A feature-based prediction method for energy consumption of machining process and its application

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Abstract. Energy consumption prediction for machining process is the basis of the study of energy performance and energy efficiency assessment in manufacturing systems. The existing energy consumption prediction methods for manufacturing process are mainly focused on processing equipment, processing parameters and material. However, part features are also important impact factors for energy consumption of manufacturing process, but these are not studied systematically. In this paper, an energy consumption prediction method based on part feature is proposed. Firstly, the energy consumption of a part feature was analyzed, and an energy consumption model was established based on part multi-features by using matter element theory. Then, a hybrid reasoning method considering case-based reasoning and rule reasoning was studied, and an energy consumption prediction method of manufacturing process was proposed. Finally, a case study of a shaft part was given to verify the effectiveness of the above methods.

1. Introduction

The large amounts of energy consumption and low utilization have become a bottleneck of green development of China's manufacturing industry. The machining process, as one of the main aspects to cause energy consumption, the energy calculation and prediction of which is the basis of energy management in manufacturing industry. Therefore, the research on energy consumption of machining processing is hot in recent years.

Such as Nils et al. [1] proposed an ‘Energy Blocks’ method to predict the energy consumption of machining process by using the power information of machine tools. He et al. [2-3] established an energy consumption forecasting model of CNC machine tools with analyzing the actions of various components. Fang et al. [4] proposed an energy prediction method of machining process based on multi-objective mixed integer linear programming, and established a prediction model by using the genetic algorithm. Alessandro et al. [5] fitted the function relation between energy consumption of machining process and machining parameters in high speed cutting conditions, and established an energy consumption prediction model of high-speed cutting process by using neural network. Narita et
al. [6] was concerned with the energy consumption of sub systems of machine tools, such as spindle system, feed shaft system and auxiliary system etc., and developed an energy consumption prediction model of CNC machining process based on genetic algorithm. Gong et al. [7] studied the energy consumption knowledge and semantic expression in machining process by using the ontology technology, and established a prediction model based on neural network. Xu et al. [8] established an energy consumption model of job batch scheduling for machining process based on the minimizing final time, and proposed a solution method by using the ant colony algorithm. Zhang et al. [9] studied the energy consumption of typical working conditions in machining process, such as turning, milling etc., and established an energy optimization model based on the neural network.

The above research mainly focuses on the energy influence relationship between cutting parameters, processing resources and machining process, the prediction model were difficult to reflect the energy consumption process systematically. However, the part feature included the most energy information, and a feature-based prediction method is proposed to describe the energy consumption of machining process in this paper.

2. Energy model of machining process based on part features

2.1. Energy consumption of single feature machining process

The part feature can be definite as a group of surfaces by continuous processing in the same processing conditions and fixtures [10]. It includes not only the geometry information of part, but also the information of processing technology, machining resource, equipment etc. the energy consumption of a part feature machining process can be expressed with the material removal rate (MRR), as shown in equation (1).

\[ MRR = \pi \cdot \left( \frac{d_{\text{blank}} \cdot a_p - a_p^2}{2} \right) \cdot f \cdot n \]  

(1)

Where, \( d_{\text{blank}} \) represents the blank outer diameter; \( a_p \) represents the cutting depth; \( f \) represents the per rotation feed; \( n \) represents the spindle speed.

The energy consumption of single feature includes cutting energy and waiting energy. The cutting energy consumption can be calculated with equation (2).

\[ E_c = P_c \cdot t_c = P_c \cdot \frac{V}{MRR} \]  

(2)

Where, \( E_c \) represents cutting energy consumption; \( P_c, t_c \) represent cutting power and cutting time respectively.

The waiting energy consumption can be expressed as equation (3).

\[ E_w = P_w \cdot t_w \]  

(3)

Where, \( E_w \) represents waiting energy consumption; \( P_w, t_w \) represent idle power and waiting time respectively.

Therefore, the energy consumption of single part feature can be expressed as equation (4).

\[ E = P_c \cdot t_c + P_w \cdot t_w = P_c \cdot \frac{V}{\pi \cdot \left( \frac{d_{\text{blank}} \cdot a_p - a_p^2}{2} \right) \cdot f \cdot n} + P_w \cdot t_w \]  

(4)

2.2. Energy consumption of Multi feature machining process

In the actual machining process, there usually includes different part features. However, the part features have a certain tree structure, and each can be regarded as an energy information collection. In order to describe the relationship between part feature and its corresponding energy information, the matter element theory is used in this paper.

A matter element is a basic element that describes the object with an ordered three tuple. It has a strong advantage in dealing with the incompatibility problems. In this paper, the matter element is used to establish an association with part multi features and the corresponding energy consumption. It can be shown as equation (5).
\[ R = (M, C, X) = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} M & C_1 & X_1 \\ & C_2 & X_2 \\ & & \vdots \\ & & C_n & X_n \end{bmatrix} \]  

(5)

Where, \( R=(R_1,R_2,\cdots,R_n)' \) is a matter element, represents the energy consumption of Multi features machining process; \( M \) is the object, represents the part; \( C=(C_1,C_2,\cdots,C_n)' \) is the attributes of \( M \), represents the different features; \( X=(X_1,X_2,\cdots,X_n)' \) is characterization or measurement of \( C \), represents the energy consumption of corresponding features.

3. Energy prediction method based on mixed reasoning

To repair the shortcomings of case-based reasoning (CBR) and rule reasoning (RR), a hybrid reasoning (HR) method is proposed to predict machining process energy consumption based on part features. In HR, the similar cases are retrieved with CBR to obtain the energy information of part feature, when the case is insufficient, the processing knowledge are mined with RR to get the relationship of feature and energy consumption [11-12].

3.1. Case retrieval with CBR

Case retrieval (CR) is to find one or more similar case according to the new problem. The nearest neighbor method was used to calculate the similarity between part features, and then the features similarity were estimated by weighted matching [13]. The local similarity calculation method was shown in equation (6).

\[
sim(p, q) = \begin{cases} 
1 & \text{Numeric type} \\
\frac{1}{1+|p-q|} & \text{Fuzzy logic type} \\
\frac{|p-q|}{X} & \text{Irrelevant type} \\
\begin{cases} 
1, & p = q \\
0, & p \neq q 
\end{cases} 
\end{cases} 
\]  

(6)

Where, \( \text{sim}(p,q) \) represents the local similarity; \( p \) and \( q \) represent the attribute values of object case and library case respectively; \( X \) represents the maximum attribute value.

The calculating method of overall similarity of part multi features are shown as equation (7).

\[
SIM(P,Q) = \sum_{i=1}^{n} \text{sim}(p_i,q) \times \omega_i
\]  

(7)

Where, \( \text{SIM}(p,q) \) represents the overall similarity; \( P \) and \( Q \) represent the assemblage of attribute values of object case and library case of a part; \( i \in (1,n) \) represents an attribute; \( \omega_i \) represents the weights, and \( \sum_{i=1}^{n} \omega_i = 1 \).

3.2. Energy mined with RR

When there is no similar case in case library, the energy consumption of part feature is mined with RR. For example, the cutting energy of a part feature is mainly composed of the energy consumption of spindle motor and feed motor, which can be shown as equation (8).

\[
\begin{cases} 
E_c = \int (f \cdot v) \, dt \\
E_f = \sum_{i=1}^{n} P_i \, dt
\end{cases}
\]  

(8)
Where, $E_c$ and $E_f$ represent the energy consumption of spindle motor and feed motor; $tc$ and $tf$ represent the duration of spindle motor and feed motor; $fc$ and $vc$ represent the cutting force and cutting speed; $P_f$ represent the power of feed motor.

3.3. Energy prediction process
Firstly, the part feature information was obtained from its CAD model, and a matter element model was established with the relevant information, such as processing scheme, machine tool etc. Then the energy consumption of each feature was calculated with HR, and stored to extend the case library. Finally, the result of each feature was added to predict the energy consumption of machining process. The forecasting process is shown in Figure 1.

![Figure 1. The energy consumption prediction flow](image)

4. Case study
Taking a grinder spindle rough lathe as an example, the material of which is 20CrMnTi, and the schematic and feature of the part are shown in Figure 1.

![Figure 2. The feature diagram of the grinder spindle](image)

The features and corresponding processing requirements of the grinder spindle were related with a matter element model, and the energy consumption of each feature was calculated with HR. The results were listed in Table 1.
In order to verify the prediction accuracy, the actual processing energy consumption of the spindle was measured with WT1800 power analyzer. The comparison results were shown in Table 2.

| No. | Feature   | method | Size (mm) | Processing quantity (mm) | Roughness | Energy consumption (wh) |
|-----|-----------|--------|-----------|--------------------------|-----------|-------------------------|
| 1   | Outer circle | Turning | L=33, D=115 | 4                       | 6.4       | 221                     |
| 2   | Outer circle | Turning | L=125, D=84.5 | 2.25                   | 6.4       | 146                     |
| 3   | Outer circle | Turning | L=36, D=80  | 4.5                     | 6.4       | 54                      |
| 4   | Outer circle | Turning | L=56, D=37.5 | 25.75                  | 6.4       | 128                     |
| 5   | Groove     | Turning  | B=2, D=74.5 | 2.75                    | 12.5      | 139                     |
| 6   | Plane      | Turning  | D=115      | 6                       | 3.2       | 211                     |
| 7   | Plane      | Turning  | D=37.5     | 3                       | 3.2       | 164                     |
| 8   | Hole       | Drilling | D=6        | 12                      | 12.5      | 94                      |

From Table 2, the energy consumption prediction error is 2.63%, and it shows the feasibility and effectiveness of the proposed method.

However, the prediction result was less than the measurement one. It is because that there were some operations (repositioning, acceleration or deceleration of machine tools, etc.) during the feature processing, and the operations may cause the energy consumption. In addition, the calculation formula of energy consumption in HR method also had simplification.

5. Conclusions

A feature-based energy consumption prediction method for machining process was proposed in this paper. A matter element model was established to relate the energy information of each part feature, and the energy consumption of each features and the part with the proposed HR method. The comparison result of a grinder spindle case shows the feasibility and effectiveness of the proposed theory and method.

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