Transverse thickness profile control of electrical steel in 6-high cold rolling mills based on the GA-PSO hybrid algorithm

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Abstract
In order to meet the shape control requirements of “dead flat” transverse thickness profile of electrical steel sheet in cold rolling process, the 3D finite element model (FEM) for roll stacks and strip of 6-high tandem cold rolling mills (TCMs) was built with the developed Edge Drop Control Work Rolls for Non-shifting (EDW-N). The efficiency curves of the work roll bending (WRB), the intermediate roll bending (IRB), and the intermediate roll shifting (IRS) in cold rolling process are obtained for transverse thickness profile control performance. The control strategy of multi-stand and multi-variable profile and flatness control actuators, i.e., WRB, IRB, and IRS of stands 1~5 in 6-high TCMs is proposed based on the GA-PSO hybrid algorithm with better optimization ability. The results show that the control strategy can fully exploit the shape control ability and achieve the high precision control for transverse thickness profile of 6-high TCMs. The industrial application on the production gives remarkable results that the rate of the measured strip crown less than 7 μm increased from 38.58 to 67.74% for electrical steel sheet in the 1420-mm 6-high TCMs. The control strategy has applied to the production successfully.

Keywords Cold rolling mill · Electrical steel · Intelligent algorithm · Multi-stand control · Shape control

1 Introduction
In recent years, the modern high-speed wide strip tandem cold rolling mills (TCMs) are main equipment with the highest degree large-scale, continuous, and automated rolling mills for strip production [1]. As a kind of high efficiency and energy saving ferrosilicon soft magnetic alloy, electrical steel is the core raw material that supports the strategic need of national mechanical, energy, national defense, and military technology development. From the practice of the national base with the largest output of electrical steel in China and the feedback of users, it is of great importance to solve the strip shape problem of “dead flat” transverse thickness profile. In general, the strip shape includes transverse thickness profile and flatness two indexes. The transverse thickness profile is also called rectangular section, which can be described by the crown and edge drop. Wide electrical steel can significantly improve utilization and productivity, and the super-high requirements of rectangular section are more urgent. To realize the rectangular section control for the strip by strictly controlling edge drop, crown, and transverse thickness difference during the rolling process, which is the shape quality requirement of high-end products for electrical steel in recent years [2].

In actual production, so as to improve the control level of the transverse thickness profile for the strip, 4-high or 6-high TCMs are often used, the former such as Germany’s Continuously Variable Crown-4 (CVC-4) [3], Austria’s SmartCrown [4], China’s Edge drop & Crown Compact (ECC) [5], Japan’s Taper Work Roll Shifting and Cross (T-WRS&C) [6], and Pair Cross (PC) [7], the latter includes Germany’s CVC-6, Edge Drop Control (EDC) work roll and CVC-6+EDC cooling technology [8], and Japan’s High Crown with Work Roll Shifting (HCM) [9]/Universal Crown Mill (UCM) [10]/Universal Crown Mill with Work roll shifting (UCMW) [11], as well as Variable Crown Middle roll Shift (VCMS)
is developed on the basis of the UCM mills [12], etc. At present, domestic cold rolling mills have introduced 6-high UCM and UCMW mills to achieve high-precision shape control for cold rolled strip. Due to design and manufacture of the work roll shifting (WRS) system for the 6-high TCMs are complicated. Therefore, except for a few adopting the international advanced level of 6-high UCMW mills, the rest of the more use 6-high UCM mills (as shown in Fig. 1), and partly using CVC-6 mills and VCMS mills. The work rolls of 6-high UCM, CVC-6 and VCMS mills lack of the WRS system, which is an important shape control method. There is a bottleneck problem in the high-precision transverse thickness profile control [13]. On the basis of the rolling mill type, the roll contour technology is the most direct and effective means to control the strip shape. Aiming at the bottleneck problem of the rectangular section control of electrical steel, a variety of work roll technology have been developed at home and abroad. For example, Edge Drop control Work roll contour (EDW) [14], single-taper work roll contour [15], double-taper work roll contour [16], and Edge Variable Crown (EVC) work roll contour [17] for 4-high TCMs, as well as single-taper k-WRS work roll contour [18] and curved work roll contour [19] for 6-high TCMs and Edge Drop Control Work Rolls for Non-shifting (EDW-N) independently developed based on the characteristics of 6-high UCMW mills and EDW technology practice of 4-high ECC mills [20] (as shown in Fig. 1). On this basis, for the sake of further achieving the ultra-high-quality requirements for the rectangular section control of electrical steel, a large number of scholars have used finite element methods and intelligent algorithms to research the shape control actuators of TCMs. The finite elements method such as Seung et al. [21] developed an online prediction model of strip profile based on the FEM. Yao et al. [22] proposed a tapered work roll shifting strategy to reduce the local high point and edge drop of hot rolling mills based on the 3D FEM. Wang et al. [23] established 3D elastic–plastic FEM of the 6-high Smart-Crown cold rolling mills, and studied the control characteristics of the IRS. Intelligent algorithms for example Shinya et al. [24] established the intelligent numerical simulation model to study the work roll shifting strategy. Wu et al. [25] developed a strip bending force prediction model based on extreme learning machine (ELM). In addition, Bu et al. [26] established a multi-objective preset model of the WRB force control.

![Diagram of 1420-mm five-stand 6-high cold rolling mill and EDW-N roll contour](image)

**Fig. 1** 1420-mm five-stand 6-high cold rolling mill and EDW-N roll contour

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by the multi-objective intelligent algorithm. Li et al. [27] adopted the Bayesian optimized Light Gradient Boosting Machine (LightGBM) algorithm to establish the prediction model for the CVC roll shifting, which uniform work roll wear and control strip shape.

The key of shape control is the correct understanding of the ability for various shape control actuators. With the in-depth development of shape control theory and artificial intelligence algorithm [28], there has been an increasing amount of literature on multi-variable optimal shape control to solve the increasingly severe rectangular section control problem. Wang et al. [29] proposed a control method based on GA-PIDNN, which transformed the multi-variable optimization model of shape control into a series of single-variable optimization models. John et al. [30] combined artificial neural network (ANN) and genetic algorithm (GA) to reduce strip shape defects by selecting the optimal process parameters. Besides, Zhang et al. [31] proposed a control strategy using Topkis-Veinott coordination algorithm and GA to solve the group of shape actuators. Raju et al. [32] established a shape prediction model of cold rolling mills based on ANN by considering various process parameters that affect the strip shape. Nappez et al. [33] developed a multi-variable closed-loop controller for the shape control of cold rolling mills, and determined the optimal adjustment amount of the shape control actuators through the global method. In addition, some scholars have studied the shape control characteristics for the multi-stand of 6-high TCMs. Wang et al. [34] proposed a new method to calculate the efficiency factor of shape actuator for the WRB, the IRB, and the IRS by combining the rolling test and the FEM. Kazutoshi et al. [35] established a global optimization model for strip crown and flatness, which achieved remarkable results when applied to the actual rolling. Li et al. [36, 37] proposed the 3D elastic–plastic coupling FEM suitable for multi-stand based on the segmented modeling strategy, and systematically studied the law of multi-objective parameters during the rolling process. Sun et al. [38] put forward the kernel partial least squares method combined with artificial neural network (KPLS-ANN) to predict the strip shape for the whole stand of the TCMs.

It provided a theoretical guidance and innovative path for fundamentally solving the bottleneck problem for rectangular section control of electric steel in the new generation of the TCMs.

2 Analysis of shape control function of 6-high TCMs

2.1 Establishment of the FEM for 6-high TCMs

With the rapid development of computer systems, the FEM has been widely used in the rolling process. In order to analyze the shape control efficiency curves of the 6-high TCMs, a 142-0 mm 6-high TCM production line for non-oriented electrical steel and the self-developed EDW-N work roll is taken as the research objects. Large-scale general finite element software ABAQUS was used to establish a 3D FEM for roll stacks and strip of 6-high TCMs, as shown in Fig. 2.

For the sake of ensuring the accuracy of the FEM, the roll system parameters and material characteristics that correspond to the actual rolling are used, as shown in Tables 1 and 2. According to the actual characteristics of the rolling process, displacement and load boundary conditions are applied to the FEM. (1) Symmetrical constraints and displacement constraints in the Z-direction (UZ = 0) are imposed on the nodes of the XY plane for the roll system. (2) The Y-direction displacement constraint (UY = 0) is applied to the node at the midpoint of the contact line for the back-up roll. (3) The X-direction displacement constraint (UX = 0) is applied to the geometric center of the work roll, the intermediate roll and the back-up roll. (4) The rolling force acts on the symmetry plane of the roll system in the form of a uniform load. (5) The WRB force and the IRB force are applied to the center of the journal section at both ends of the work roll and the intermediate roll respectively.

Given the above-mentioned contributions, in order to further meet the shape control requirements of “dead flat” transverse thickness profile of electrical steel sheet in cold rolling process, a 3D FEM for roll stacks and strip of 6-high TCMs was built with the developed EDW-N technology. The efficiency curves of the WRB, the IRB, and the IRS in cold rolling process are obtained for transverse thickness profile control performance. The control strategy of multi-stand and multi-variable profile and flatness control actuators, i.e., WRB, IRB, and IRS of stands 1 ~ 5 in 6-high TCMs, for “Dead flat” transverse thickness profile of electrical steel sheet is proposed based on the GA-PSO hybrid algorithm.

Fig. 2 The FEM of 6-high TCMs
In order to verify the accuracy of the FEM, the simulation was carried out with the stand 1 (S1) exit shape, a coil of 50W1300 electrical steel on site (the width is 1260 mm, the incoming thickness is 2.7 mm, the reduction is 30%, the rolling force is 8.7kN/mm, the WRB is $-46kN$, the IRB is $96kN$, and the IRS is 55 mm) is executed simulation. And the transverse thickness profile of electrical steel is measured online by ultrasonic thickness gauge, and the comparison between the FEM simulation and the measured results is shown in Fig. 3. It can be seen from the figure that the maximum error between the measured and the simulated value is 5.46%, which is within the allowable range. It indicated that the FEM can simulate the actual rolling process.

### 2.2 Establishment of shape regulation function

In the actual rolling process, it is very important to accurately understand the characteristics of shape control actuators. The essence of shape control is to control the load roll gap. Various shape adjustment actuators can achieve the purpose of the transverse thickness profile control by regulating the load roll gap. The shape regulation function [39] can be regarded as the variation of the load roll gap of the strip along the width direction under the unit adjustment amount of the certain shape control actuators. The formula is expressed as:

$$E(x) = \frac{\Delta h(x)}{\Delta S}, x = [-1, +1]$$

(1)

where $E(x)$ is shape regulation function, $\Delta h(x)$ is the change for load roll gap of strip, $S$ is adjustment amount of shape control actuators. $x$ is the coordinate along the strip width.

Effectiveness of shape control quantifies the ability of the shape control mechanism to improve shape quality and reduce shape deviation as much as possible through the coordination of different shape control actuators. At present, the efficiency curves are basically determined by the FEM. It is more difficult by rolling experiment. The finite element simulation method can flexibly simulate various rolling conditions under ensuring rolling accuracy, and it is widely used. Therefore, this paper relies on the finite element software ABAQUS to analyze the efficiency curves of the WRB, the IRB, and the IRS for 6-high TCMs.

### 2.3 Analysis of the efficiency curves of various shape actuators

The shape control actuators can change the load roll gap by affecting the roll deformation, and then affect the uneven compression and extension of the strip. Different shape control actuators have different adjustment performance, which will reflect different shape efficiency curves. The FEM was used to simulate the influence of shape control actuators on the transverse thickness distribution of the strip. The width ($B = 1260$ mm) of strip commonly used on the site was selected. The shape efficiency curves were calculated by formula (1), and the strip width coordinates were normalized. The efficiency curves of the WRB (10kN), the IRB (10kN), and the IRS (10 mm) in cold rolling process are obtained for transverse thickness profile control performance, as shown in Fig. 4.

It can be seen from Fig. 4 that the WRB, the IRB, and the IRS have different effects for the shape. There are nonlinear, strong coupling, and time-varying characteristics among shape control actuators. Among them, the WRB has better shape control effect than the IRB and the IRS. The shape

| Table 1  | Main parameters for roll stacks and strip |
|---------|------------------------------------------|
| Item    | WR/mm | IMR/mm | BR/mm | Strip/mm          |
| The parameter value | $\varnothing 440 \times 1420$ | $\varnothing 480 \times 1450$ | $\varnothing 1200 \times 1420$ | $1260 \times 500 \times 3$ |

| Table 2 | Material characteristics for roll stacks and strip |
|---------|---------------------------------------------------|
| Items   | Strip                                    | Roll stacks                     |
| Material model | Bilinear elastic–plastic isotropic hardening material | Linear elastic isotropic material |
| Density ($kg/m^3$) | 7850 | 7850 |
| Elasticity modulus (GPa) | 210 | 210 |
| Poisson’s ratio | 0.3 | 0.3 |
| Yield stress (MPa) | 255 | - |

![Fig. 3](The International Journal of Advanced Manufacturing Technology (2022) 121:295–308)
The efficiency curve for the WRB is parabolic, which can regulate the quadratic shape, while the efficiency curves for the IRB and the IRS are complex high-order curve. Therefore, the WRB can be the first to work as a priority adjustment to achieve the purpose of quickly adjusting the strip shape, while the IRB and the IRS can be used as secondary adjustment means. Meanwhile, the WRB and the IRB can be combined to maintain good strip shape.

The WRB force is designed 10kN, 50kN, and 100kN, while the IRB force is 0kN, and the IRS is 0 mm. The influence for different WRB force on shape efficiency curves is shown in Fig. 5. It can be seen from Fig. 5 that the WRB force has a great influence on the shape regulation effect, which gradually increasing from the center to the edge of the strip, and presenting an approximate parabolic distribution. It is effective for both secondary and fourth-order shape defects, but has stronger control ability to secondary shape. When the WRB force increases, the work roll will produce greater bending deformation under the action of the bending force, and the control ability of the shape will be significantly increased, so that the strip profile will also produce greater changes.

The IRB force is designed 10kN, 50kN, and 100kN, while the WRB force is 0kN, and the IRS is 0 mm. Figure 6 shows the influence of different IRB forces on the shape efficiency curve. It can be seen from Fig. 6 that the influence of the IRB on the shape regulation gradually increases from the center to the edge of the strip. The shape regulation effect of the IRB was significantly weaker than that of the WRB. The IRB has little influence in the center of the strip, but it has an obvious shape regulation effect on the edge of the strip. As the IRS force becomes larger, the shape regulation effect gradually increases. The IRS is designed 10 mm, 50 mm, and 100 mm, while the WRB force and the IRS force are 0kN. Figure 7 shows the influence of different IRS on the shape efficiency curve. It can be seen from Fig. 7 that the IRS has little influence on the shape control effect, which gradually increases from the center to the edge of the strip.
and presenting a form of higher order curve. The IRS has obvious shape regulation effect on the center and edge of the strip, and with the increase of IRS, the shape regulation effect at the center and edge of the strip increases gradually. To sum up, it can be seen that the shape control actuators of the WRB, the IRB, and the IRS for the 6-high TCMs have certain differences in the strip shape. Meanwhile, the shape control actuators are strong coupling and nonlinear characteristics. Therefore, it is necessary to optimize and analyze the coordinated control of shape control actuators.

3 The control strategy of multi-stand and multi-variable based on the GA-PSO hybrid algorithm

Due to the shape control actuators have the characteristics of multi-variable, nonlinear, and strong coupling. In addition, the main shape control shape control actuators for the WRB, the IRB, and the IRS of stands 1 ~ 5 in 6-high TCMs have different shape control characteristics. Using the control characteristics of shape control actuators is an important way to realize rectangular section accurate control of electrical steel. Consequently, the control strategy of multi-stand and multi-variable profile and flatness control actuators, i.e., WRB, IRB, and IRS of stands 1 ~ 5 in 6-high TCMs, for “dead flat” transverse thickness profile of electrical steel is proposed based on the GA-PSO hybrid algorithm.

3.1 GA-PSO hybrid algorithm

3.1.1 Basic PSO algorithms

Particle swarm optimization (PSO) algorithm was proposed by Eberhart and Kennedy [40] in 1995. This algorithm imitates predation behavior of birds randomly searching for food, that is, birds made the group reach the optimal state through mutual cooperation. Particles in PSO algorithm mainly rely on the population in the decision space velocity and position update to evolve, the dual effects of particles by self-memory and group in each update process, as shown in Fig. 8. Assuming that initializes the individual number for a population of \(N\), decision-making space for \(D\), the position of the \(i\)th particle is \(X_i = (x_{i1}, x_{i2}, \ldots, x_{id})\), the speed of the \(i\)th particle is \(V_i = (v_{i1}, v_{i2}, \ldots, v_{id})\), the individual optimal extremum is \(pbest_i = (pbest_{i1}, pbest_{i2}, \ldots, pbest_{id})\), and the global optimal extremum is \(gbest_i = (gbest_{i1}, gbest_{i2}, \ldots, gbest_{id})\). Then, the updating formula of the particle swarm from time \(t\) to \(t+1\) is as follows:

\[
\begin{align*}
  v_{id}^{t+1} &= w \times v_{id}^t + c_1 \times r_1 \times (pbest_{id}^t - x_{id}^t) + c_2 \times r_2 \times (gbest_{id}^t - x_{id}^t) \\
  x_{id}^{t+1} &= x_{id}^t + v_{id}^{t+1}
\end{align*}
\]

(2)

where \(v_{id}^{t+1}\) is the velocity in the \(d\)th dimension of the \(i\)th particle in the \(t+1\) generation, \(v_{id}^t\) is the \(d\)th dimension velocity of the \(i\)th particle in the \(t\) generation, \(x_{id}^{t+1}\) is the position of the \(d\)th dimension of the \(i\)th particle in the \(t+1\) generation, \(x_{id}^t\) is the position of the \(d\)th dimension of the \(i\)th particle in the \(t\) generation. \(r_1\) and \(r_2\) are two independent random numbers in the range \((0,1)\). \(c_1\) and \(c_2\) are self-cognition factor and social cognition factor, respectively. \(w\) is inertia weight. \(pbest_{id}^t\) and \(gbest_{id}^t\) are the position of the \(d\)th dimension of the \(i\)th individual optimal particle and global optimal particle, respectively. The advantages of the PSO algorithm are simple and easy to implement, short iteration time, good self-organization, and robustness. The disadvantage is easy to fall into local optimum.

3.1.2 Basic GA algorithms

Genetic algorithm (GA) was first proposed by Professor Jholland [41] in 1975, which is derived from natural selection and genetic mechanism that simulate Darwin’s theory of biological evolution. The main feature of GA is the group exploration strategy and the information exchange between individuals in the group. Due to its strong adaptability, robustness, and global search capabilities, it is also widely used in the rolling fields. The optimization of the objective function is transformed into the adaptability of the population to the environment, the independent variable to be optimized is encoded and corresponds to each individual in the population, and then selection, crossover (as shown in Fig. 9), and mutation (as shown in Fig. 10) are performed genetic operations. The fitness function is used to evaluate each generation of individuals, and finally get the best individual for the environment, then the optimal solution to the
problem is acquired. The advantage of the GA is that it can reduce the risk of falling into the local optimal solution by processing multiple individuals simultaneously, but it also has disadvantages such as low efficiency and inaccurate results caused by non-standard coding.

3.1.3 Steps of the GA-PSO hybrid algorithm

Both GA and PSO algorithms start from randomly initialized population and use fitness function to conduct random search. The GA has low requirements for the optimization of its internal parameter, can find the global optimal solution well, and avoids falling into the local optimal solution. At the same time, it has high scalability and is convenient to combine with other algorithms. The PSO algorithm has a simple structure, requires fewer parameters, and has a fast convergence speed. It can complement each other with its own advantages. In view of this, GA-PSO hybrid algorithm is used to optimize the shape control actuators of the multi-stand for the 6-high TCMs to obtain the optimal rectangular section of electrical steel. So as to quickly find the global optimal solution, avoid falling into the local optimal solution, and ensure that the prediction model has a high accuracy. The flow of GA-PSO hybrid algorithm is shown in Fig. 11, and the optimization steps are as follows:

Step 1: Initialize the particle swarm, including the population size $N$, the position and speed of each particle, then substitute the position and speed of each particle into the objective function to calculate the corresponding fitness value.

Step 2: Evaluate the fitness function and record the optimal solution of the particle itself (individual extreme point $p_{best}$) and the current optimal solution of the entire population (global extreme point $g_{best}$).

Step 3: Update the position $x_i$ and velocity $v_i$ of the particles according to the above formula (2):

\[
x_{i+1} = x_i + v_{i+1}
\]

\[
v_{i+1} = \phi \cdot v_{i+1} + \omega \cdot \nabla f(x_i) - p_i
\]

Where $\phi$ and $\omega$ are the learning factors, $\nabla f(x_i)$ is the search direction of the objective function, $p_i$ is the individual extreme point.

Fig. 9 Crossover operation of the GA

Fig. 10 Mutation operation of the GA

Fig. 11 Flow chart of the GA-PSO hybrid algorithm
Step 4: Perform genetic algorithm crossover operation on the updated particles, as shown in Fig. 9. The crossover probability \( P_c \) is determined according to the adaptive genetic operator, as shown in Eq. (3), so that it can automatically change with the change of the fitness function.

\[
P_c = \begin{cases} 
\frac{P_{c1}(f_{\text{max}} - f^{'}) + P_{c0}f}{f_{\text{max}} - f_{\text{avg}}} & f_{\text{avg}} < f^{'}, \\
\frac{P_{c1}f_{\text{avg}} + P_{c0}f}{f_{\text{max}} - f_{\text{avg}}} & f_{\text{avg}} \geq f^{'}, \\
\end{cases}
\] (3)

where \( P_{c1} \) and \( P_{c0} \) are proper decimals in the interval of \((0,1)\). \( f_{\text{max}} \) is the maximum fitness value in the population; \( f_{\text{avg}} \) is the average fitness value of each generation. \( f' \) is the largest fitness value of the two individuals to be crossed. \( f \) is the fitness value of the individual to be mutated.

Step 5: The mutation operation of the genetic algorithm is carried out on the updated particles to enhance the random search ability and maintain the diversity of the population. The mutation probability \( P_m \) is determined according to the adaptive genetic operator, as shown in formula (4).

\[
P_m = \begin{cases} 
\frac{P_{m1}(f_{\text{max}} - f^{'}) + P_{m0}f}{f_{\text{max}} - f_{\text{avg}}} & f_{\text{avg}} < f^{'}, \\
\frac{P_{m1}f_{\text{avg}} + P_{m0}f}{f_{\text{max}} - f_{\text{avg}}} & f_{\text{avg}} \geq f^{'}, \\
\end{cases}
\] (4)

where \( P_{m1} \) and \( P_{m0} \) are proper decimals in the interval of \((0,1)\). The values of \( f_{\text{max}}, f_{\text{avg}}, f', \) and \( f \) are the same as above.

Step 6: Calculate the particle fitness values after the crossover and mutation of the genetic algorithm, and compare the individual and global extreme values with the previous generation of particles, and update the individual and global extreme values.

Step 7: If the convergence condition (preset convergence accuracy or maximum number of iterations) is not reached, return to step 2, otherwise, the optimization stops and the optimal results of the GA-PSO hybrid algorithm are output.

### 3.2 The control processes of the GA-PSO hybrid algorithm

#### 3.2.1 Parameter settings

When GA-PSO hybrid algorithm is used to optimize the shape control means, the parameters should be set reasonably to improve the applicability and accuracy of GA-PSO hybrid algorithm. The parameters of GA-PSO hybrid algorithm are shown in Table 3.

### 3.2.2 Establishment of multi-variable shape optimization objective

In general, the shape quality of the strip is mainly evaluated by the crown. Crown \( CR \) refers to the difference between the thickness \( h_c \) of the marking point in the middle of the strip and the average thickness of the marking point on both sides, as shown in Fig. 12. The formula is as follows:

\[
CR = h_e - \frac{h_{eo} + h_{ed}}{2}
\] (5)

where \( h_e \) is the thickness of the midpoint in the width direction of the strip, mm. \( h_{eo} \) and \( h_{ed} \) are the thickness of the marking point at 15 mm from the strip operating side and the transmission side of the edge, mm, respectively.

Influencing factors of strip shape are mainly incoming material factors and shape control actuators factors. After summarizing various influencing factors on exit shape, the equation of exit crown can be obtained as follows:

\[
C_{\text{exit}} = (1 - \eta) \left( \frac{P}{K_p} + K_w \cdot F_w + K_I \cdot F_I + K_S \cdot S + K_W \cdot C_W + K_I \cdot C_I + K_B \cdot C_B \right) + \eta \cdot \frac{h}{H} \cdot C_{\text{entrance}}
\] (6)

where \( P \) is the unit rolling force, kN. \( K_p \) is transverse stiffness difference, kN/mm. \( h \) is the strip thickness at the mill exit, mm. \( F_w \) is the WRB force, kN. \( F_I \) is the IRB force, kN. \( S \) is the IRS, mm. \( K_w, K_I, K_S \) are the influence coefficients of the WRB, the IRB, and the IRS, respectively. \( C_W, C_I, \) and \( C_B \) are the crown of work roll, intermediate roll, and backup roll, mm, respectively. \( K_W, K_I, \) and \( K_B \) are the

![Fig. 12 The diagram of strip crown](image-url)
influence coefficients of work roll crown, intermediate roll crown, and backup roll crown, mm, respectively. $C_{\text{entrance}}$ is the incoming crown of the strip, mm. $\eta$ is the shape genetic coefficient.

The main purpose of the shape control is to find the optimal shape control actuator, so as to ensure that the exit crown for the last stand to achieve the target crown. Therefore, the exit shape deviation is the minimum control objective:

$$\min S_1 = \sum_{i=1}^{n} \left( C_{\text{exit},i} - C_{\text{target}} \right) \tag{7}$$

where $C_{\text{exit},i}$ is the exit crown of the $i$th stand, mm. $C_{\text{target}}$ is the target crown for the strip, mm.

In the rolling process, due to the different thickness of the strip at each stand, the proportional crown is also different. Therefore, it is necessary to keep the same proportion of each stand to ensure the good shape quality of the finished strip. Stands 1~3 mainly controlled the crown of the strip, and stands 4~5 mainly control the flatness and crown of the strip. The optimal target is established according to the distribution of the crown of each stand:

$$\min S_2 = \sum_{i=1}^{n} \left( \frac{C_{\text{entrance},i}}{h_{\text{entrance},i}} - \frac{C_{\text{exit},i}}{h_{\text{exit},i}} \right) \tag{8}$$

where $C_{\text{entrance},i}$ is the entrance crown of the $i$th stand, mm. $h_{\text{entrance},i}$ is the inlet thickness of the $i$th stand, mm. $C_{\text{exit},i}$ is the exit crown of the $i$th stand, mm. $h_{\text{exit},i}$ is the exit thickness of the $i$th stand, mm.

Target of adjusting margin of the WRB, the IRB, and the IRS:

$$\min S_3 = \sum_{i=1}^{n-1} \sum_{j=1}^{n} \left[ \frac{F_{W,i}/F_{W,\text{max},i} - F_{W,j}/F_{W,\text{max},j}}{F_{M,i}/F_{M,\text{max},i}} \right] + \left[ \frac{F_{M,i}/F_{M,\text{max},i} - S_j/S_{\text{max},i}}{S_i/S_{\text{max},i}} \right] \tag{9}$$

where $F_{W,\text{max},i}$, $F_{M,\text{max},i}$, and $S_{\text{max},i}$ are the maximum adjustment range of the WRB, the IRB, and the IRS, respectively.

Objective of balance of adjustment allowance for the WRB, the IRB, and the IRS:

$$\min S_4 = \sum_{i=1}^{n} \left[ F_{W,i}/F_{W,\text{max},i} - F_{M,i}/F_{M,\text{max},i} - S_j/S_{\text{max},j} \right] \tag{10}$$

This optimization problem has the characteristics of multi-objective and multi-constraint. The weight coefficient method can make the target focus different, and the multi-objective shape optimization target is set as the combination of (7)~(10). Each objective function is multiplied by a weight coefficient, and the objective function of multi-stand and multi-variable shape optimization setting can be obtained:

$$\min S = \min (\lambda_1 S_1 + \lambda_2 S_2 + \lambda_3 S_3 + \lambda_4 S_4) \tag{11}$$

where $\lambda_1$, $\lambda_2$, $\lambda_3$, and $\lambda_4$ are the weight coefficients, $\lambda_1 = 0.5$, $\lambda_2 = 0.3$, $\lambda_3 = 0.1$, and $\lambda_4 = 0.1$.

In the actual production process, according to the characteristics of 6-high TCMs, the above objective function also has the constraint conditions shown in Eq. (11), which is the WRB, the IRB, and the IRS constraints.

$$\begin{align*}
-200kN &\leq F_{W,i} \leq 200kN \\
-200kN &\leq F_{M,i} \leq 200kN \\
-150mm &\leq S_j \leq 150mm
\end{align*} \tag{12}$$

### 3.2.3 Multi-variable shape optimization process

The steps of GA-PSO hybrid algorithm to optimize the multi-stand shape control means are as follows:

Step 1: Initialize the parameters, use finite element simulation, and cold rolling the mathematical model to calculate the rolling process parameters except for the shape control parameters.

Step 2: Call the MATLAB program of the GA-PSO hybrid algorithm, search for the particle that makes the objective function reach the minimum, and get a set of optimized values.

Step 3: If the convergence condition (preset convergence accuracy or maximum number of iterations) is not reached, return to step 2, otherwise the optimization stops and the optimal result of the GA-PSO hybrid algorithm is output.

### 4 Results and discussion

The rolling parameters of SG50W1300 with 1260 mm width are optimized. The GA-PSO hybrid algorithm is programmed and simulated in MATLAB R2021a to optimize the multi-stand and multi-variable shape control actuators. The iterative curves of optimization objectives of GA, PSO, and GA-PSO algorithms are shown in Fig. 13. It can be seen from Fig. 13 that the GA-PSO hybrid algorithm reaches the stable state after 57 generations of operation. Compared with GA and PSO algorithms, the GA-PSO hybrid algorithm has the advantages of high precision, rapid convergence, and better stability. It had better global and local optimization ability. After 50 to 60 generations of evolution, the evolutionary iteration curves of the WRB force, the IRB force, and the IRS for stands 1~5 optimized by GA-PSO hybrid algorithm tend to be stable, as shown in Fig. 14.
In order to further verify the effectiveness of the control strategy, 100 coils SG50W1300 rolling data of 1420-mm 6-high TCMs were selected. Among them, strip width is 1260 mm, the thickness of incoming material is 2.7 mm, and the exit thickness is 0.5 mm. The results of the control strategy were compared with the field rolling shape data, as shown in Table 4. In order to make a more intuitive comparison of the shape control quantity before and after optimization, the optimization results of the WRB force, the IRB force, the IRS, and exit crown of stands 1 ~ 5 are compared with the measured data, as shown in Fig. 15.

It can be seen from Fig. 15 that the control strategy of multi-stand and multi-variable shape control actuators, i.e., WRB, IRB, and IRS of stands 1 ~ 5 in 6-high TCMs can fully exploit the shape control ability under the condition of
considering multiple optimization objectives. It can reduce the fluctuation of the WRB force, the IRB force, and the IRS. As shown in Fig. 16, the control strategy can realize effective control for exit crown and significantly improve

| Stand | Optimization method       | The WRB force $F_w$/kN | The IRB force $F_m$/kN | The IRS $S$/mm | Exit crown $C_{15}/\mu$m |
|-------|---------------------------|------------------------|------------------------|----------------|--------------------------|
| S1    | Before optimization       | 36.53                  | 87.35                  | 66.81          | 15.87                    |
|       | GA-PSO optimization       | 60.56                  | 121.99                 | 50.39          | 13.72                    |
| S2    | Before optimization       | 22.95                  | 93.39                  | 74.64          | 13.64                    |
|       | GA-PSO optimization       | 72.82                  | 90.39                  | 55.59          | 10.93                    |
| S3    | Before optimization       | 39.08                  | 78.65                  | 74.62          | 11.62                    |
|       | GA-PSO optimization       | 50.14                  | 88.85                  | 55.85          | 9.82                     |
| S4    | Before optimization       | 63.27                  | 97.13                  | 74.69          | 10.69                    |
|       | GA-PSO optimization       | 45.47                  | 93.13                  | 55.13          | 8.24                     |
| S5    | Before optimization       | -76.74                 | 212.16                 | 74.77          | 9.87                     |
|       | GA-PSO optimization       | 30.55                  | 130.16                 | 55.16          | 7.47                     |

Fig. 15 Optimize the parameter of stands 1~5 before and after. a The work roll bending force. b The intermediate roll bending force. c The intermediate roll shifting
the accuracy of strip shape control. The exit crown of stands 1–5 is reduced by 13.54%, 20.08%, 15.48%, 22.92%, and 24.32% respectively by comparing with the actual field value. Moreover, the exit crown for stand 5 is less than 7 μm, achieving the high-precision shape control of electrical steel. Therefore, the control strategy based on GA-PSO hybrid algorithm is high efficiency and accuracy, through optimize the shape control actuators to achieve rectangular section control of electrical steel. It has a better control accuracy than the traditional shape setting model, which is beneficial to give full play to the shape control ability of the 6-high TCMs to ensure the ultra-high shape quality of electrical steel and other high-end plates.

5 Industrial application and effect analysis

In recent years, the large industrial 1420-mm 6-high UCM mills with 1.05 million tons of non-oriented electrical steel have been newly built in China. It lacks an effective the WRS system for stands 1–5. There are bottleneck problems for the transverse thickness profile control. In order to meet the quality requirements with the rectangular section control of electrical steel, the industrial tests were carried out in the UCM mills. According to the continuous testing feedback data in the site, compared with the UCM mills, the proportion of high precision exit crown C15 less than 7 μm of electrical steel increased from 38.58% (Japan’s UCM mills) to 53.18% (application EDW-N technology), and the control strategy combined with the developed EDW-N technology application increased to 67.74%, as shown in Fig. 17. The results show that the control strategy of multi-stand and multi-variable profile and flatness control actuators for stands 1–5 in 6-high TCMs based on GA-PSO hybrid algorithm can keep stable, excellent, and accurate shape quality of the strip. It can control the shape quality in a wide range of regulation, giving full play to the shape control ability of various control means of 6-high TCMs. The results show that the shape quality of electrical steel is improved significantly, which provides an innovative solution for the new generation of high-tech cold rolling mills.

6 Conclusion

1. The 3D FEM for roll stacks and strip of 6-high TCMs was built with the developed EDW-N technology, and the efficiency curves of the WRB, the IRB, and the IRS in the cold rolling process are obtained for transverse thickness profile control performance. The control effect of the WRB is significantly better than the IRB and the IRS. The shape efficiency curve for the WRB is parabolic, while the efficiency curves for the IRB and the IRS are a complex high-order curve.
2. Taking the optimal rectangular section of electrical steel as the control target, the control strategy of multi-stand and multi-variable profile and flatness control actuators, i.e., WRB, IRB, and IRS of stands 1–5 in 6-high TCMs, for “dead flat” transverse thickness profile of electrical steel sheet is proposed based on the GA-PSO hybrid algorithm. The results show that the GA-PSO algorithm has better global and local optimization ability, and the control strategy can fully exploit the shape control ability, as well as the exit crown of stands 1–5 is reduced by 13.54%, 20.08%, 15.48%, 22.92%, and 24.32% respectively by compared with the actual value.
3. The industrial application on the production gives remarkable results that the rate of the measured strip crown less than 7 μm increased from 38.58 to 67.74% for electrical steel in the 1420-mm 6-high TCMs. The control strategy has applied to the production success-
fully. It provides theoretical guidance and innovative path for break through the bottleneck problem of rectangular section control of electrical steel in 6-high TCMs without the work roll shifting.

Author contribution Chunning Song: investigation, theoretical analysis, validation, writing—original draft. Jianguo Cao: conceptualization, supervision, project administration. Leilei Wang: investigation, validation, writing—review and editing. Jing Xiao: investigation, validation, writing—review and editing. Qiuang Zhao: supervision, resources, validation.

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Availability of data and material The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval The authors claim that they are non-life science journals and there are no ethical issues.

Consent to participate The authors claim that they agree to participate.

Consent for publication The authors claim that they agree to publish.

Competing interests The authors declare no competing interests.

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