Multi-objective Optimization of High Speed Milling Parameters Based on Genetic Algorithm

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Abstract. In order to optimize the high-speed milling parameters and reduce the experimental work in the actual processing, a multi-objective optimization model is established. The improved genetic algorithm NSGA-II combined with penalty function method is used to solve the mathematical model, and the optimal cutting parameters are obtained when the high-speed milling conditions are known, which provides guidance for the process decision-making of high-speed milling.

Keywords: High Speed Milling, Cutting Parameters, Multi objective Optimization, Genetic Algorithm

1. Introduction
Processing efficiency, processing cost and product quality are the basic standards to evaluate the advantages and disadvantages of CNC processing technology [1-3]. In the actual production and processing, the selection of cutting parameters is related to the quality, production cost and processing efficiency of the processed parts, directly. Under the existing processing conditions, according to the requirements of the parts, the most suitable cutting parameters are selected to achieve the best economic index, that is to achieve the multi-objective optimization of cutting parameters [4-5], which can process the parts that meet the requirements faster and better under the same conditions, and can greatly reduce the test workload used to determine the more optimized milling parameters in actual production.

However, the selection of cutting parameters is affected by many and complex variables, so the optimization process is more complex. In the actual mold high-speed milling production, the constraints and optimization objectives are various, belonging to a typical multi-objective multi constraint optimization problem. Therefore, with the help of mathematical modeling knowledge, this paper establishes the multi-objective optimization mathematical model of mold high-speed milling parameters, and selects the appropriate method to solve the mathematical model, so as to obtain the optimal high-speed milling parameters to meet the processing efficiency, quality and cost at the same time.
2. Multi-objective Optimization Mathematical Model of Milling Quantity

Optimization problem is to search for the optimal solution for some targets in some possible choices. In the actual production process, the optimization objectives are incompatible and cannot be realized simultaneously. However, multi-objective optimization is not to hope that these goals can be achieved at the same time, but to obtain a set of relatively satisfactory solutions for each target by determining the relative importance of these objectives according to the actual situation. Therefore, the optimization of the high-speed milling amount of die can be described by transforming the multi-objective optimization problem.

The three elements of establishing mathematical model are [6]: decision variables, objective functions and constraints.

2.1. Optimize Decision Variables
The independent parameters that need to be optimized in optimization problems are called optimization decision variables. When the conditions of high-speed milling are determined, the milling parameters such as milling speed $V_c$, feed per tooth $f_z$, axial milling depth $a_p$ and radial milling spacing $a_e$ are the most important factors affecting the realization of high-speed milling. Therefore, in the optimization model of high-speed milling parameters, the optimal decision vector is as follows:

$$X = [v_c, f_z, a_p, a_e]^T = [x_1, x_2, x_3, x_4]^T$$

2.2. Optimization Objective Function
In order to obtain the optimal parameters of high-speed milling, the optimization objective function including optimization decision variables should be established firstly, and the optimal decision variables can be found by solving the maximum or minimum value of the objective function. In this paper, processing time, surface roughness and processing cost are selected as the optimization objectives.

$$f_i(X) = f_i[v_c, f_z, a_p, a_e] = f_i[x_1, x_2, x_3, x_4] \quad i = 1, 2, 3$$

2.2.1. Productivity Objective Function of High Speed Milling
Productivity is generally reflected by processing time, and cutting time accounts for the main part of processing time. This paper uses cutting time to describe productivity. The cutting time model of flat end mill is [7]:

$$f_1(X) : t_m = \frac{L_w}{v_f} = \frac{\pi d}{1000Zv_c f_z}$$

2.2.2. Objective Function of Surface Roughness in High Speed Milling
The surface roughness of high-speed milling is the main parameter to measure and evaluate the machined surface quality. In this paper, the surface roughness is used as the index to evaluate the machining quality. The surface roughness model of flat end mill with fillet is as follows:

$$f_2(X) : R_a = 8r_z f_z^2$$

2.2.3. Objective Function of High Speed Milling Cost
Low cost and high profit is the ultimate goal of machining enterprises, this paper takes the processing cost as one of the optimization goals. Empirical formula for tool life of flat end milling cutter [7]:

$$T = \frac{K_f C_f d^q}{v_c^{m_u} f_z^{m_z} a_p^{x_1} a_e^{y_1} Z^{w_1}}$$

$K_f$ - correction factor related to cutting condition; $C_f$ - coefficient related to cutting condition; $m, x, y, u, w, q$ - index related to cutting condition.
2.3. Optimization Constraints and Functions
In the process of mold high-speed milling, due to the limitations of processing equipment and processing conditions, the range of milling parameters can be selected is limited. Therefore, it is necessary to consider the limitations of these factors on the selection of milling parameters. In this paper, the constraint conditions are as follows:

(1) Torque constraint of machine tool spindle \( g_1(X) : M_0 - \frac{10^{-3} F_c d}{2} \geq 0 \)

\( F_c \) - main milling force (n); \( M_0 \) - maximum allowable torque of high speed milling machine.

(2) Power constraint of machine tool spindle \( g_2(X) : P_0 \eta - \frac{F_c v}{1000} \geq 0 \)

— the total efficiency of the high-speed machine tool; \( P_0 \) - the rated power of the machine tool.

(3) Work-piece machining accuracy constraints \( g_3(X) : \delta - \frac{10^{-3} F_c L^3}{3EI} \geq 0 \)

\( I \) - Tool moment of inertia \( (mm^4) \), \( I = \frac{\pi d^4}{64} \);
\( L \) - Tool overhang (mm); \( E \) - Elastic modulus of workpiece material \( (GPa) \).

(4) Axial cutting depth \( a_p \) constraint \( g_4(X) : \Delta - a_p \geq 0 \)

\( \Delta \) - Process allowance.

(5) Radial milling spacing \( d_a \) constraint \( g_5(X) : d - d_a \geq 0 \)

\( d \) - Milling cutter diameter.

(6) Stability constraints of milling cutter diameter in high speed milling \( g_6(X) : \)

\( n_{max} a_p \lim = \frac{1000 v_c}{\pi d} - a_p \geq 0 \)

\( n_{max} \) - Maximum speed of machine tool in stable milling.

(7) Regional constraints for optimizing decision variables:

\[ \frac{8000 \pi d}{1000} = v_{c, min} \leq v_c \leq v_{c, max} = \frac{\pi d n_{max}}{1000} \]

\( n_{max} \) - Maximum speed allowed for high speed milling centers. This paper discusses the high-speed milling of the mold, set up \( n_{min} = 8000(\text{r} / \text{min}) \). In addition, the constraint condition of feed rate per tooth should be satisfied as follows:

\[ \frac{v_{f, min}}{n Z} = f_{z, min} \leq f_z \leq f_{z, max} = \frac{v_{f, max}}{n Z} \]

\( f_{z, min}, f_{z, max} \) - Minimum and maximum feed per tooth allowed in high speed milling centers.

3. Algorithm for Solving Multi-objective Optimization Model of Milling Parameters
Genetic algorithm uses random search for multiple points, which can effectively use historical information to find better offspring, and can be used to solve large and complex optimization problems [8]. Because genetic algorithm itself does not have the ability to deal with constrained functions, the constrained optimization problem must be transformed into an unconstrained optimization problem when genetic algorithm is used to optimize functions with constraints. For this reason, this paper selects the improved genetic algorithm NSGA-II combined with penalty function method [9-10] for constraint processing, and the multi-objective optimization mathematical model of mold high-speed
milling parameters is shown in the following formula (1), which can be used as the fitness function of multi-objective genetic algorithm NSGA-II.

\[
F_i(X) = f_i(X) + R \sum_{j=1}^{6} \min\{0, g_j(X)\} \quad i = 1,2,3
\]

Among them, constraint 7 is used as the initialization and coding range of optimization variables.

4. An Example of Multi-objective Optimization of Milling Parameters in Mold High-speed Milling

4.1. Optimization Example

In order to facilitate comparative analysis, this paper uses the literature data, NSGA-II combined with penalty function method to solve the optimized milling parameters. The specific processing conditions and parameters are as follows [7]:

1. Mold related parameters
   Material: S136 (4crmov) pre-hardened plastic mold steel, hardness 51hrc, processing surface of shallow depth cavity.
2. Machine tool: Deckel MAHO dmu-60t machining center.
3. The cutting tool is Sandvik carbide flat end milling cutter with rounded corner.
4. Milling parameters: milling stroke \(l_u = 8000mm\), maximum surface roughness required to be machined \(Ra \max = 0.6 \mu m\), allowable deformation of dimensional accuracy \(\delta = 0.05mm\), finishing allowance \(\Delta = 0.3mm\), machine tool cost \(C_m = 0.3\) yuan/min.
5. Correlation index and coefficient of tool life: \(m = 0.25\), \(y = 0.2\), \(x = 0.1\), \(u = 0.15\), \(w = 0.1\), \(q = 0.25\), \(K_r = 0.37\), \(C_r = 2.51 \times 10^{12}\), \(k_{F_c} = 1.0\).
6. Correlation index and coefficient of main milling force: \(C_F = 116\), \(x_F = 1.0\), \(y_F = 0.75\), \(u_F = 0.85\), \(w_F = -0.13\), \(q_F = 0.73\).

By substituting the above parameters, the optimization objective functions and constraints are obtained.

4.2. Algorithm Solving Process

Floating point coding method is used to code the four parameters to be optimized in high-speed milling. According to the constraints of constraint 7 and the milling parameters recommended in the tool manual, the initial values are \(200m/min \leq v_c \leq 350m/min\), \(0.04mm/z \leq f_z \leq 0.2mm/z\), \(0.1mm \leq a_p \leq 1mm\), \(0.04mm \leq a_e \leq 0.2mm\) respectively. If the penalty parameter is \(R_1 = 0.1\), \(R_2 = 0.001\), \(R_3 = 0.01\), the fitness function expression can be obtained. NSGA-II algorithm is used to solve the mathematical function constrained by penalty function, and the algorithm program combined with an example is implemented in Matlab platform.

4.3. Optimization Results and Analysis

In this example, set the population size of the algorithm as 500, the number of iterations as 500, the crossover rate \(p_c = 0.9\), and the mutation rate \(p_m = 0.02\), and optimize the high-speed milling parameters of the mold. The operation effect is shown in Figure 1.
Figure 1. Optimization effect of milling parameter optimization example

It can be seen from the operation in Figure 1 that the optimal fitness value fluctuates greatly at the beginning of iteration. With the evolution of the population, after about 20 iterations, the fitness value of each objective function value changes very little, and the corresponding three objective function values of individuals have converged to a very small region. By weighing the relative proportion of the three objective functions in the finishing stage, a group of optimal parameters can be selected in the area where the fitness of the objective value changes little. The comparison table of milling parameters and optimization objectives is shown in Table 1.

Table 1. Comparison of optimization results

| Milling speed \(v_c\) \((m/min)\) | Feed per tooth \(f_z\) \((mm/z)\) | Axial milling depth \(a_p\) \((mm)\) | Radial milling spacing \(a_r\) \((mm)\) |
|---|---|---|---|
| Draft optimization | Draft optimization | Draft optimization | Draft optimization |
| 240 | 345 | 0.075 | 0.05 | 1 | 1 | 1 | 0.06 |

Processing time \(t_m\) \((min)\) | Surface roughness \(R_s\) \((\mu m)\) | Processing cost \(C\) \((yuan)\) |
|---|---|---|
| Draft optimization | Draft optimization | Draft optimization |
| 8.73 | 9.01 | 0.0675 | 0.03 | 4.37 | 2.73 |

Compared with the above two sets of optimization target results, it can be concluded that a set of milling parameters obtained by the optimization solution can reduce the processing efficiency (expressed by processing time) by 3.2%, improve the surface roughness by 55.6%, and reduce the processing cost by 37.5%, only because of the reduction of milling feed, the processing efficiency is reduced.

Because the main goal of finishing stage is to improve the processing quality as much as possible, the requirement of processing efficiency is not very high. Therefore, the optimized milling parameters basically achieve the expected optimization goal, which solves the multi-objective optimization selection problem of mold high-speed milling parameters.

Therefore, the multi-objective optimization mathematical model of high-speed milling parameters and its solution algorithm established in this paper can better optimize the high-speed milling parameters and achieve the expected optimization objectives, which also has certain guiding significance for production practice.

5. Conclusion

In this paper, a multi-objective optimization mathematical model of mold high-speed milling parameters is established, and NSGA-II algorithm is used to solve the mathematical model constrained by penalty function method. Combined with an example, Matlab is used to compile the algorithm
program, and the optimization objective function values corresponding to two groups of parameters before and after optimization are compared, which shows that the multi-objective optimization mathematical model and algorithm of mold high-speed milling parameters established in this paper are feasible. It provides a new idea for the optimization of high-speed milling parameters under specific processing conditions, and also reduces the experimental workload in actual production.

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