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JOURNAL OF IRON AND STEEL RESEARCH, INTERNATIONAL. 2013, 20(2): 27-32, 61

Multi-Objective Load Distribution Optimization for Hot Strip Mills

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Abstract: Load distribution is a key technology in hot strip rolling process, which directly influences strip product quality. A multi-objective load distribution model, which takes into account the rolling force margin balance, roll wear ratio and strip shape control, is presented. To avoid the selection of weight coefficients encountered in single objective optimization, a multi-objective differential evolutionary algorithm, called MaximinDE, is proposed to solve this model. The experimental results based on practical production data indicate that MaximinDE can obtain a good pareto-optimal solution set, which consists of a series of alternative solutions to load distribution. Decision-makers can select a trade-off solution from the pareto-optimal solution set based on their experience or the importance of objectives. In comparison with the empirical load distribution solution, the trade-off solution can achieve a better performance, which demonstrates the effectiveness of the multi-objective load distribution optimization. Moreover, the conflicting relationship among different objectives can be also found, which is another advantage of multi-objective load distribution optimization.

Key words: hot strip mill; load distribution; multi-objective optimization

Load distribution is critical for the hot rolling process, which not only directly affects product quality such as strip thickness and shape precision, but also has a major impact on rolling energy, roll consumption, production stability and efficiency, etc[1]. Since the 1960s, load distribution of hot strip mills have gone through several stages such as experience form method, power curve method, load distribution factor method, and artificial intelligence method[2].

Many scholars have worked in this field. Ref. [3] presented an immune genetic algorithm to optimize load distribution of hot strip mills, and built an optimal load distribution model combining with strip shape. Ref. [4] proposed an improved particle swarm optimization algorithm with the mutation in weighted gradient direction based on the evaluation of the fitness variance to optimize load distribution of hot strip mills. A minimum variance objective function of shape and gauge control was proposed in the condition of ensuring good shape. Ref. [5] proposed an improved adaptive search area particle swarm optimization and applied it to the optimum design of load distribution for hot strip mills. These papers have a common defect: load distribution of hot strip mills is a multi-objective optimization problem, but it is usually converted into a single objective one by weighted-sum method. However, the weight coefficients are not easy to determine in practice, especially when the objectives have different order of magnitudes. To overcome this defect, Ref. [6] proposed a multi-objective differential evolution, and then this algorithm was applied to the load distribution calculation of hot strip mills. This paper further explores the advantages of multi-objective load distribution optimization, and proposes a new multi-objective differential evolution algorithm, called MaximinDE, to optimize the load distribution problem for hot strip mills.

1 Multi-Objective Load Distribution Model

A reasonable load distribution can provides a good

Foundation Item: Item Sponsored by National Natural Science Foundation of China (50974039)

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starting point for the control of strip shape and strip thickness, hence, load distribution optimization taking into account strip shape has become a research hot focus. This paper builds a multi-objective load distribution model considering rolling force margin balance, roll wear ratio and strip shape control.

1.1 Decision variables of load distribution

Objective functions and constraint conditions of load distribution optimization have to do with the exit thicknesses of finishing mill stands directly or indirectly, so the exit thickness of each stand can be taken as the decision variable of the load distribution optimization problem.

To avoid aimless search, take the result of empirical load distribution method[7] as the initial value of optimization calculation:

$$h_i^0 = H_0 \exp\left[\frac{C_2 - \sqrt{C_2^2 + 4C_1 \varphi_i \alpha_n}}{2C_1}\right] \qquad (1)$$
$$\alpha_n = C_1\left[\ln\frac{H_0}{h_n}\right]^2 + C_2 \ln\left[\frac{H_0}{h_n}\right]$$

where, h_i^0 is the initial exit thickness of stand i; H_0 is the slab thickness; h_n is the product target thickness; C_1, C_2 are the statistics coefficient of actual production; α_n is an initial parameter; and φ_i is the cumulative energy distribution coefficient of stand i.

1.2 Optimization objectives of load distribution

Rolling force margin balance, roll wear ratio control and strip shape control are taken to be the optimization objectives. The upstream three stands take rolling force margin balance as the optimization objective, and should provide rolling reduction as far as possible within the equipment capacity, while the downstream four stands focus on roll wear ratio control and strip shape control. In view of the special process of schedule free rolling (SFR) of hot rolling, and the factors influencing strip shape, a multi-objective load distribution model is built. This model mainly takes into account the following three aspects.

1) Rolling force margin balance

In view of the factors such as the fluctuation of strip thickness and the difficulty to bit slab into the first stand F1, the rolling reduction of F1 should be somewhat smaller, while the second and third stands should make full use of the equipment capacity to give bigger rolling reductions as far as possible. Hence, rolling force margin balance of the upstream three stands is taken to be the first objective (f_1):

$$f_1 = (P_1 - K_1 P_2)^2 + (P_2 - K_2 P_3)^2 \qquad (2)$$

where, P_i is the rolling force of stand i, $i = 1, 2, 3$; K_1 and K_2 are the rolling force margin balance ratios.

2) Roll wear control

Roll wear control is a key technology of SFR of hot rolling. It hopes that the roll wear of the downstream four stands should be distributed according to a certain ratios to prevent excessive roll wear of individual pass, which is beneficial to the roll change cycle of a rolling schedule and surface quality of hot strips:

$$f_2 = \sum_{i=4}^{6} (w_i - G_i \cdot w_{i+1})^2 + \sum_{i=4}^{7} w_i^2 \qquad (3)$$

where, w_i is the midpoint wear of stand i, whose formula can be referred to Ref. [8-9]; G_i is the roll wear ratio and f_2 is the second objective.

3) Strip shape control

For downstream stands, the difference of entrance relative crown and exit relative crown of each stand should meet the strip flatness dead zone condition and ensure a good strip shape between stands.

$$f_3 = \sum_{i=4}^{7} [(C_h^i/h_i - C_H^i/H_i \pm \Delta_i)^2] \qquad (4)$$

where, H_i and h_i are the entry and exit thicknesses of stand i, respectively; C_H^i and C_h^i are the entry and exit crowns of stand i; Δ_i is the optimal adjustment, whose value is relative to the allowable difference of entrance relative crown and exit relative crown of stand i; and f_3 is the third objective.

Based on the above analysis, the multi-objective load distribution model is given by:

$$\min \boldsymbol{f} = (f_1, f_2, f_3)$$
$$\text{s. t.} \begin{cases} 0 \leqslant P_i \leqslant P_m \\ 0 \leqslant I_i \leqslant I_m \\ H_{i+1} < H_i \end{cases} \qquad (5)$$

where, I_i is the motor current of stand i; and P_m and I_m are the maximum rolling force and motor current, respectively.

2 Multi-Objective Load Distribution Optimization

2.1 Main procedure of MaximinDE

Fig. 1 shows the schematic diagram of MaximinDE.

Step 1: Initialize the population of N individuals and store them in P_0; Generation counter $t=0$.

Step 2: Generate the offspring population Q_t through differential evolution algorithm[10].

1) Mutation. For each individual $\boldsymbol{x}_i$ in P_t, a mutant vector $\boldsymbol{v}_i$ is generated according to

$$\boldsymbol{v}_i = \boldsymbol{x}_{r1} + F(\boldsymbol{x}_{r2} - \boldsymbol{x}_{r3}) \qquad (6)$$

where i, r_1, r_2, $r_3 \in \{1, \cdots, N\}$ are mutually different integers; $F > 0$ is a real parameter.

2) Crossover. A trial vector $\boldsymbol{u}_i = (u_{i1}, \cdots, u_{iD})$ is generated with