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REGULAR PAPER

Exergy-based Energy Efficiency Evaluation Model for Machine Tools Considering Thermal Stability

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Abstract

Machine tools, as the extensively used basic equipment of manufacturing industry, are characterized by intensive and inefficient energy consumption. With the launch and implementation of ISO 14955-1, energy efficiency has become an important criterion for machine tool evaluation. However, most ongoing research on energy efficiency evaluation of machine tools emphasizes on workpiece material removal energy efficiency and rarely considers energy consumption needed to ensure machining accuracy and accuracy consistency, especially energy consumption for thermal stability control of machine tools. In light of this, an exergy analysis based approach is presented to assess the comprehensive energy efficiency of machine tools, including energy consumption for material removal and thermal stability control. The key performance indexes of exergy efficiency, exergy destruction, and specific exergy consumption are analyzed. The feasibility of the proposed approach was demonstrated by a case study, in which the comprehensive energy efficiency of a machine tool was found to be 21.57% instead of 14.38% of material removal energy efficiency. The proposed method is more effective to evaluate the comprehensive energy efficiency, to support designers to design high-efficient machine tool and users to operate machine tool for green and precision machining.

Keywords Machine tools · Comprehensive energy efficiency · Thermal stability · Exergy efficiency

List of symbols

A_{surf}	surface area of machine tool shell
A_{nc}	The area of natural heat convection
c_{ho}	Specific heat of hydraulic oil
c_{co}	Specific heat of cooling fluid
c_{lu}	Specific heat of lubricant
c_{ca}	Specific heat of compressed air
c_{a}	Specific heat capacity of air
$E_{elec,MT}$	Electrical energy input of machine tool drives
$E_{elec,PD}$	Electrical energy input of peripheral devices
E_{MR}	Material removal energy
E_{loss}	Electrical energy loss
$\dot{Ex}_{dest}$	Exergy destruction rate
$\dot{Ex}_{elec,MT}$	Electrical exergy rate of machine tool drives
$\dot{Ex}_{elec,PD}$	Electrical exergy rate of peripheral devices
$\dot{Ex}_{MR}$	Material removal exergy rate
$\dot{Ex}_{mass,\mathrm{ca}}$	Flow exergy rate of compressed air
$\dot{Ex}_{mass,co}$	Flow exergy rate of coolant
$\dot{Ex}_{mass,ha}$	Flow exergy rate of hot air
$\dot{Ex}_{mass,ho}$	Flow exergy rate of hydraulic oil
$\dot{Ex}_{mass,lu}$	Flow exergy rate of lubricant
$\dot{Ex}_{nc}$	Thermal exergy output rate of heat transfer by natural convection
h_{nc}	Convection heat transfer coefficient
$\dot{m}_{ca}$	Mass low rate of compressed air
$\dot{m}_{co}$	Mass low rate of cooling fluid
$\dot{m}_{ha}$	Mass low rate of hot air
$\dot{m}_{ho}$	Mass low rate of hydraulic oil
$\dot{m}_{lu}$	Mass low rate of lubricant
$P_{elec,feed}$	Electrical power input of feed motor
$P_{elec,sp}$	Electrical power input of spindle
p_0	Ambient air pressure
p_{ca}	Compressed air pressure
$\dot{Q}_{hr}$	Heat transfer rate of radiation
$\dot{Q}_{nc}$	Heat transfer rate of natural convection
R_g	Gas constant
T_0	Ambient air temperature
T_{ca}	Temperature of compressed air
T_{co}	Temperature of cooling fluid

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T_{ha}	Temperature of hot air
T_{ho}	Temperature of hydraulic oil
T_{lu}	Temperature of lubricant
T_{surf}	Average temperature of machine tool surface
y_{PD}	Exergy destruction ratio of the *k*th peripheral device
y_{MT}	Exergy destruction ratio of machine tool drives
ε_{surf}	Emissivity of machine tool shell
ε_{PD}	Exergy efficiency of peripheral device
ε_{MT}	Exergy efficiency of machine tool drives
ε_{tot}	Total exergy efficiency
σ	Stefan–Boltzmann constant
η_I	Traditional energy efficiency
η_{II}	Comprehensive energy efficiency

1 Introduction

Due to tremendous environmental and economic pressures on energy utilization, energy-saving in manufacturing industry has become a topic of major concern [1]. Machining system dominates electricity consumption in manufacturing, therefore, it is important to reduce machining system energy consumption for manufacturing industry sustainability improvement [2–6].

As the most representative machining system, machine tool is a complex mechatronic system characterized by intensive and inefficient energy consumption and large emissions [7–9]. Because energy efficiency evaluation is a prerequisite of energy efficiency improvement, the first step is to devise evaluation methods for machine tool energy efficiency.

Numerous research work has been carried out to evaluate the energy efficiency of machine tools. For instance, Kara and Li [10] established an empirical model to characterize the relationship between specific energy consumption and machining parameters in metal cutting processes. They verified the prediction accuracy of the model by a series of turning and milling experiments. Balogun et al. [11] researched the specific energy consumption in milling process and the developed specific energy model was used for machining efficiency evaluation. Cai et al. [12] developed a specific energy consumption model to assess the energy efficiency of dry hobbing machines and indicated that dry hobbing machines have much higher energy efficiency than wet hobbing machines. Liu and Guo [13] presented an integrated method for specific cutting energy prediction in milling processes and the results indicated that the prediction accuracy of the model was higher than that of traditional models based on mechanics. Ghosh et al. [14] developed a specific energy consumption model for calculating energy requirement of deep-grinding. Heinzel and Kolkwitz [15] proposed a method for energy efficiency evaluation in grinding process with total specific energy and concluded that adapted fluid supply conditions have a significant effect on the process.

It is observed that most previous research on energy efficiency were conducted based on specific energy consumption for material removal. The energy consumption for ensuring machining accuracy and accuracy consistency is not considered as useful energy consumption, especially energy consumption for thermal stability control of machine tools.

Due to the fact that the total machining errors of machine tools are mainly induced by thermal influences, the control of thermal stability is essential to ensure the machining accuracy and accuracy consistency of machine tools [16, 17], especially for dry machining and precision machine tools [18, 19]. One of our previous studies developed a thermal energy control model of the motorized spindle system of dry hobbing machine tools to maintain the thermal stability and results indicated that the hobbing accuracy and accuracy consistency were improved effectively through the thermal stability control of motorized spindle system [20]. A thermal energy optimization model was developed in our another study to reduce the thermal energy accumulation in cutting space of dry hobbing machine tools and results indicated that the machined gear's accuracy was controlled effectively through optimizing the thermal energy accumulation of cutting space [21]. Shi et al. revealed the influence of thermal expansion on thermal errors of ball feed drive system of a precision boring machine tool and concluded that the thermally induced errors has very important effect on the positioning accuracy of ball feed drive system [22].

Based on above remarks, to evaluate the energy efficiency of a machine tool for green and precision machining, energy consumption for thermal stability control of machine tool should be considered as useful energy consumption. In the thermo-energetic behavior of machine tool cooling systems, Regel et al. [23] defined thermo-energetic efficiency as the ratio between dissipated thermal energy and consumed electrical energy. However, thermal energy, which is closely associated with the thermal stability of machine tools, is a form of disorganized energy (low-quality energy) and only a portion of it can be converted to work [24]. Moreover, thermal energy is varied with the internal heat generation and ambient temperature of a machine tool. Therefore, based on the second law of thermodynamics, exergy is needed to measure the maximum useful work of thermal energy [24].

Exergy, which is defined as the maximum amount of useful work, can be obtained from a system at a given state in a specified environment [24, 25]. It is used increasingly to identify the occurrence of energy inefficiencies in a system and to guide performance improvement and efficient design of engineering systems, such as the grate clink cooling system [26], heat pump system [27], photovoltaic thermal system [28], marine steam power plant

[29], coal-fired industrial boilers [30], milk processing factory [31], and adsorption cooling system [32]. There is also several research work on exergy analysis of manufacturing. For instance, Gutowski et al. investigated the energy and material flows in different manufacturing processes by using exergy analysis and the results indicated that exergy analysis can provide a unified scale for evaluating energy with different quality [7, 33]. Wang et al. applied the exergy analysis based method to evaluate the energy efficiency of machine tool cooling system and the results indicated that many efforts should be focused on the compressor and heat exchanger for energy efficiency optimization due to their higher exergy destruction rates [34]. One of our previous studies investigated the energy efficiency of air cooling system of dry hobbing machine tool with exergy analysis, and a multi-objective optimization model was developed to balance the exergy efficiency and total cost rate of air cooling system [35]. Another previous study proposed an exergy efficiency optimization model for the motorized spindle system of high-speed dry hobbing machine tool to balance the total exergy efficiency and temperature rise of the motorized spindle system [36]. All of these studies show that the exergy analysis based method is superior to traditional energy analysis in energy efficiency evaluation. In addition, exergy analysis can identify the location, reason, and magnitude of energy degradation in a system. Therefore, energy improvement potentials can be quantified more accurately and energy improvement strategies can be formulated more appropriately with exergy analysis. However, little has been done to evaluate the comprehensive energy efficiency of machine tool by using exergy analysis based method in previous research. Exergy analysis can provide a unified measurement scale for the quality and quantity of electrical energy, mechanical energy and thermal energy in comprehensive energy efficiency evaluation.

Based on the above remarks, an exergy-based method is proposed to evaluate the comprehensive energy efficiency of machine tools, where thermal stability control energy is also regarded as useful energy in addition to material removal energy. A total exergy efficiency model is developed to measure the comprehensive energy efficiency of machine tools. Finally, a case study is included to demonstrate the benefits and practicability of the proposed method, and the exergy based performance indexes of machine tools are quantified.

The rest of the paper is arranged into four section. A comprehensive energy efficiency index is proposed in Sect. 2. In Sect. 3, the exergy characteristics are analyzed and a total exergy efficiency model is established. Section 4 provides a case study on exergy analysis and validation of the proposed method. Final conclusions and suggested future work are given in Sect. 5.

2 Preliminary Work

The energy efficiency of a machine tool can be defined as the ratio between material removal cutting energy and machine input energy [37]:

$$\eta_I = \frac{\int_o^t P_{cut}(t)dt}{\int_o^t P(t)dt} \tag{1}$$

where η_I is the energy efficiency, P_{cut} is the material removal power, $P(t)$ is the power input of machine tool, t is the processing time.

It is observed that most ongoing research also uses specific energy consumption to express the energy efficiency of a machining process or machine tool [11, 13]. The specific energy consumption is defined as energy consumption of machine tool used to remove a unit volume of workpiece material [10]:

$$\text{SEC} = C_0 + \frac{C_1}{\text{MRR}} \tag{2}$$

where SEC is the specific energy consumption, MRR is the material removal rate, C_0 and C_1 are constants.

This implies that current energy efficiency of machine tools emphasizes merely on the energy efficiency for workpiece material removal. Due to the fact that up to 75% of overall geometrical errors of machined workpiece are induced by thermal effect [17], energy consumption for the control of machine tool's thermal stability should be taken as useful energy consumption, especially for dry machining and precision machine tools. As shown in Fig. 1, the fluids flowing through the machine tool is beneficial for thermal stability control of the machine tool. Therefore, a portion of electrical energy consumption of peripheral devices, which is quantitatively equal to the discharged thermal energy by flowing fluids, can be considered as useful energy consumption. Moreover, heat exchange by radiation and natural convection can also be considered as useful energy because it is also beneficial for thermal stability control. However, heat radiation is normally ignored because its value is small and it has little influence on the thermal stability of machine tool [38, 39]. Therefore, the comprehensive energy efficiency is defined as Eq. (3):

$$\eta_{II} = \frac{E_{MR} + \Delta Q}{E_{elec,tot}} \tag{3}$$

where η_{II} is the comprehensive energy efficiency, E_{MR} is the material removal energy, $E_{elec,tot}$ is the electrical energy input, ΔQ is the thermal energy dissipated by the flowing fluids and heat exchange and calculated as:

$$\Delta Q = Q_{out} + Q_{nc} - Q_{in} \tag{4}$$

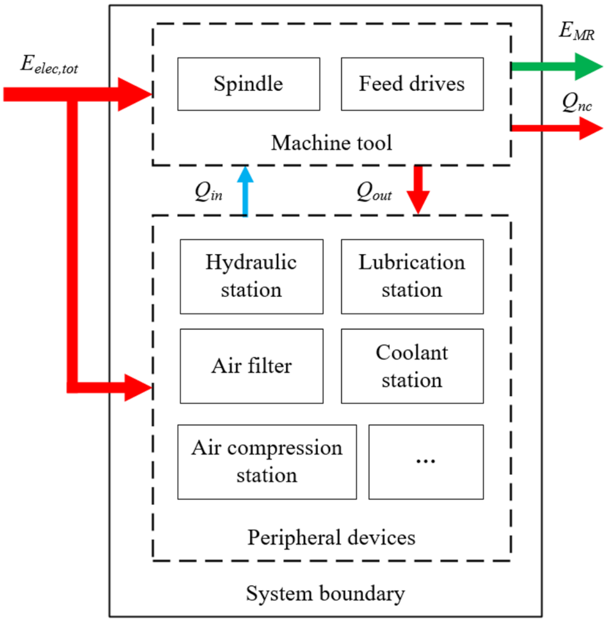

Fig. 1 System boundaries related to relevant energy flows of a machine tool

where Q_{in} and Q_{out} are respectively the thermal energy carried by the auxiliary fluids flowing in and out of the machine tool, Q_{nc} is the heat transfer by natural convection of machine tool.

Considering the quality property of thermal energy, exergy is used to measure its maximum useful work ($Ex_Q = (1 - T_0/T_{source})\Delta Q$) [24]. Therefore, the total exergy efficiency is applied to measure the comprehensive energy efficiency, as presented in Eq. (5):

$$\varepsilon_{tot} = \frac{E_{MR} + Ex_Q}{E_{elec,tot}} \tag{5}$$

where ε_{tot} is the total exergy efficiency of machine tools, T_{source} is the temperature of heat source.

3 Exergy Efficiency Modelling

In order to perform exergy analysis and establish a exergy efficiency model of machine tools, the following assumptions are made to simplify the complexity of calculations [32, 40–43]: (1) the working condition of system reaches the steady state; (2) the pressure of ambient air is constant; (3) the kinetic and potential energy changes of material flows are negligible; (4) the working fluids, such as lubricant, coolant and hydraulic oil are incompressible; (5) the air inside and outside the systems is assumed to be ideal gas; and (6) the efficiency of all motors and pumps in the system remain unchanged.

3.1 Energy Analysis

Based on the energy conservation principle, the basic energy balance equation of machine tool is:

$$E_{elec,MT} + E_{elec,PD} = E_{MR} + \sum E_{elec,loss} \tag{6}$$

where $E_{elec,MT}$ and $E_{elec,PD}$ are the electricity input of machine tool drives and peripheral devices, respectively, $E_{elec,loss}$ is the electricity loss of machine tool.

The electricity requirement of machine tool drives mainly includes the spindle motor, feed drives. Therefore, the electricity input of machine tool drives can be expressed as Eq. (7):

$$E_{elec,MT} = \int_0^t \left[P_{elec,sp}(t) + \sum_i P^i_{elec,feed}(t) \right] dt \tag{7}$$

where $P_{elec,sp}$ and $P_{elec,feed}$ are the electrical power inputs of spindle motor and feed motor, respectively.

The main peripheral devices of machine tool include electrical cabinet, numerical control system, coolant station, lubrication station, pneumatic station, hydraulic station, air filter, etc. As illustrated by Kolar et al. [44], the electricity requirement of peripheral devices can be considered as a constant value and can be obtained by measurement and calculation. Therefore, the total electrical energy input of peripheral devices can be determined by Eq. (8) [44]:

$$E_{elec,PD} = \sum_k a_k(t) \cdot P_{input,k} \tag{8}$$

where $a_k(t)$ is the activity time characteristic of the kth peripheral device, $P_{input,k}$ is the required active power of the kth peripheral device for normal operation. In which, based on one of our previous studies, the energy consumption to prepare the compressed air can be calculated by Eq. (9) [35].

$$P_{input,ca} = C_{ca}\dot{m}_{ca}\left\{ T_0\left[r^{(k-1)/k} - 1\right] + \left[T_0 r^{(k-1)/k} - T_{ca,in}\right]^2 / T_{ca,in} \right\} \tag{9}$$

where $P_{input,ca}$ is the electrical power consumption for compressed air preparation, C_{ca} is the specific heat capacity of compressed air, $\dot{m}_{ca}$ is the flow rate of compressed air, r the compressed ratio, k is the specific heat ratio, $T_{ca,in}$ is the temperature of compressed air flowing into the machine tool, T_0 is the ambient air temperature.

The material removal energy can be determined based on the specific cutting energy of workpiece material and the material removal volume. Based on the above, the traditional energy efficiency of a machine tool can be calculated by Eq. (10):

$$\eta_I = \frac{E_{MR}}{E_{elec,MT} + E_{elec,PD}} \tag{10}$$

3.2 Exergy Analysis

Unlike energy, exergy undergoing a system or process can be destroyed, therefore it is not conserved [24]. As no chemical reactions take place in energy conversion process in mechanical machining, the change in chemical exergy is not taken into account in the present study. The exergy balance equation of a machine tool system at the steady state is expressed as:

$$\begin{aligned}&\sum_{in} \dot{E}x_{elec,k} + \sum_{in} \dot{E}x_{mass,k} \\ &= \sum_{out} \dot{E}x_{mass,k} + \sum_{out} \dot{E}x_{TH,k} + \dot{E}x_{MR} + \sum \dot{E}x_{dest,k}\end{aligned} \tag{11}$$

where $\dot{E}x_{elec,k}$, $\dot{E}x_{TH,k}$, and $\dot{E}x_{dest,k}$, represent the rates of electrical exergy input, thermal exergy output, and exergy destruction of the kth component/subsystem of a machine tool, respectively, $\dot{E}x_{mass,k}$ is the flow exergy rate of fluid k. $\dot{E}x_{MR}$ is the mechanical exergy rate associated with the material removal energy.

The electrical exergy and mechanical exergy of a machine tool are respectively equivalent to the electrical energy and material removal energy because they are “high-quality energy” and have 100% exergy [27]. Therefore, the exergy associated with the electrical energy and material removal energy are expressed as:

$$\begin{cases}\dot{E}x_{elec,MT} = \dot{E}_{elec,MT} \\ \dot{E}x_{elec,PD} = \dot{E}_{elec,PD} \\ \dot{E}x_{MR} = \dot{E}_{MR}\end{cases} \tag{12}$$

where $\dot{E}x_{elec,MT}$ and $\dot{E}x_{elec,PD}$ are the exergy rates of the electrical energy input of machine tool drives and peripheral devices, respectively.

According to Cengel and Boles, heat transfer by natural convection of machine tool can also be considered as the useful energy output because of higher surface temperature of machine tool than that of surrounding ambient air, which is beneficial to reduce the thermal energy accumulation and ensure the thermal stability of machine tool [24]. For a general machine tool, its outer shape can be considered as a cuboid for simplicity. Based on Newton’s law of cooling, the heat transfer rate of natural convection can be calculated by Eq. (13) [45]:

$$\dot{Q}_{nc} = h_{nc} A_{nc} (T_{surf} - T_0) \tag{13}$$

where h_{nc} is the natural convection heat transfer coefficient and appropriately determined as 9.7 W/(m^{2}K) [46], A_{nc} is the area of natural heat convection, T_{surf} is the average temperature of machine tool surface.

Therefore, the thermal exergy rate associated with natural convection heat transfer can be calculated by Eq. (14) [24].

$$\dot{E}x_{nc} = \left(1 - T_0/T_{surf}\right)\dot{Q}_{nc} \tag{14}$$

The flow exergy rate of mass flow of a fluid k can be calculated by [24]:

$$\dot{E}x_{mass,k} = \dot{m}_k ex_k \tag{15}$$

where $\dot{m}_k$ is the mass flow rate of fluid k, ex_k is the specific flow exergy of fluid k and it can be calculated by Eq. (16) [24].

$$ex_k = (h_k - h_0) - T_0(s_k - s_0) \tag{16}$$

where h_k and s_k are the specific enthalpy and specific entropy of the fluid k, respectively.

Based on flow exergy calculation models presented in Eqs. (15) and (16), the detailed flow exergy characteristics of all fluids are presented in Table 1.

Finally, substituting Eqs. (14)–(21) into Eq. (11) the total exergy destruction can be derived as Eq. (22):

Table 1 Flow exergy characteristics of fluids

Type of fluid	Flow exergy rate	
Hydraulic oil supplied by hydraulic station	$\dot{E}x_{mass,ho} = \dot{m}_{ho}c_{ho}\left[\left(T_{ho,out} - T_{ho,in}\right) - T_0 \ln\left(\frac{T_{ho,out}}{T_{ho,in}}\right)\right]$	(17)
Coolant supplied by cooling station	$\dot{E}x_{mass,co} = \dot{m}_{co}c_{co}\left[\left(T_{co,out} - T_{co,in}\right) - T_0 \ln\left(\frac{T_{co,out}}{T_{co,in}}\right)\right]$	(18)
Lubricant supplied by lubricant station	$\dot{E}x_{mass,lu} = \dot{m}_{lu}c_{lu}\left[\left(T_{lu,out} - T_{lu,in}\right) - T_0 \ln\left(\frac{T_{lu,out}}{T_{lu,in}}\right)\right]$	(19)
Compressed air supplied by air compression station	$\dot{E}x_{mass,ca} = \dot{m}_{ca}\left\{c_{ca}\left(T_{ca,out} - T_{ca,in}\right) - T_0\left[c_{ca} \ln\left(\frac{T_{ca,out}}{T_{ca,in}}\right) - R_g \ln\left(\frac{p_{ca,out}}{p_{ca,in}}\right)\right]\right\}$	(20)
Hot air pumped out by air filter	$\dot{E}x_{mass,ha} = \dot{m}_{ha}\left\{c_a\left(T_{ha} - T_0\right) - T_0\left[c_a \ln\left(\frac{T_{ha}}{T_0}\right) - R_g \ln\left(\frac{p_{ha}}{p_0}\right)\right]\right\}$	(21)

$$\begin{aligned}\dot{E}x_{dest,tot} &= \sum_{k} \dot{E}x_{dest,k} = \dot{E}x_{elec,MT} + \dot{E}x_{elec,PD} - \dot{E}x_{MR} - \dot{E}x_{nc} \\ &\quad - \dot{E}x_{mass,ho} - \dot{E}x_{mass,co} - \dot{E}x_{mass,lu} - \dot{E}x_{mass,ca} - \dot{E}x_{mass,ha}\end{aligned} \tag{22}$$

where $\dot{E}x_{dest,tot}$ is the total exergy destruction rate of machine tool.

Combining the definition of exergy efficiency and the exergy transfer characteristics of machine tool, the total exergy efficiency is presented as:

$$\varepsilon_{tot} = \frac{\dot{E}x_{MR} + \dot{E}x_{mass} + \dot{E}x_{nc}}{\dot{E}x_{elec,MT} + \dot{E}x_{elec,PD}} = 1 - \frac{\dot{E}x_{dest,tot}}{\dot{E}x_{elec,MT} + \dot{E}x_{elec,PD}} \tag{23}$$

where $\dot{E}x_{mass}$ is the total flow exergy rate of flowing fluids.

In order to identify exergy destruction characteristics, the exergy efficiency of machine tool drives and peripheral devices are investigated. The exergy efficiency of machine tool drives and peripheral devices can be expressed as Eq. (24):

$$\begin{cases} \varepsilon_{MT} = \frac{\dot{E}x_{MR}}{\dot{E}x_{elec,MT}} \\ \varepsilon_{PD,k} = \frac{\dot{E}x_{mass,j}}{\dot{E}x^{k}_{elec,PD}} \end{cases} \tag{24}$$

where ε_{MT} is the exergy efficiency of machine tool drives, $\varepsilon_{PD,k}$ is the exergy efficiency of the kth peripheral device.

According to Atmaca and Yumrutaş, the index of exergy destruction ratio can be used to evaluate the impact of each exergy destruction in a system to the total exergy efficiency [47]. Therefore, the exergy destruction ratio of the kth peripheral device can be defined as Eq. (25) [47]:

$$y_{PD,k} = \frac{\dot{E}x^{k}_{elec,PD} - \dot{E}x_{mass,k}}{\dot{E}x_{elec,MT} + \dot{E}x_{elec,PD}} \tag{25}$$

where $y_{PD,k}$ is the exergy destruction ratio of the kth peripheral device.

Similarly, the exergy destruction ratio of machine tool drives is defined as:

$$y_{MT} = \frac{\dot{E}x_{elec,MT} - \dot{E}x_{MR}}{\dot{E}x_{elec,MT} + \dot{E}x_{elec,PD}} \tag{26}$$

where y_{MT} is the exergy destruction ratio of machine tool drives.

In order to evaluate the exergy efficiency, not bound by machined workpiece parameters, specific exergy consumption, SExC, is proposed to measure the total exergy consumption for removing unit volume of workpiece material. SExC is defined as the ratio between total exergy consumption rate and material removal rate. According to Lin et al., the exergy consumption refers to the total exergy destruction of machine tool system [48]. Therefore, the specific exergy consumption can be calculated as [47]:

$$SExC = \frac{\dot{E}x_{dest,tot}}{MRR} \tag{27}$$

where $SExC$ is the specific exergy consumption of machine tool.

4 Case Study

4.1 Case Study on High-Speed Dry Hobbing Machine

A high-speed dry hobbing machine is used in this study for exergy analysis and validation of the practicality of the proposed method. This machine tool is very suitable for green production of external cylindrical gears, and thermal effect is an important factor affecting the machining accuracy and accuracy consistency of machined gears [49]. The main peripheral devices for thermal stability control of the machine tool include an electrostatic air filter, a lubrication station, an air compression station, and a hydraulic station. In this case, the electrical cabinet and numerical control system are not considered separately due to the fact that these two devices are separating from the machine tool and have no effect on thermal stability of machine tool. During the high-speed dry hobbing process, cold compressed air is used to cool the hob and workpiece and to carry the hot chips out of the machine tool quickly.

In the case study, an external cylindrical gear was machined by a PM-HSS hob. Table 2 shows the main technical parameters of hob and workpiece.

Under the actual production condition, the spindle rotation speed and axial feed rate were set as 800 rpm and 2 mm/rev, respectively. The flow rate and pressure

Table 2 The main technical parameters of hob and workpiece

Item	Value
Normal modulus (m_n)	2.5 mm
Hob outer diameter (d_h)	70 mm
Gear tooth width (B_w)	15 mm
Hob threads (N)	3
Hob gashes (Z)	17
Gear teeth (z)	32
Lead angle of hob (λ)	5°19′ (RH)
Helix angle of gear (β)	25° (RH)
Normal pressure angle (α_n)	20°
Gear workpiece material	AISI 1045

of compressed air were 10 m^3/h and 0.6 MPa, respectively. The flow rate and pressure for hydraulic oil were 10.5 ml/r and 7.5 MPa, respectively, and for lubricant were 9.8 ml/r and 0.7 MPa, respectively. The rotation speed of both hydraulic pump motor and lubricant pump motor was 1500r/min. The mass flow rate of air pumped by air filter was 0.48 kg/s. Other operational parameters of machine tool were set as the recommended values. The cutting space temperature (T_{am}) can be used to measure the air temperature at the cutting space ($T_{\mathrm{ca,out}}$ and T_{ha}) [21]. The calculation for the mechanical power output for workpiece material removal is obtained based on one of our previous studies [50].

The experimental setup of high-speed dry hobbing is shown in Fig. 2. The Pt 100 type of temperature sensor was used to measure the reference points' temperature of machine tool and workshop ambient. The data was acquired by NI data acquisition card NI9214 and recorded by a laptop. A refrigerated air dryer was used to control the compressed air temperature. The power requirement of machine tool were measured by a power analyzer HIOKI 3390. It is indicated from Fig. 2b that the cutting stage of gears includes cut-in stage, full-cut stage and cut-out stage, in which the formed chips in cut-in and cut-out stages are part of the chips in the full-cut stage [51].

4.2 Results and Discussion

Based on the power on and off operation of peripheral devices, the power demand for peripheral devices is shown in Fig. 3. It reveals that the energy consumption of each peripheral device is a constant value (as shown in Fig. 3a), and the electrical power demands of hydraulic motor, lubrication motor, chip conveyor, air filter, and refrigerated air dryer were respectively 1.94 kW, 0.75 kW, 1.16 kW, 1.62 kW, and 0.34 kW, as shown in Fig. 3b.

Figure 4 shows the total power input profile of machine tool during the high-speed dry hobbing process. It is observed that the power input of machine tool during the cutting stage is variable due to the fact that the formed chips in cut-in, full-cut and cut-out stages (as shown in Fig. 2b) are different, which affect the cutting loads of hob tool. It can be seen that the average power requirements of the machine tool were respectively 2.07 kW, 3.62 kW, 3.81 kW, and 7.13 kW during the idle stage, rapid feed stage, air-cutting stage, and cutting stage. Combining the power values presented in Figs. 3 and 4, the power consumption of machine tool drives can be obtained by decomposing the machine tool power with the peripheral devices power.

Figure 5 shows the temperature measurements of reference points of machine tool. The machining starts after a certain period of pre-warming of machine tool. It can be observed that the temperature of machine tool increases gradually along with processing time. This indicates that the thermal energy accumulates gradually in the machine tool. After a period of time, the rate of temperature rise slows down and it maintains a relatively steady value. Eventually, when the machine tool is shut down, the temperature drops sharply.

Based on calculations and experiments, the conventional energy efficiency is calculated as 14.38% with Eq. (10). It indicates that the energy efficiency of machine tool is very low because plenty of auxiliary electrical energy is required in the machining process, which is not considered as useful energy consumption. When thermal stability control energy is considered, the total exergy efficiency is calculated as

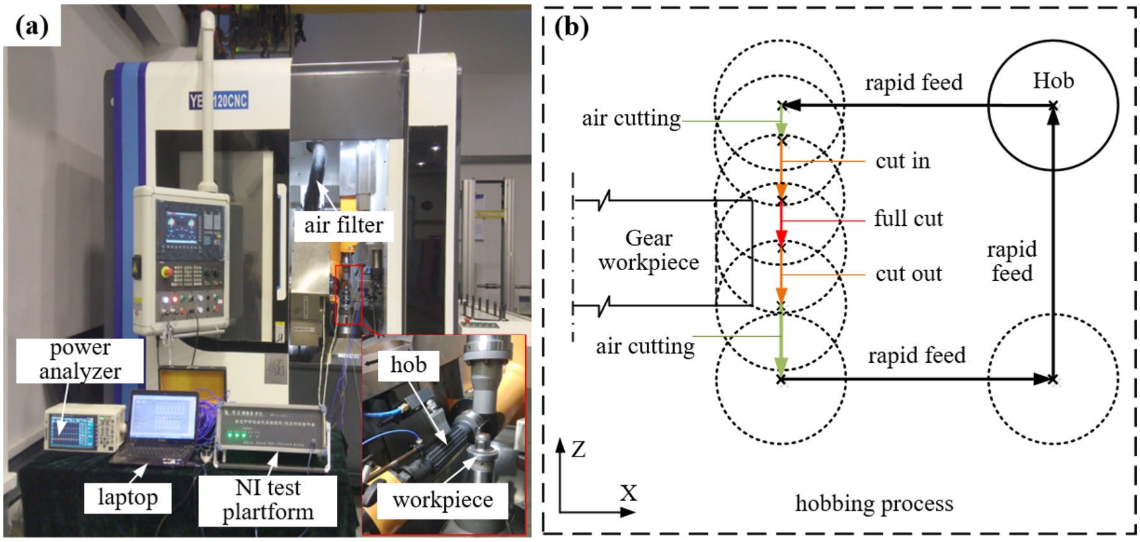

Fig. 2 Experimental setup

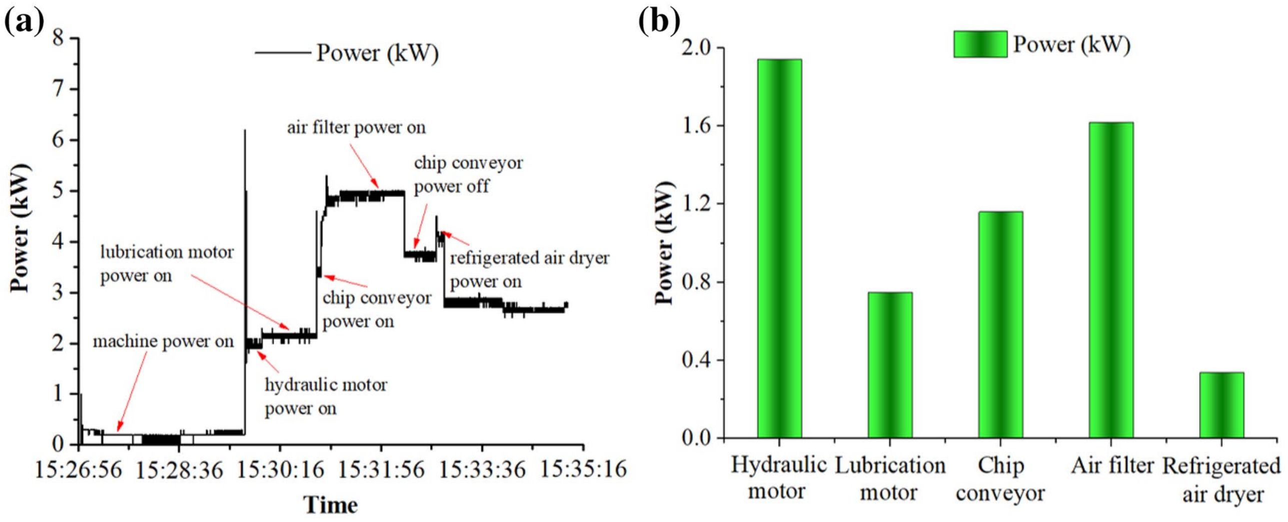

Fig. 3 Power demands of machine tool's auxiliary units

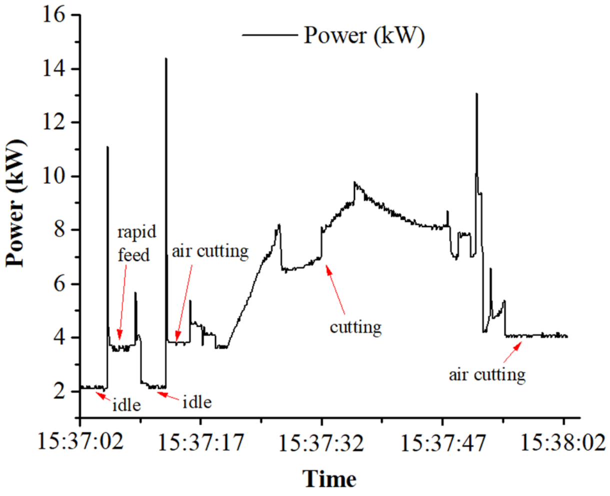

Fig. 4 Power profile of machine tool for machining a workpiece

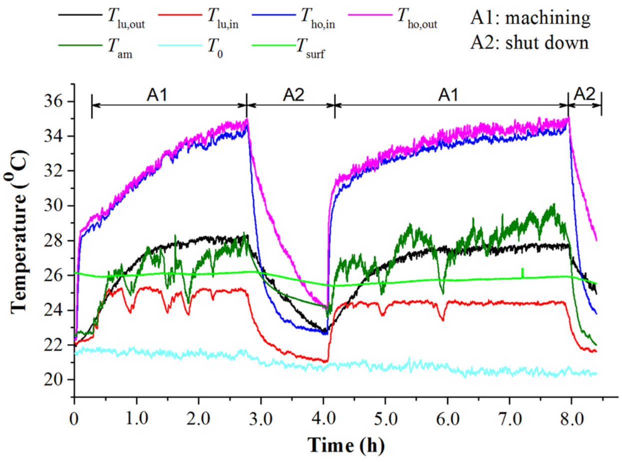

Fig. 5 Temperature measurements

21.57% with Eq. (23). It indicates that the thermal exergy efficiency of machine tool is only 7.19%, and reason behind this is that the quality degradation of electrical energy of peripheral devices is serious due to a large amount of thermal energy loss. Moreover, the specific exergy consumption is calculated as 59.49 J/mm^3 with Eq. (27). It indicates that 59.49 J of electrical energy is degenerated or destructed for unit workpiece material removal, which needs to be reduced for energy-efficient machining.

When a machine tool reached the steady state, the runout of hobbed gear workpiece was measured in the Klingberg Gear Measurement Center, as shown in Fig. 6. The runout of hobbed gear workpiece has the capability to reflect the thermal stability of machine tools [20]. It indicates that the rouout of the hobbed gear workpiece is 18.5 μm under this production condition (dimensional tolerance—32 μm). In fact, there exists a certain correlation between thermal exergy efficiency and machining quality, and the relationship between them will be investigated in the future to reveal the impact of thermal exergy efficiency on machining quality.

In order to understand why low total exergy efficiency and identify energy degradation locations, the key performance indexes related to the exergy analysis of the main components/subsystems of machine tool are investigated. The exergy efficiency and destruction characteristics of machine tool and its subsystems, as shown in Fig. 7, can be used together to evaluate the energy performance and support energy efficiency improvement of machine tool system. It indicates that the machine tool drives (MT) have

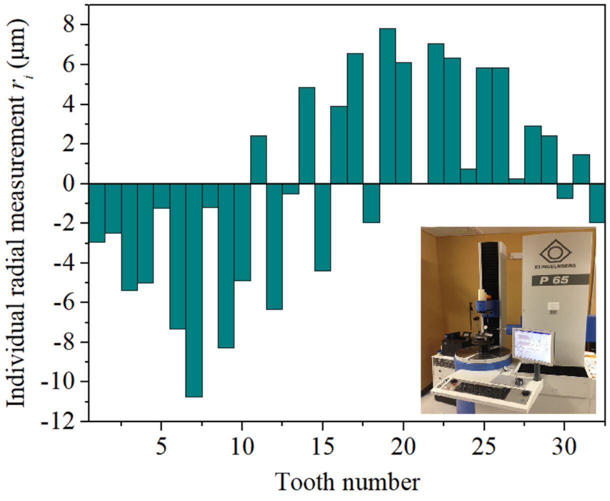

Fig. 6 Runout of a hobbed gear

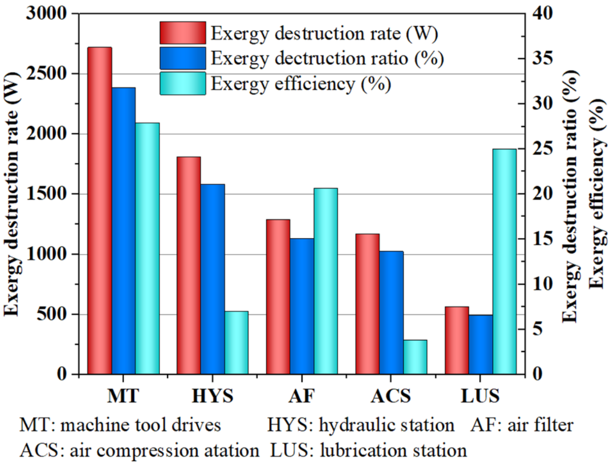

Fig. 7 Exergy efficiency and destruction characteristics of machine tool

the largest exergy destruction rate (2721 W) and dominates the exergy destruction of the machine tool (31.8%) because of the large energy losses of machine tool drives and large electricity consumption of feed motors during the machining process. However, their exergy efficiency is the largest (27.9%) due to the fact that the material removal energy is the main part of useful energy output.

This is followed by hydraulic station (HYS), which contributes to 21.1% (1806 W) of the total exergy destruction of machine tool. Due to higher electricity consumption (Fig. 3) and smaller thermal energy dissipation (Fig. 5), the exergy efficiency of hydraulic station is very low, i.e., 7.0%. Although the exergy destruction rates and ratios of compressed air (1169 W and 13.7%) and air filter (1285 W and 15.0%) are approximately equal to each other, the exergy efficiency of air compression station (ACS) is lower due to its larger electrical energy consumption. The effect of lubrication station (LUS) on the total exergy efficiency of machine tool is not significant due to its lower exergy destruction (563 W). Moreover, compared to other peripheral devices, the exergy efficiency of lubricant station (25.0%) is higher because it consumes lower electrical energy (Fig. 3) and the lubricant dissipates larger amount of thermal energy (Fig. 5).

The above obtained results not only identify the place and extent to improve the exergy efficiency of machine tool system, but also indicate the order of precedence for exergy efficiency improvement. It can be found that the reduction of exergy destruction of machine tool drives and hydraulic station has a significant contribution to the total exergy efficiency improvement of machine tool because these two parts dominate the exergy destruction of machine tool. Hence, improvement efforts should be concentrated essentially on both two parts.

Moreover, it is suggested that great improvement can also be achieved by reducing exergy destruction of air filter and air compression station. The exergy destruction of lubrication station is relatively low, therefore it has insignificantly influence on total exergy efficiency of machine tool and has the lowest priority to be improved. On the other hand, reducing exergy destruction of machine tool can also be achieved through increasing material removal rate based on the results of specific exergy consumption. The increase of material removal rate will increase the power demand and heat generation of machine tool; therefore, it should select the cutting parameters appropriately for energy-efficient and precision machining, and this will be one of our future study work.

5 Conclusion

Machine tools are characterized as equipment with intensive and inefficient energy consumption in manufacturing sectors. In this paper, an exergy analysis based approach is proposed to evaluate the comprehensive energy efficiency of machine tools, where both material removal energy and thermal energy are regarded as useful energy. The feasibility of the proposed method are demonstrated by a case study, and exergy transfer, exergy efficiency, exergy destruction, and specific exergy consumption of machine tool and its main subsystems are characterized with full mathematical modelling approach. The traditional energy efficiency is found to be 14.38%, while the total exergy efficiency is found to be 21.57% when energy consumption for thermal stability control is considered as useful energy consumption. Moreover, the specific exergy consumption is calculated as 59.49 J/mm^3.

It is anticipated that the proposed method in this work can be employed to effectively evaluate the comprehensive energy efficiency of machine tool as well as provide more insightful information to support designers and users to improve energy efficiency of machine tools. Future work to be considered is to reveal the relationship between energy consumption and machining accuracy of machine tools. Another research work is to optimize controllable parameters of machine tools for the trade-off exergy efficiency and machining accuracy for achieving green and precision machining.

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Compliance with Ethical Standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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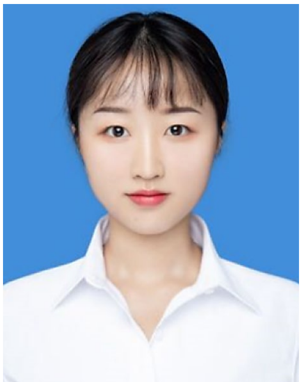

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