixed electricity its peripherals consumed. The variable includes energy consumption to processing material and energy consumption of axial acceleration and deceleration. This part of the energy consumption often accounts for 20%–30% of total energy consumption of machine tools, and is related to material properties, processing parameters, processing conditions and tool conditions. There is a complex dynamic interaction and coupling effect between these relevant variables as shown in Fig. 5. For example, material properties of workpiece have an impact on the choices of machine tools and cutting tools. The geometry of a workpiece will impact the machining tool path. Both cutting tools and materials have impact on the selection of cutting parameters. Opening the cooling fluid device has influence on processing quality, which will undoubtedly affect the fixed and variable energy consumption of machine tools. The relationship between energy consumption and the various parameters has become the key point and difficulty in researches. The purpose is to accurately estimate the energy consumption of

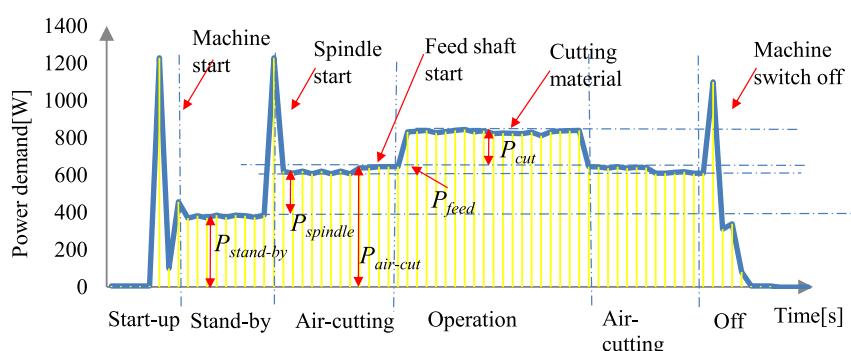


Fig. 2. A schematic diagram of power profile of the milling process.

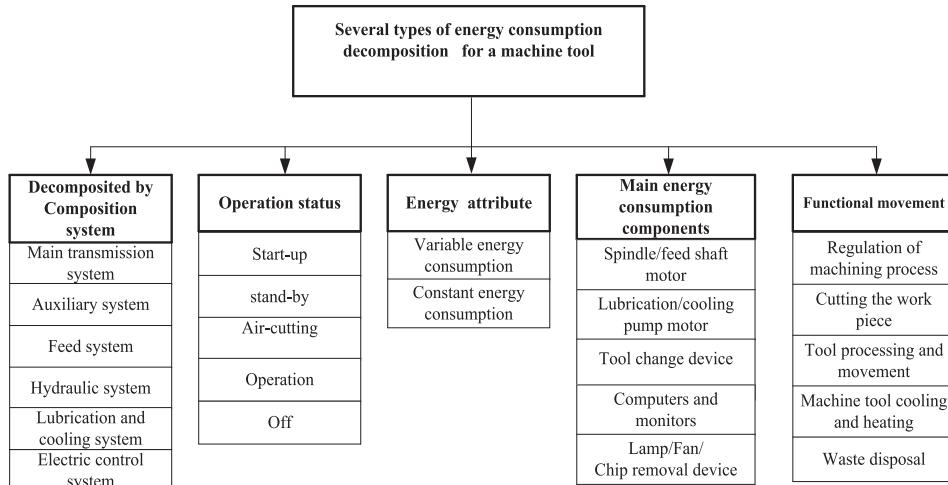


Fig. 3. Different ways of energy consumption decomposition for machine tools.

machining and reduce the energy consumption. For example, reducing standby time or reducing the empty cutting path can reduce the fixed energy consumption, while improving the processing conditions, optimizing cutting parameters and blank dimensions can reduce the energy consumption of variable.

4.2. The establishment and comparison of different energy consumption models

Energy consumption is equal to power multiplied by time, while power is equal to force multiplied by speed. The Force reflects the deformation of metal material and the speed reflects the variation of processing parameters, which is the theoretical basis for building energy consumption model. After understanding the characteristics of energy or power transmission of a machine tool then energy or power balance equation can be established.

According to the expression form of existing energy consumption models, it can be roughly divided into three categories. The characteristic of the first category (section 4.2.1) is to quickly get a linear relationship between the SEC and the MRR for estimating machine cutting energy consumption, but specific meaning of

coefficient is not very clear. The second characteristic (section 4.2.2) is to parse the relationship between energy consumption and the processing parameters. Characteristic of the third kind (section 4.2.3) is to build a general process model to calculate energy consumption of the parts processing.

4.2.1. The linear type of cutting energy consumption model based on MRR

Gutowski et al. (2006, 2007, 2009) simplified the input and output balance problems of energy flows and material flows in manufacturing process with concepts entropy, enthalpy and exergy from the perspective of thermodynamics. The study proposed that there was a function relationship between energy consumption and material removal rate in machining process for the first time. Power of the machine tool was divided into idle power(power for the auxiliary function: cooling and lubricating device, chip removal device, the computer control device, tool change device, workpiece transmission device, tool wear detection device, etc.) and cutting power(power for material removal)in his research. The SEC model was established as follows:

$$P = P_0 + k \cdot MRR \quad (11)$$

$$SEC = \frac{P_0}{MRR} + k \quad (12)$$

Where P was the input power and P_0 was the idle power, $k \cdot MRR$ represented the power for cutting materials. P_0 depended on the characteristics of the machine tool itself, while k was a constant with units of kJ/cm^3 closely related to the workpiece and cutting mechanism. But the study did not explore what would happen to k when influencing factors changed.

Kara and Li (2011a) also proposed a similar empirical model in which power was inversely proportional to mass rate removal. The model has been proved in the lathe and milling machine and the energy consumption prediction accuracy can reach above 94% on average.

$$SEC = C_0 + \frac{C_1}{MRR} \quad (13)$$

Where C_0 and C_1 were specific coefficients of the machine tool. Kara's research showed that C_1 obtained by experiment data was not the same with P_0 , because that spindle power and the friction

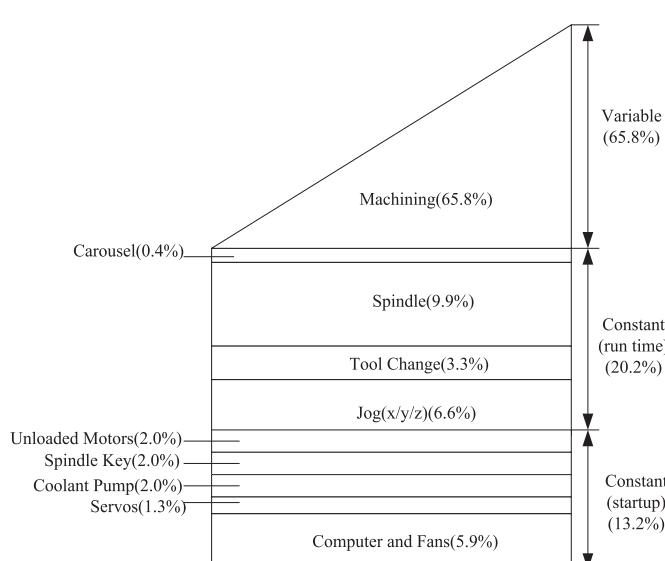


Fig. 4. Energy used of a 3-axis CNC milling machine (Gutowski et al., 2006).

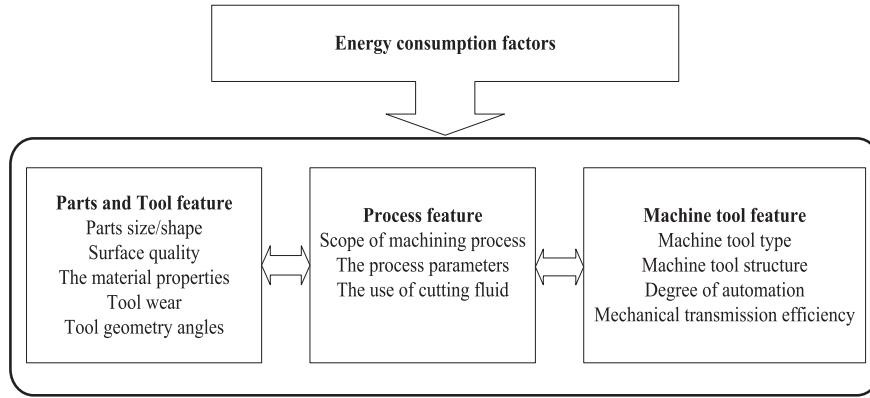


Fig. 5. Factors of energy consumption of machine tools.

power consumption were highly depending on the processing parameters in the air-cutting condition. Kara also compared differences of the model under the condition of dry and wet cutting, pointing out that the application of cooling device had a great effect on C_1 .

Li et al. (2013) proposed an improved SEC model Eq. (16) on the basis of Eq. (12) and Eq. (13), considering the spindle rotation speed in air-cutting status.

$$P_0 = P_{\text{standby}} + P_{\text{spindle}} = P_{\text{standby}} + k_1 n + b \quad (14)$$

$$P = P_{\text{standby}} + k_1 n + b + k_0 MRR \quad (15)$$

$$\text{SEC} = \frac{P}{MRR} = k_0 + k_1 \frac{n}{MRR} + k_2 \frac{1}{MRR} \quad (16)$$

$$k_2 = P_{\text{standby}} + b \quad (17)$$

Where P_0 was decomposed into standby power P_{standby} and spindle power P_{spindle} . P_{spindle} was the function of spindle speed n . Constant b was the main drive system power loss caused by motor and transmission chain. $k_0 MRR$ represented the power for material removal. k_0 and k_1 were experimental coefficients. The model ignored feed power because it took very small proportion. This study showed that the model's prediction accuracy is 95% for milling process.

Diaz et al. (2011) proposed a similar model Eq. (18), but the coefficients' meaning was not the same. Where b was defined as the energy in stable state, and k had a unit for kW, but no specific definition. They obtained the relationship curve between SEC and MRR by changing the cutting depth and width continuously in the experiment. They pointed out that higher material removal rate made higher machine input power, but presented a tendency of lower energy consumption due to shortening of processing time.

$$\text{SEC} = k \cdot \frac{1}{MRR} + b \quad (18)$$

Models like Eq. (12), Eq. (13), Eq. (16) and Eq. (18) have a wide application range, and are verified in estimating the energy consumption of the turning, milling, and grinding machine. The correlation coefficients in the model can be quickly determined through experiment and numerical fitting method. However, the coefficients' definition are not very clear, and volatility of them will be influenced by what kind of processing factors and characteristics of machine tools are also not clear. In addition, the linear model means that the same MRR has the same SEC, but in fact, MRR is the product of cutting speed v_c (mm/min), feed rate v_f (mm/min) and

cutting depth a_p (mm). Some studies pointed out that using a combination of different cutting parameters could obtain the same MRR, but the actual measured energy consumption value was not the same (Newman et al., 2012).

4.2.2. Detailed parameter type of cutting energy consumption correlation models

According to different emphasis of variable selection in energy consumption modeling, the detailed parameter type of cutting energy consumption correlation models can be divided into four classes (see sections 4.2.2.1–4.2.2.4). The four classes focus on deformation of metal, tool wear, cutting force and cutting parameters in the process of modeling respectively.

4.2.2.1. Energy consumption model based on metal deformation theory. Some researches established a theoretical energy consumption model based on metal plastic deformation for thinking that the cutting energy was used to make metal deformation (Bayoumi et al., 1994; Pramanik et al., 2006). Munoz and Sheng (1995) set up an energy calculation model Eq. (19) using cutting force and the material removal rate vector. The study suggested that cutting energy consumption was closely related to cutting fluids, tool, material properties and the material removal amount.

$$E_{\text{cut}} = \left(\frac{\cos(\beta - \gamma) \cos \eta_s \cos \lambda + \cos(\varphi + \beta - \gamma) \sin \eta_s \sin \lambda}{\cos(\varphi + \beta - \gamma)} \right) \times \frac{\tau \cdot V_{\text{material}}}{\sin \varphi \cos \lambda} \quad (19)$$

Where β was normal friction angle, γ was cutting tool rake Angle, η_s was shear flow angle, φ was shear plane angle, τ was workpiece flow stress and λ was oblique angle. The precision of the model is not high due to modern tools emerging.

Kishawy et al. (2004) developed an energy model as a function of volume fraction and material properties. The study divided cutting energy into three parts, the specific energy for plastic deformation in the primary shear zone E_p , the specific energy for plastic deformation in the secondary shear zone E_S and E_D the energy per unit volume consumed for debonding the particle from the matrix. This model was verified on cutting Al_2O_3 .

$$E_{\text{cut}} = E_p + E_S + E_D \quad (20)$$

$$E_p = \frac{G}{e+1} \left[\frac{1}{\sqrt{3}} \frac{\cos \gamma}{\sin \varphi \cos(\varphi - \gamma)} \right]^{n+1} \quad (21)$$

$$E_S = (F_\mu h^\alpha / a_e h) \quad (22)$$

$$\frac{dU}{da} = \left[\frac{1 - \nu^2}{Y} \right] \pi \sigma^2 w_1 w_2 \quad (23)$$

Where G was the specific stress in the shear zone, e was the strain hardening exponent, φ was the Shear plane angle in the primary shear zone, F_μ was the frictional force on the chip, h was chip thickness, h^α was he chip thickness ratio, a_e was the cutting width, dU was the strain energy, ν was material Poisson's ratio, Y was young's modulus, w_1 was material crack length, w_2 was material crack width, σ was material fracture stress.

4.2.2.2. Energy consumption model based on the amount of tool wear. Some studies found that cutting energy was closely related to the tool condition, and there was a linear relationship between cutting power and the amount of tool wear (Cuppini et al., 1990). Shao et al. (2004) considering the influence of the average tool flank wear to cutting power, proposed the following face milling cutting energy consumption model.

$$P_{cut} = ZnDa_p \left\{ Kh^{-c} f_z [\cos \varphi_{in} - \cos(\varphi_{in} + \psi)] + \mu H \bar{V} B \psi \right\} / 2 \quad (24)$$

$$t_{cut} = \frac{V_{material}}{60\nu_f a_p a_e} \quad (25)$$

$$E_{cut} = \left\{ \frac{DKh^{-c} [\cos \varphi - \cos(\varphi_{in} + \psi)]}{2a_e} + \frac{D\mu H \bar{V} B \psi}{2a_e f_z} \right\} V_{material} \quad (26)$$

Where Z was the number of teeth on the cutting tool, D was cutting tool diameter, c was the chip thickness constant, f_z was feed per tooth, H was the Brinell hardness of work piece, K was the cutting force constant, $\bar{V}B$ was average flank wear width of cutting tool, μ was coefficient of sliding friction between a workpiece and cutting tool, φ_{in} was angle of a cutting tooth entering a cutting zone, ψ was immersion angle, and t_{cut} was cutting time.

Yoon et al. (2013, 2014) also introduced tool wear in building energy consumption model of milling machine, and found that the material-removal power increased with the flank wear of the tool. The model was empirically modeled using response surface methodology under three kinds of tool wear condition, mild, moderate and severe.

$$E = E_{const} + E_{spindle} + E_{feed} + E_{cut} \quad (27)$$

$$P_{spindle} = a_1 n^{b_1} + c_1 \quad (28)$$

$$P_{feed} = a_2 f^{b_2} + c_2 \quad (29)$$

$$P_{cut} = f_1(n, v_f, a_p) + f_2(n, v_f, a_p) \cdot \bar{V}B(t_{tool}) \quad (30)$$

Where E_{const} was constant energy consumption for the machine basic operation, $E_{spindle}$ was the energy consumption of the spindle, E_{feed} was the energy consumption of feed shaft. a_1, a_2, b_1, b_2, c_1 and c_2 are coefficients obtained by experiment. Function $f_i(n, v_f, a_p)$ representing the load power to remove material could be solved by selecting the second order regression model, and $f_2(n, v_f, a_p) \cdot \bar{V}B(t_{tool})$ was the increment of power caused by tool wear. Research indicated that P_{cut} would increase linearly as the amount of tool wear increased, as well as n, v_f and a_p . But the growth

rate depended on the processing conditions. Eq. (24) and Eq. (30) could predicted the P_{cut} precisely, but due to the consistency between the cutting tool life and different processing parameters is difficult to measure, so this model has a certain difficulty to calculate the total energy consumption of machining process.

4.2.2.3. Energy consumption model based on cutting force. Some models mainly reflect the function relationship between cutting force and energy consumption. Draganescut al. (1999, 2003) pointed out that the SEC was the function of machine efficiency η , while η was the function of the tangential component of the cutting force F_t and other processing parameters. The SEC model was established using Response Surface Methodology for a vertical-milling machine.

$$SEC = \frac{P_{cut}}{60\eta MRR} \quad (31)$$

$$\eta = f(n, M_t, v_f, F_{feed}) = f(v_c, D, F_t) \quad (32)$$

Where M_t was Cutting torque, F_{feed} was feed force. When D was certain, then n was a function of v_c and M_t was a function of F_t . η can be solved by using second order approximation polynomial with interaction, with independent variables as natural logarithms of working parameters of machine tools.

Mohammed et al. (2009) set up a SEC model for bandsawing. The model was validated in sawing different material. The study found that wear and degradation of the blade had a significant effect on the SEC, then put forward that the SEC could be considered as a parameter to predict the various stages of the blade wear, which also could measure the performance of the bandsaw processing.

$$SEC = \frac{E}{V_{material}} = \frac{(Fv_c + F_{feed}v_f) \times T}{A_{chip}L_{cut}} = \frac{F}{A_{chip}} + \frac{TF_{feed}v_f}{A_{chip}L_{cut}} \quad (33)$$

$$SEC = \frac{F}{A_{chip}} \quad (34)$$

Where F was cutting force, L_{cut} was the horizontal length of cut (m), A_{chip} was the chip cross-sectional area (m^2). The SEC could be simplified as Eq. (34) neglecting the vertical feed energy consumption (accounted for only 1% of the total energy consumption in the study).

Rodrigues and Coelho (2007) proposed a SEC model for the high speed cutting, pointing out that the cutting tool geometry parameter can directly affect the cutting force and SEC. Compared with the high speed machining, influence on cutting energy caused by the tool geometric parameters was more. Study also pointed out that SEC had obvious influence on the workpiece surface roughness.

$$SEC = \frac{v_c}{V_{material}} \int_0^{t_{cut}} (F_x^2 + F_y^2)^{\frac{1}{2}} dt \quad (35)$$

Where F_x was the X axial cutting force component, F_y was Y axial cutting force component.

Some research (Kara and Li, 2011b) pointed out that the energy consumption model based on cutting force only reflected the theory of minimum energy for material removal, and therefore could only reflect the tip energy demand.

4.2.2.4. Energy consumption model based on the main cutting parameters. Many studies suggest that cutting parameter v_f, v_c and a_p

are the mainly significant factors affecting energy consumption. These models can be divided into explicit analytical and neural network black-box model according to expressions.

4.2.2.4.1. 1Explicit analytical model. Diaz et al. (2010) proposed a model Eq. (36) considering the energy consumption characteristics of the shaft in the process of acceleration and deceleration. Study used main cutting parameters to establish the E_{cut} as Eq. (37).

$$E = E_{const} + E_{var-steady} + E_{var-trans} + E_{cut} \quad (36)$$

$$E_{cut} = k \cdot a_e \cdot a_p \cdot z^b \cdot v_f^{1-b} \cdot n^b \quad (37)$$

Where $E_{var-steady}$ was the energy consumption of spindle and feed shaft during the process of speed stable, $E_{var-trans}$ was the energy consumption of spindle and feed shaft during the process of acceleration and deceleration. b and k were experimental coefficients.

Guo et al. (2012) pointed out that SEC was not only related to the cutting parameters, also related to the component size. The experiment got the same v_c by adjusting n and without changing v_f and a_p , respectively processing parts with diameter of 50 mm and 66 mm. The study found that the smaller d (caused a high spindle speed) would produce a higher energy consumption. SEC Model was established as follows:

$$SEC = \frac{C_1}{v_c \cdot v_f \cdot a_p} + C_0 \cdot v_c^{C_2} \cdot v_f^{C_3} \cdot a_p^{C_4} \cdot d^{C_5} \quad (38)$$

Where $C_0 \sim C_5$ were experimental coefficients obtained by the least squares curve fitting method. The study pointed out that the accuracy of the model was 90%.

4.2.2.4.2. Neural network black-box model. Neural networks have nonlinear characteristic and information distribution characteristic. Using the neural network to estimate energy consumption value becomes a viable option, as shown in Fig. 6. Scholars at home and abroad did a lot of researches to set up energy consumption model through neural network combined cutting parameters as shown in Table 1. This kind of model to prediction energy consumption had a accuracy of 95% on average, but the problem is that neural network is a kind of local optimization algorithm, so the model easily falls into local limit value.

4.2.3. Process oriented machining energy consumption model

This kind of model is established from the point of view of the machine tool's movement process. The model form has a better extensibility, making parts processing, machine tool motion, power transmission and energy consumption one to one correspondence.

Oliver and Paul (2011) calculated the energy consumption of milling process for a part by reading processing numerical control programming code in which tool position and cutting parameter data could be obtained. The established energy consumption model according to the certain part processing code was as follows:

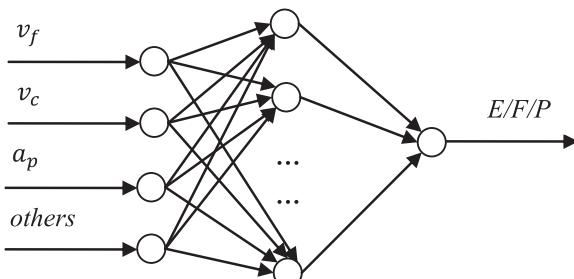


Fig. 6. Machining energy consumption prediction based on neural network.

$$E = \int_{t_0}^{t_1} P_{aY} dt + \int_{t_1}^{t_2} P_{SY} dt + \int_{t_2}^{t_3} P_{dY} dt + \int_{t_0}^{t_3} P_{run} dt + \int_{t_1}^{t_2} P_{cut} dt \quad (39)$$

Where P_{aY} , P_{SY} and P_{dY} represented power of feed axis Y in acceleration, deceleration and the stable operation status respectively. P_{run} and P_{cut} represented spindle power under empty cutting and cutting condition respectively. t_0 , t_1 , t_1 , t_2 , t_2 , t_3 , t_0 , t_3 were the corresponding period of time.

Liu and Liu (2012) established a power model of main drive system considering that the mechanical and electrical main transmission system was the main body consuming energy. The simplified integral model was as follows:

$$E = \int_0^{t_1} P_{in}(t) dt + P_0 t_2 + \left(P_0 t_3 + \int_0^{t_3} P_\alpha [P_{cut}(t)] dt + \int_0^{t_3} P_{cut}(t) dt \right) \quad (40)$$

$$P_\alpha = \alpha_1 P_{cut}(t) + \alpha_2 P_{cut}(t)^2 \quad (41)$$

Where t_1 , t_2 and t_3 represented time in start, idle and cutting status respectively. $P_{in}(t)$ was the input power for main transmission system. P_α was a function of P_{cut} representing loss power due to mechanical and electrical load, which could be got using quadratic function Eq. (42). α_1 , α_2 are additional load loss coefficients and could be got through the numerical fitting (Liu et al., 1995).

Lv et al. (2014) proposed that each function module of the machine tool represented one basic action element. According to that, calculating energy consumption was to merge action elements.

$$P = P_{SO} + P_L + P_{CC} + P_{CFS} + P_{spindle} + (P_x + P_y + P_z) + P_{TS} + P_{TC} + P_{cut} \quad (42)$$

$$P_{cut} = (1 + \alpha) F v_c \quad (43)$$

Where P_{SO} , P_{CFS} , P_{CC} and P_L respectively represented the basic module power, cooling power, automatic chip removal power and lighting power. $P_{spindle}$, P_x , P_y and P_z represented power of spindle, x, y, and z feed shaft respectively, and the calculation method was same as the Eq. (28) and Eq. (29). P_{TS} and P_{TC} represented power for tool selection and tool change. $F v_c$ represented the cutting power in theory. α was additional load loss coefficient due to the cutting power, and could be roughly estimated using the Eq. (44) (Levit, 1958).

$$\alpha = P_{pn} + c_1 P_{3n} + c_2 P_{nk} + c_3 P_{nc} \quad (44)$$

Where P_{pn} , P_{3n} , P_{nk} and P_{nc} represented the additional load loss coefficients due to belt transmissions, gear transmissions, rolling bearings and plain bearings. $c_1 \sim c_3$ were the number of gears, rolling bearings and plain bearings in the spindle transmission system respectively. For flat belts $P_{pn} = 2\%$, $P_{3n} = 1\%$, $P_{nk} = 0.25\%$, $P_{nc} = 2\%$. The study pointed out the maximum error between the predicted and measured values was 6.6% by using Eq. (42) and Eq. (43) achieves over 84% accuracy to predicting the cutting power consumption.

But when calculating the cutting power, the accuracy of Liu's model and Lv's model are highly depending on the determination of additional load loss coefficient which need a large number of experimental data. At present, a practical method to quickly obtain the accurate α remains to be studied. Some scholars Mori et al. (2011), He et al. (2012b), Balogun and Mativenga (2013)

Table 1

Energy consumption model based on neural network.

Input	Output	Observations	Author
v_f, a_p, a_e n, f_z, a_p, a_e, R and lubrication	SEC P	The prediction value of energy consumption by neural network was close to actual value. P mainly depended on n . The parameters f_z, a_p, a_e, R and lubrication were second factors for output.	(Gong, 2012) (Quintana et al., 2011)
n, v_f, a_p n, v_f, a_p	E_{cut} F	The prediction value of energy consumption by neural network was close to actual value. When a_p and v_f increased, the F increased. When n decreased, then F increased.	(Gong et al., 2009) (Radhakrishnan and Nandan, 2005)
v_f, v_c, a_p and rake angle of cutting tool	E_{cut} and P	When v_f, v_c, a_p or rake angle increased, the P in the process was increasing. v_c was the most significant factors for output.	(Al-Hazza et al., 2011)

established other similar models taking energy consumption of tool change process into account, which will not be described in detail here.

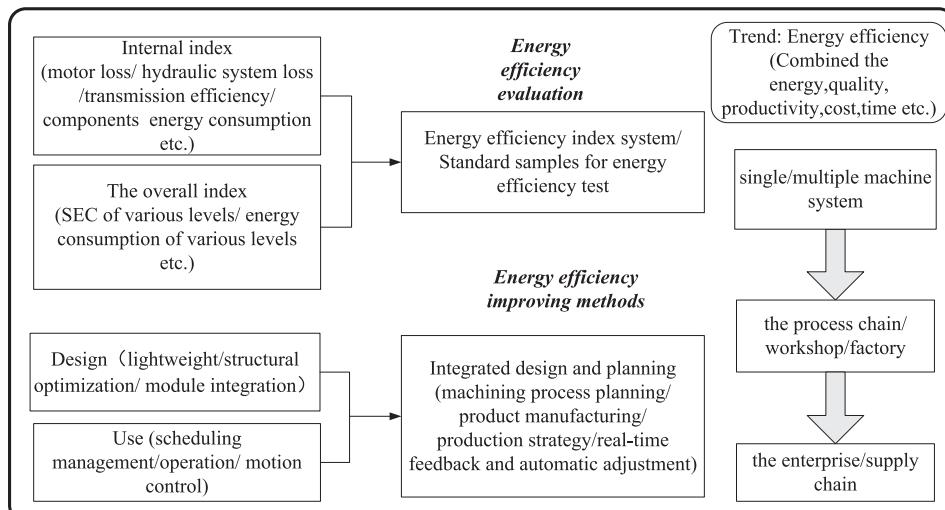
5. Conclusion

Environmental, legal and economic pressures require manufacturing enterprises to reduce the energy consumption and carbon emission. Machine tool, as the basis energy consumed device in manufacturing system, its energy consumption modeling and energy efficiency evaluation are the prerequisite for energy-saving in manufacturing and also a step toward to sustainability. Thus, in recent years, research in this field has been the hot topic of the academia. In this article, the connotation energy efficiency of machine tools was discussed. Then design, scheduling, optimization and assessment based on energy efficiency of machine tools were introduced detailedly. This article divided the existing energy consumption models into three categories for the first time and summarized the application characteristics of these models. Study focuses in the past and the trends in future are shown in Figs. 7 and 8, and we draw the following conclusions:

(1) Correctly evaluating energy efficiency of machine tools or machining system needs to clearly define the research system boundary and unify different unit of input and output variables. Energy efficiency of machine tools is usually defined from the perspective of thermodynamics or physical input and output. The SEC is a common form used to estimate the energy consumption and evaluate energy efficiency of machine tools, covering the mapping relationship of

energy consumption and the MRR which reflects the production efficiency. Due to the complexity of function of machine tools, using only some energy consumption figures to reflect machine energy efficiency has limited significance. In addition, it is very important to determine an industry comparable benchmark for energy efficiency assessment. Therefore, a more scientific index system or an overall evaluation indicator of energy efficiency of machine tools remains to be studied.

- (2) The energy efficiency of machine tools can be improved from aspects of design and use. Design for energy efficiency may require companies to invest a lot of technology and capital. So they tend to choose optimization of use which also has obvious energy-saving potential. In general, for the machine tools, the background consumes a great deal of energy associated with types of machine tools and production intervals, while less energy used for processing closely related to the processing parameters and conditions. So approaches to integrating the product design, manufacturing execution and process planning may reduce both the energy consumption of variable and fixed, increasing energy efficiency from the angle of system.
- (3) This article classified the energy consumption models into three categories for the first time according to their expressing forms and application characteristics, namely the linear type of cutting energy consumption model based on MRR, detailed parameter type of cutting energy consumption correlation models and process oriented machining energy consumption model. The characteristic of the first category is to quickly get coefficients between the SEC and the MRR to

**Fig. 7.** The past study focuses and trends in machine tool energy efficiency.

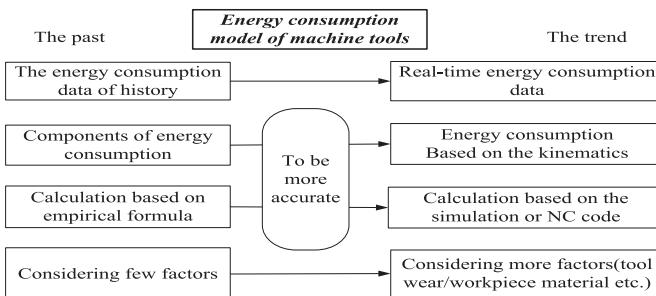


Fig. 8. Study trends in energy consumption model of machine tools.

estimate machine cutting energy consumption, and the specific meaning of some coefficients are analyzed briefly. The characteristic of the second category is to parse the relationship between energy consumption and the processing parameters, such as material properties parameters, cutting tool angle, cutting parameters and so on. Characteristic of third type is to build a universal type energy consumption model to calculate energy consumption of parts processing process.

- (4) The energy consumption model can be established through empirical formulas or experimental data fitting method, such as mathematical statistics, interpolation method, surface response method, least-square method and neural network method. Then use new experimental data to validate the reliability of the model. The model coefficients depend on the selection and control of experimental variables and experimental conditions. In recent years, the energy model is moving toward the high precision direction. Both the influence factors considered of energy consumption and the decomposition of machine tools power are more and more detailed, which determine the computational complexity and forecast precision of the energy model. However, parts and tool characteristics (geometry, material properties, tool wear ratio), the processing characteristics (process type, cutting parameters, cutting fluid used) and machine characteristics have a comprehensive influence on energy consumption. Finding the key factors and their correlation is the foundation to establish energy consumption model of higher accuracy. So, series of experiments for different machine tools need to be done. In addition, real-time energy consumption data and calculation based on the movement of NC code will help to forecast the process energy consumption precisely.
- (5) In the past, some test standard samples were designed to test the machine tool's processing performance whether could meet the precision grade, such as test samples defined by ISO10791. With the ISO 14955 standard drafting, metal cutting machine tool energy consumption standard test procedure and the corresponding standard test samples for energy efficiency become a hot topic in academia, which will provide strong help for the evaluation of machine tools' energy efficiency in the future.

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Nomenclature

a_p	Cutting depth (mm)
a_e	Cutting width (mm)
d	Workpiece diameter (mm)
D	Cutting tool diameter (mm)
E	The total energy consumption of the machine tool (kWh)
E_{cut}	Energy consumption of material removal (kWh)
E_{const}	Constant energy consumption maintains the machine's basic operation (kWh)
$E_{spindle}$	Energy consumption of the spindle (kWh)
E_{feed}	Energy consumption of feed shaft (kWh)
$E_{var - steady}$	Energy consumption of spindle and feed shaft during the process of acceleration and deceleration (kWh)
$E_{var - trans}$	Energy consumption of spindle and feed shaft during the process of speed stable (kWh)
f_z	Feed per tooth (mm)
F	Cutting force (N)
F_{feed}	Feed force (N)
F_t	The tangential component of the cutting force (N)
F_x	X axial cutting force component (N)
F_y	Y axial cutting force component (N)
F_μ	The frictional force on the chip (N)
h	Chip thickness (mm)
h^α	The chip thickness ratio
H	Brinell hardness (N/mm^2)
MRR	Material remove rate (mm^3/min)
M_t	Cutting torque ($\text{N}\cdot\text{m}$)
n	Spindle speed (rpm)
P	Machine tool power input (kW)
P_{out}	Machine tool power output (kW)
P_{loss}	Machine tool power loss (kW)
P_{cut}	Power for the material removal (kW)
P_0	No-load power of machine tool (kW)
$P_{spindle}$	Spindle power (kW)
$P_{standby}$	Machine tool standby power (kW)
R	The cutting tool radius (mm)
SEC	Specific energy consumption (kWh/mm^3)
t_{cut}	Cutting time (min)
t_{tool}	Cutting tool life (min)
T	The total processing time (min)
v_c	Cutting speed (mm/min)
v_f	Feed speed (mm/min)
$V_{material}$	Material removal volume (mm^3)
\overline{VB}	Average flank wear width of Cutting tool (mm)
w_1	Material crack length (mm)
w_2	Material crack width (mm)
Y	Young's modulus (N/mm^2)
Z	The number of teeth on the Cutting tool
$\eta_{energy}(t)$	Machine tool instantaneous energy efficiency
η_{energy}	Machine tool process energy efficiency
η	The efficiency of machine tool
β	Normal friction angle (rad)
γ	Cutting tool rake Angle (rad)
η_s	Shear flow angle (rad)
λ	Oblique angle (rad)
φ	Shear plane angle (rad)
φ_{in}	Angle of a cutting tooth entering a cutting zone (rad)
ψ	Immersion angle (rad)
ν	Material Poisson's ratio
τ	Workpiece flow stress (Pa)
σ	Material fracture stress(Pa)

μ Coefficient of sliding friction between a workpiece and cutting tool

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