Energy Consumption Model for pulse-laser Selective Laser Melting

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Abstract. As a widely used additive manufacturing (AM) technology, the selective laser melting (SLM) technology shows great potential for the sustainable development. Therefore, it is essential to conduct an accurate prediction of the AM energy consumption. In this paper, a new prediction method of SLM energy consumption is proposed. Through analysing the working states of each machine subsystem, this method established an energy consumption prediction model concerning the exposure time, point distance, laser power, and hatch spacing based on the characteristics of the pulse-laser-SLM machine. The model contributes to the improvement and optimization of the energy consumption prediction accuracy in the printing stage.

1. Introduction

Additive manufacturing (AM) technology, as a method of stacking materials in layers, could fabricate a part from the 3D data to the part directly, which allows for more flexible design and manufacturing of parts and is gaining increasing interest due to its high material utilization, short part production life cycle and sustainability potential [1-3]. Parts produced through AM technologies are widely used in the aviation, gas turbine and medical fields [4-6]. While the AM technology has been widely promoted, it should be noted that the AM technology has an increasing demand for the electrical energy consumption [7]. Studies have demonstrated that the energy consumption of different AM processes may be one or two orders of magnitude higher than the traditional manufacturing methods [8]. At present, the manufacturing industry is facing the problems of the environmental degradation and the resource shortage [9]. If the energy consumption can be reduced in the industrial production process, it will play a vital role in promoting the environmental protection and economic benefit.

The current methods concerning the energy consumption modeling mainly include: (1) modeling based on sub-processes; (2) modeling based on subsystems; (3) modeling using specific energy consumption (SEC) of materials. According to Li, the FDM manufacturing process can be divided into three stages: preparation, printing and post-processing [10]. By analyzing the working status of each system component of the FDM machine in each stage, the total energy consumption model can be established based on the time and power of a single system component in the entire printing process. However, compared with the SLM process, the process flow of FDM is quite different in terms of forming method and forming temperature. Ratnadeep Paul et al. calculated the energy consumption in the printing process of SLS from the angle of area energy density by calculating the energy required by unit area of laser sintering multiplied by the size of total sintered area [11]. Hae-Sung Yoon et al. modeled the energy consumption of the AM process through the unit energy consumption of the manufacturing process [12]. This prediction method can quickly predict the energy consumption of
different models after obtaining the relevant data of the material. Lv et al. established a prediction model of the SLM energy consumption based on sub-phases and sub-systems [13]. The power consumption model of the machine sub-system is established by analyzing its operating status and parameters. The time model of the sub-process is established based on the volume and surface area parameters of the part. The total energy consumption of the SLM can be calculated in virtue of the state matrix of the subsystem in the sub-phase to calculate. Peng et al. found that the exposure time only had an effect on the scanning power through experiments, but no further analysis was made on the construction of the exposure time on the overall energy consumption [14].

This article aims to establish a power consumption prediction model concerning pulse-laser SLM. Based on the four key process parameters of exposure time, point distance, hatch spacing and layer thickness, the time model of the printing stage is constructed. Through the product of the time model in different printing stage, working status and power of each subsystem, the energy consumption prediction model of this stage is obtained. Finally, combining the prediction models of the preparation phase and the cooling phase, the energy consumption prediction model of the whole process is obtained.

2. Energy consumption prediction modelling

This paper aims to conduct the modeling and analysis on the electrical energy consumption in the whole process of pulse-laser SLM. The energy consumption proposed below is the electrical energy consumption of SLM. Initially, the sub-systems of the SLM process were categorized. It was divided into six subsystems: the computer and lighting subsystem, the heating subsystem, the gas circulation subsystem, the laser subsystem, the cooling subsystem and the recoating subsystem. Then, the printing process of pulse-laser SLM was divided into the pre-step phase, the manufacturing phase and the cooling phase from the installation of the substrate to the removal of the parts. By considering the working status of each system in each stage, we can determine the actual working time of each subsystem. For the main manufacturing phase, it can be divided into the exposure, the jumping, the platform movement and the materials recoating stage as shown in Figure 1. In the part construction process of the pulsed laser-based SLM system, the laser scans the part discontinuously, point by point. To obtain more accurate laser system energy consumption data, this paper would calculate the time and power of the laser exposure and the jumping. As shown in Figure 2, the energy consumption of the entire printing process of the SLM is calculated by multiplying the working time and power of each subsystem in each printing stage. For the subsystem in the intermittent working state, the working state coefficient $K$ at this stage can be obtained through experiments. The product of the working state coefficient and the system in this stage is the actual working time of the subsystem.

2.1. Printing environment preparation

According to the working status of each part in the preparation stage of the printing environment, it can be divided into the computer and lighting system, the heating device and the gas circulation system. The computer and lighting system work continuously throughout the printing process. The heating device and gas circulation system work intermittently.

2.2. The computer and lighting system

The computer and lighting system are in full operation throughout the printing process. The system controls the operating status of each working subsystem of the machine and provides lighting for the work space. The power of the system is only related to the hardware configuration of the computer itself and the lighting power. It has nothing to do with the geometric characteristics of the part, which can be regarded as a constant. The energy consumption of the computer and lighting system can be expressed as:

$$E_{con} = P_{con} \times t_{total}$$  \hspace{1cm} (1)

where $P_{con}$ is the working power of the computer and the lighting system. The average power is obtained through the measuring instrument. $t_{total}$ is the total time of the entire manufacturing process.
2.3. Heating system
At the beginning of the pre-step stage, the heating system needs to continuously heat the printed substrate. This process lasts until the part was finished. When the substrate reaches a predetermined temperature, the heater enters a standby state. When the temperature drops below the pre-set temperature, the heater restarts. This process is repeated in total printing process. Therefore, the working power can be simplified to a fixed value. The energy consumption of the heating device can be expressed as follows:

\[ E_{\text{heat}} = E_{\text{heats}} + E_{\text{heatma}} = P_{hw} \times t_{ps} + P_{hw} \times K_h \times t_{ma} \]  

(2)
where $E_{heatps}$ and $E_{heatma}$ represent the energy consumption of the pre-step stage and the manufacturing phase. $P_{hw}$ represents the working power. $t_{ps}$ and $t_{ma}$ represent the working time of the pre-step stage and the manufacturing phase. $K_h$ is the working condition coefficient of the heater at this stage. $K_h = P_h / P_{hw}$, $P_h$ is the average power when the heating system works intermittently.

2.4. Gas circulation system

In the pre-step stage, it is necessary to extract the air in the printing cabin and pass in a certain amount of inert gas as the protective gas. Argon is the common protective gas. Since the absorption of the suction pump is determined, the time taken for absorption is related to the initial oxygen content in the cabin. The initial oxygen content of the cabin is positively correlated with the volume of the working cabin. In the air extraction process, the power of the air extraction pump decreases with the decrease of the oxygen content of the cabin. When the inert gas is introduced, the power of the air intake pump changes with the time showing a certain regularity. The working state of the intake pump is intermittent. When the size of the chamber of the equipment is fixed and the external gas environment does not change significantly. The energy consumption of the gas circulation system at this stage is a fixed value, so the average power of the air pump is also a fixed value.

The total energy consumption $E_{gas}$ of the gas circulation system is expressed as follows:

$$E_{gas} = E_{gasps} + E_{gasma} = P_{gasps} \times t_{ps} + P_{gasma} \times t_{ma}$$

where $E_{gasps}$ and $E_{gasma}$ represent the energy consumption of the pre-step stage and the manufacturing phase. $P_{gasps}$ is the average power of the pre-step gas circulation system. $P_{gasma}$ is the average power of the gas circulation system that maintains this stable state.

2.5. Laser system

As shown in Figure 3, when scanning the i-th layer part, the laser scans point by point discontinuously. The working state of the laser is divided into two types including the exposure state and the laser jumping state. In the exposure state, the laser and optical components in the laser system are in working state. In the jumping state, the laser does not produce a light source, only the optical components such as galvo scanner work. The energy consumption in the two states are: exposure energy consumption and jump energy consumption. The previous point is offset by one point pitch. The energy consumption of the laser system scanning the i-th layer can be calculated by the following formula:

$$E_{el} = E_{el} + E_{el} = t_{el} \times P_{el} + t_{el} \times P_{j}$$

where $E_{el}$, $E_{el}$, $E_{el}$ are the scanning energy consumption, exposure energy consumption, and jump energy consumption of the laser when printing the i-th layer of the part.

The dwell time that the laser stays at each exposure point is defined as the exposure time. The exposure power is expressed as the sum of the power of the laser generator and other optical components of the laser system. When the laser stays at a certain point for the set exposure time, the galvo scanner and other components in the optical element are set by the program to deflect a certain angle so that the light spot moves a certain distance according to the predetermined printing track. This distance is called as the dot pitch. The time required for the light spot to move from one point to another is called the jump time. The jump power is the power of the entire laser system when the laser generator is not working. The jump power is usually less than the exposure power. The exposure time will cumulatively affect the total component time. The scan time is actually the sum of the exposure time and the jump time. In the scanning state of the laser system, the laser scanning state is divided into three scanning states: the contour scanning, the filling scanning and the supporting scanning due to the different laser scanning methods. The total exposure time of the laser system when printing the i-th layer graphics is determined by the set exposure time and the number of exposure points contained in the i-th layer.

$$E_{el} = t_{el} \times (a_i + b_i + c_i) \times P_{el} = t_{el} \times \left( \frac{S_j}{h \times B} + \frac{L_{pi}}{B_i} + \frac{S_{ui}}{h_i \times B_i} \right) \times P_{el}$$

$$E_{el} = t_{el} \times (a_i + b_i + c_i) \times P_{el} = t_{el} \times \left( \frac{S_j}{h \times B} + \frac{L_{pi}}{B_i} + \frac{S_{ui}}{h_i \times B_i} \right) \times P_{el}$$
\[ E_{ji} = (t_i - t_{ei}) \times P_j \]  
\[ t_i = \frac{S_i}{h \times v_b} + \frac{S_{si}}{h_s \times v_{sb}} + \frac{L_{pl}}{v_{bl}} \]  

where \( t_{ei} \) and \( t_{ji} \) are respectively the exposure time and jumping time of the laser when printing the i-th layer of the part. \( t_{ei} \) is the exposure time of a single point. \( t_i \) is the printing time of i-th layer, \( a_i \), \( b \) and \( c_i \) are the numbers of exposure points of filling scanning, contour scanning, and supporting scanning. \( S_i \) and \( S_{si} \) are the cross-sectional area and the support structure area of the i-th surface, respectively. \( L_{pl} \) is the length of the profile line of the i-th layer. \( h \) and \( h_s \) are the filling hatch distance and support hatch distance. \( B \) is the dot distance, and \( B_s \) is the support dot distance. \( P_e \) and \( P_l \) are the laser exposure power and jumping power of the laser system. \( v_b \) and \( v_{sb} \) are the scanning speed of the contour and filling state, and \( v_{bl} \) is the supporting scanning speed.

\[ E_{cool} = E_{wp} + E_{cw} = P_{wp} \times t_{total} + P_{cw} \times K_{cw} \times t_{total} \]  

where \( E_{cool} \) is the energy consumption of the cooling system. \( E_{wp} \) and \( E_{cw} \) are the energy consumption of the circulating water pump and the refrigeration component. \( P_{wp} \) and \( P_{cw} \) are the power of the circulating water pump and the refrigeration component. \( K_{cw} \) is the working state coefficient of the refrigeration component. \( K_{cw} = \frac{t_{cw}}{t_{total}} \), \( t_{cw} \) is the working time of the refrigeration components.

2.6. Cooling system

The cooling system cools the laser through the cooling water circuit. In the process of converting electrical energy into the output energy of the laser, a large part of the energy is lost due to the Joule effect. This part of the thermal energy is not enough to be dissipated only by convection between the laser itself and the air. Therefore, it is necessary to use a medium with a larger specific heat capacity (usually water) to cool the laser through the circulating water circuit to protect the internal components of the laser system. The cooling system consists of two parts: the circulating water circuit and the refrigeration components. The circulating water pump operates to form a circulating water circuit between the cooling water tank and the laser. When the temperature of the cooling water reaches the set temperature of the refrigeration system, the refrigeration components start to work to cool down the cooling water flowing back from the laser to realize the cooling of the laser system. The power of the circulating water pump and refrigeration components are related to the characteristics of the system. They are all fixed values.

2.7. Recoating system

The recoating system includes a powder spreading device and a platform lifting device. After the printing of the current layer is completed, the lifting motor drives the printing platform and the printed
parts to move down by a distance of one layer thickness. Afterwards, the powder spreading scraper moves horizontally to take out the powder in the powder reservoir and spread the powder evenly on the original layer to prepare for the printing of the next layer.

The moving distance, moving speed and motor power of the powder squeegee are only related to the equipment itself, not to the features of the parts. Therefore, the working time, power and energy consumption of a single powder spreading of the motor are fixed values.

\[ E_{ca} = P_{ca} \times t_{cas} \times n = P_{ca} \times t_{cas} \times \frac{Z}{L_{layer}} \]  \hspace{1cm} (9)

where \( E_{ca} \) is the total energy consumption of the powder spreading device during the printing process. \( P_{ca} \) is the power of the powder spreading system. \( t_{cas} \) is the time required for a single layer of powder. \( n \) is the number of layers required to print the part. \( Z \) is the height of the printed part. \( L_{layer} \) is the layer thickness.

The lifting of the platform is controlled by the motor. The power and lifting speed of the motor are determined by the characteristics of the machine itself and have nothing to do with the process parameters. The single moving distance of the platform is set for the process parameters. The total working time of the lifting platform is related to the height of the part and the number of layers.

\[ E_p = P_p \times t_{ps} \times n = P_p \times t_{ps} \times \frac{Z}{L_{layer}} \]  \hspace{1cm} (10)

where \( E_p \) is the total energy consumption of the lifting device in the printing process. \( P_p \) is the power of the lifting system. \( t_{ps} \) is the time required for single-layer lifting.

2.8. Total energy consumption

Corresponding to Figure 1, the energy consumption of each subsystem can be expressed as the following matrix:

\[ E = \begin{bmatrix} E_{con} \\ E_{wp} \\ E_{heat} \\ E_{e} \\ E_{j} \\ E_{cw} \\ E_{ca} \\ E_{p} \end{bmatrix} = \begin{bmatrix} P_{con} & P_{con} & P_{con} & P_{con} & P_{con} & P_{con} \\ P_{wp} & P_{wp} & P_{wp} & P_{wp} & P_{wp} & P_{wp} \\ P_{hw} \times K_h & P_{hw} \times K_h & P_{hw} \times K_h & P_{hw} \times K_h \times 0 \\ 0 & P_e & 0 & 0 & 0 & 0 \\ 0 & P_j & P_j & P_j & P_j & 0 \\ P_{cw} \times K_{cw} & P_{cw} \times K_{cw} & P_{cw} \times K_{cw} & P_{cw} \times K_{cw} & P_{cw} \times K_{cw} \times 0 \\ 0 & 0 & 0 & 0 & P_{ca} & 0 \\ 0 & 0 & 0 & 0 & P_p & 0 \end{bmatrix} \begin{bmatrix} t_{ps} \\ \sum_{i=1}^{n} t_{el} \\ \sum_{i=1}^{n} t_{el} \\ \sum_{i=1}^{n} t_{el} \\ \sum_{i=1}^{n} t_{el} \\ \sum_{i=1}^{n} t_{el} \end{bmatrix} \]  \hspace{1cm} (11)

where \( t_{ci} \) is the time of the cooling phase. The time consumed in the cooling phase is related to the characteristics of the machine cooling system, the initial cooling temperature and the cooling termination temperature. When the initial temperature and the end temperature are fixed, the cooling time is a fixed value.

The total energy consumption of the whole process of SLM is expressed as follows:

\[ E_{total} = \|E\|_1 \]  \hspace{1cm} (12)

3. Conclusion

Under the circumstances of the energy shortages, the industry and academia are paying increasing attention to the energy saving. In order to meet the demands of the energy saving, the emission reduction, the green manufacturing and the sustainable development, this article attempts to provide a new energy consumption prediction method for pulse-laser SLM and proposes a prediction energy consumption
model for the energy consumption prediction problem of AM. This method takes into account the characteristics of the pulsed-laser in the SLM machine laser system. This paper constructs a single-layer filling time model and a laser system energy consumption model using exposure time, point distance, jumping time, and scanning spacing. Based on this model, the entire process of SLM can be optimized. At present, there are relatively few energy consumption prediction models concerning pulse-laser SLM process. This predictive model can help designers predict the energy consumption in the design stage and provide a reference for the energy consumption prediction and optimization of other AM processes.

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