Optimization of Milling Cutting Parameters under Carbon Efficiency Target

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Abstract: In order to improve the energy efficiency of the CNC milling process and reduce the carbon emissions during the milling process, this paper presents a method for cutting parameters selection by considering both materials remove rate and carbon emissions. First, a metric called carbon emissions efficiency is proposed with consideration of the materials remove rate and carbon emissions. Second, the carbon emissions evaluation model for NC milling process is built based on the input-output flows. Third, an optimization model for the parameters used in a milling operation is built where the spindle speed and feed rate are taken into account as optimization variables. Constraints are proposed based on the machine tool performance parameters and the quality requirements of the workpiece. A genetic algorithm is employed to solve the optimization problem. A case is studied to validate the model.

1. Introduction

Global warming is a common concern in today's society. As the main energy source of manufacturing, machine tools and industrial machines are widely used in the manufacturing process of various industries, directly or indirectly generating a large amount of carbon emissions. However, the energy utilization efficiency of the machine is not satisfactory. Aiming at the problem of machine tool energy consumption, the scholars have carried out a series of researches. Avram et al. proposed an energy consumption calculation model of machine tool during operation stage. The method of consuming energy [1], Liu Fei et al. established the energy balance equation of the machining system by studying the energy characteristics of the machine tool [2]. By analyzing the energy consumption characteristics of the machine tool, Hou Chunhong divided the energy consumption of the machining process into three parts, namely fixed energy consumption, cutting energy consumption and no-load energy consumption, meanwhile verified the feasibility of the model through experiments [3].

In response to the issue of carbon emissions, scholars have conducted in-depth research and achieved a series of results. Jeswiet J. et al. built a carbon emissions calculation model which used the carbon emissions index of the power plan as a calculation parameter. The carbon emissions of the manufacturing process are quantified indirectly by the model [4]. Cao Huajun et al. proposed a carbon emissions assessment method for the life cycle of the machine tool [5].

Milling processing as a main processing method, the selection of cutting parameters is directly related to the quality of the processed products and carbon emissions. Therefore, a series of studies about the topic of choosing reasonable cutting parameters to reduce energy consumption and carbon emissions during milling have been carried out. Levi F et al. established a related mathematical model by
multiple regression method. The model was solved by genetic algorithm [6]. Wu et al. built the corresponding cutting parameter model by applying high-speed machining parameters optimization theory and adopting the maximum productivity as the optimization target [7]. Subramanian et al. presented a mathematical model to study the relationship between cutting parameters and cutting forces of milling by the multi-regression method [8]. Gao et al. established a multi-step process parameter optimization model for milling machining with the aim of machining time by comprehensively considering the machining constraints such as workpiece material and geometry [9].

In this paper, a metric called carbon emissions efficiency is proposed with consideration of the materials remove rate and carbon emissions. Based on the input and output characteristics of milling, the carbon emissions evaluation model for NC milling operation is built. Then an optimization model for the parameters used in a milling process is built where the spindle speed and feed rate are taken into account as optimization variables. The genetic algorithm is employed to solve the problem. In the end, a case is studied to validate the model.

2. Carbon emissions efficiency

2.1. Carbon emissions evaluation model for milling operation

According to the input/output flows of NC milling operation, the carbon emissions can be divided into direct carbon emissions and indirect carbon emissions. Indirect carbon emissions include energy carbon emissions and material carbon emissions. Material carbon emissions refer to the indirect carbon emissions produced by the auxiliary material consumption. Comparing the carbon emissions cause by electrical power consumption during the milling operation, the quantity of material carbon emissions is very small, which can be ignored. The paper only takes the energy consumption into account.

The carbon emissions of electric energy during milling operation mainly includes two parts: constant carbon emissions and cutting carbon emissions. It can be obtained from the electric energy consumption and the carbon emissions factor. The carbon emissions caused by the electric energy consumption during the cutting process is shown as the equation (1).

\[ C_e = F_c \times E_{cf} + F_c \times E_{mf} \]  

(1)

Where \( C_e \) is the carbon emissions of electric energy consumption (kgCO2e), \( E_{cf} \) is the constant electric energy consumption \((kW \cdot h)\), \( E_{mf} \) is the cutting electric energy consumption \((kW \cdot h)\), \( F_c \) is Electric energy carbon emissions factor \((kgCO2e/kW \cdot h)\).

The constant electric energy consumption represents the energy consumption generated by the numerical control system, the lighting system, the lubrication system, the hydraulic system, the chip evacuation system, the cooling system, etc.

2.2. Carbon emissions efficiency for milling operation

Considering carbon emissions and production efficiency, the carbon emissions efficiency \( T_{cm} \) is proposed. It is defined as “the material removal rate of the operation divided by carbon emissions from the operation”. For an operation, operation with higher \( T_{cm} \) value will remove more material and produce more parts when the carbon emissions budget is determined by the government. The carbon emissions efficiency can be expressed as follows equation (2):

\[ T_{cm} = \frac{MRR \times t_s}{c_{et}} \]  

(2)

Where \( T_{cm} \) is the carbon efficiency \((mm^3/kgCO2e)\), MRR is the material removal rate refers to the volume of the workpiece material removed per unit time \((mm^3/s)\), \( c_{et} \) is the sum of all carbon emissions in one process \((kg)\), and \( t_{is} \) is the cutting time of the operation \((s)\).
3. Optimization model of cutting parameters of CNC milling based on carbon efficiency

3.1. Determining the objective function

According to the definition of carbon efficiency, the variables affecting carbon efficiency are mainly related to the total carbon emissions of the milling operation and the material removal rate during the cutting operation. When the material removal rate takes the maximum value and the total carbon emissions of the operation takes the minimum value, the carbon efficiency of the machined part can reach the maximum value. In this paper, the unified objective function method is used to convert the multi-objective function into single-objective optimization with reference to the relevant literature [10]. The function is solved, and the corresponding single-objective optimization function can be expressed as equation (3).

\[ \text{min} F(n, f_z) = (\text{min} - \text{MRR}, \text{min} C_{\text{w}}) \]  

(3)

3.2. Constraints

The choice of cutting parameters is affected by a number of factors and constraints must be set as follows:

1. Maximum power constraint

The power constraint is expressed as equation (4).

\[ F_{\text{cut}} \times V_c / 1000 \leq \eta P_{\text{max}} \]

(4)

Where \( \eta \) means the machine efficiency factor; \( P_{\text{max}} \) is the machine's maximum power (kW).

2. Cutting parameters constraints

The cutting parameters, which include speed rate, feed rate, cutting depth and cutting width should meet the parameters requirement about the maximum value and minimum value which are determined by the machine tool performance.

4. Case analysis

4.1. Model parameter settings

The effectiveness of the above-built model is verified by milling a workpiece end face which made of 45 steel. The parameters of machine tool are shown in Table 1. The part parameters are shown in Table 2, the tool parameters are shown in Table 3. The experience cutting parameters are shown as Table 4.

| Table 1. CNC milling machine specifications |
|--------------------------------------------|
| \( n \) (\( r \cdot \text{min}^{-1} \)) | \( P_{\text{max}} \) (\text{kW}) | \( f_z \) (\text{mm} \cdot \text{r}^{-1}) | \( \eta \) | \( k_n \) | \( M_{\text{max}} \) (\text{N} \cdot \text{m}) |
| 50–3500 | 2 | 0.02–5 | 0.8 | 0.2 | 20 |

| Table 2. Part parameters |
|--------------------------|
| Part material | length (\text{mm}) | width (\text{mm}) | thickness (\text{mm}) | Processing methods |
| 45 steel | 180 | 80 | 30 | Milling |

| Table 3. Tool parameters |
Table 4. Initial cutting parameters

| Tool type                  | Tool diameter (mm) | Number of cutter teeth | Tool nose radius $r_e$ (mm) |
|----------------------------|-------------------|------------------------|----------------------------|
| YT15 Cemented carbide      | 125               | 4                      | 3                          |

The calculated data were substituted into the corresponding formula to calculate that the carbon emission generated by this plane was $985.39 \, g_{\text{CO}_2e}$, the material removal rate was $746.4 \, (mm^3 \cdot s^{-1})$, and the carbon efficiency was $0.76 \, (mm^3 \cdot g^{-1})$.

4.2. Optimization Algorithm and Results Analysis

In this paper, the genetic algorithm is used to solve the problem. The number of iterations is 150, cross probability is 0.5, the mutation probability is 0.06. The final optimization results are shown in Table 5 below.

Table 5. Optimized data

| $n$ (r·min⁻¹) | $f_c$ (mm·r⁻¹) | $a_p$ (mm) | $a_e$ (mm) | $T_{cm}$ (mm³·g⁻¹) | MRR (mm³·s⁻¹) | $C_{ce}$ (gco2e) |
|----------------|---------------|------------|------------|---------------------|---------------|------------------|
| 424.124       | 0.516         | 2          | 70         | 1.22                | 2041.86       | 1675.4           |

In this paper, the genetic algorithm is used to optimize the carbon efficiency model. After optimization, the optimal cutting parameters are obtained: the speed is $424.124 \, (r \cdot \text{min}^{-1})$, the feed is $0.516 \, (mm \cdot r^{-1})$, and the optimized milling parameters are used for material removal. The rate is $2041.86 \, mm^3 \cdot s^{-1}$, which is 170% higher than the $746.4 \, mm^3 \cdot s^{-1}$ before optimization. The carbon efficiency is $1.22 \, mm^3 \cdot g^{-1}$ after optimization, which is 60% higher than the $0.76 \, mm^3 \cdot g^{-1}$ before optimization. It can be seen that the proposed optimization model can be effectively used to select milling parameters. Milling parameters are important for guiding actual production, which proves the effectiveness of the method.

5. Conclusion

Based on the analysis of the relationship between carbon emissions and material removal rate during milling operation, this paper presents the evaluation index of carbon efficiency. An optimization model for the parameters of milling operation is built where the spindle speed and feed rate are taken into account as optimization variables. Constraints are proposed based on the machine tool performance parameters and the quality requirements of the workpiece. The genetic algorithm was employed to solve the optimal problem. In the end, a case is studied to validate the model. The calculation results show that the model can help manufacturers optimize the selection of milling parameters and ensure that more materials are removed while controlling carbon emissions.

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References

[1] Avram, O.I., Xirouchakis, P. Evaluating the use phase energy requirements of a machine tool system [J]. Journal of Cleaner Production, 2011, 19(6-7):699-711.

[2] Liu Fei, Xu Zongjun, Dan Bin. Energy Characteristics of Mechanical Processing System and Its Application[M]. Beijing: Mechanical Industry Press, 1995:8-39

[3] Hou Chunhong, Zhao Guoyong, Qiao Jianfang. The Calculation and Prediction Method of Energy Consumption in CNC Milling Machine Process[J]. Combined Machine Tool & Automatic Processing Technology, 2017(07):86-88.

[4] Jeswiet J., Kara S. Carbon emissions and CESTM in manufacturing [J]. CIRP Annals-Manufacturing Technology, 2008, 57(1):17-20.

[5] Cao Huajun, Li Hongwu, Song Shengli et al. Method and application of life cycle carbon emission assessment based on life cycle assessment[J]. Computer Integrated Manufacturing Systems, 2011, 11:2432-2437.

[6] Levi F, Maffeis S. Optimization of Cutting Parameters for Cutting Force in Shoulder Milling of Al7075-T6 Using Response Surface Methodology and Genetic Algorithm [J]. Procedia Engineering, 2013, 64(12):690-700.

[7] Wu M.P, Liao W.H. Internet-base machining parameter optimization and management System for high-speed machining[J]. Transactions of Nanjing university of Aeronautic&Astronautics, 2005, 22(1):42-46.

[8] Subramanian M, Sakhthivel M, Sooryaprakash K, et al. Optimization of Cutting Parameters for Cutting Force in Shoulder Milling of A17075-T6 Using Response Surface Methodology and Genetic Algorithm[J]. Procedia Engineering, 2013, 64: 690-700.

[9] Gao L, Huang J D. An effective cellular particle swarm optimization for parameters optimization of a multi-pass milling process[J]. Applied Soft Computing, 2012, 12(11): 3490-3499.

[10] Liang Shangming, Yin Guofu. Modern Mechanical Optimization Design Method [M]. Chemical Industry Press. 2005-7