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Research Article

Structural Parameters Optimization of the Steel Bar Straightening Machine Based on the PSO Algorithm

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In the process of steel bar straightening processing, the straightening rollers are often damaged by fatigue due to uneven force, which causes frequent replacement of the straightening rollers. Therefore, the structural parameters optimization of the steel bar straightening machine is very important to improve the machining accuracy of the straightening machine and prolong the service life of straightening roller. In this paper, an optimization method based on the particle swarm optimization (PSO) algorithm was proposed and used to optimize the structural parameters of the steel bar straightening machine. First, the main parameters that affect the accuracy of the straightening machine were comprehensively analysed, and the optimization range of each parameter was determined. Second, in order to minimize the fluctuation of the contact stress, the objective function was established by fitting the roller spacing, roller diameter, roller number, and so on. Then, the PSO algorithm was used to find the optimal solution of structural parameters. Finally, the proposed structural optimization method was verified in practice and compared with the single variable algorithm. As a result, the straightness of the steel bar is increased by 2.88%, and the total straightening force is reduced by 16.25%, compared with the single variable algorithm. In conclusion, it was demonstrated that the proposed optimization method based on the PSO algorithm is better than the single variable algorithm in optimizing the structural parameters of the steel bar straightening machine.

1. Introduction

The steel bar straightening machine is a kind of engineering machinery commonly found on construction sites. It is a key equipment to change the straightness, surface quality, and material properties of steel bars. However, due to the high strength and large diameter of steel bars used in the modern construction industry, the traditional straightening machine cannot meet the requirements of the industry. In addition, the traditional straightening machine already has the dilemma of insufficient straightening force in the modern steel straightening industry. Some high-strength steel bars need to be straightened repeatedly to meet the requirements, which makes the efficiency of the straightening machine seriously reduced.

To solve the problem of the straightening machine, a large number of researchers have proposed the structure optimization plan of the straightening machine. Meanwhile, the straightening process is improved to meet the requirements of the practical application. Jiang et al. [1] specially designed a roller cleaning device on the straightening machine to extend the life of the straightening rollers and eliminate the impact of residues on the product quality. Although the installation of a quick-change roller system can reduce nonoperation time and improve work efficiency, it makes the structure of the straightening machine more complicated and increases the difficulty of the equipment maintenance. In order to increase the straightening thickness of the wedge-shaped plate, improve the straightening quality, and understand the relationship between the roller diameter, roller spacing of the straightening machine, and the straightening effect of the wedge-shaped plate, Sun et al. [2] proposed a wedge-shaped plate straightening method based on the matching roller system. However, whether the rollers with small diameter are added to the straightening process depending on the operation experience. Therefore, this method lacks theoretical basis. Zhang and Bai [3] used an orthogonal experiment to explore the influence of the three factors of roller diameter, roller spacing, and reduction on the straightening effect. However, the solutions obtained by the orthogonal experiment cannot be determined to be the optimal values. By strengthening the connection between the upper rollers and the movable crossbeam and changing the base of the lower roller into an integral structure, Wang et al. [4] improved the assembly accuracy and the disassembly efficiency of the supporting roller to increase the stiffness of the overall structure so as to improve the stability and the service life of the roller system. In order to improve the straightening quality of the steel bar, Yin [5] proposed a new multiobjective optimization model. By precisely adjusting the position of the straightening roller and reducing the reduction of the first adjustable roller, the residual stress of the steel bar is reduced. When the diameter of the straightening roller is small, it is difficult for straightening roller to meet the strength requirement. When the roller diameter and roller spacing are relatively large, the biting condition of the steel bar will be destroyed. Zhao and Wu [6] analyzed the biting condition of the straightening machine and solved the problem by setting a pinch roller at the entrance side. In order to increase the bending times, Zhou et al. [7] added a straightening roller in front of and behind the roller system of the straightening machine, thereby improving the straightening quality. This method has achieved good straightening effect, which is worth learning. Zhang [8] redesigned the parameters of the straightening machine. However, various types of parameters that need to be determined, and in many cases, which was estimated by experience, resulting in limited accuracy. Shinkin [9] calculated the optimal reduction of the steel blank by the working rollers of the straightening machine so that the sheet produced has the minimum residual stress and curvature. In the simulation of sheet straightening in multiroller machines, the curvature and bending torques of the steel sheet at contact points with the working rollers are first calculated and then the straightening forces are determined. In the straightening steel sheet, it is important to calculate the forces in the multiroller straightening machine. Maksimov and Shatalov [10] conducted a theoretical study on the alternate bending and straightening process of steel plate rollers. Through the analysis of experimental data, the reduction and straightening speed have a great influence on the bending moment and straightening force. These two factors must be considered in the design and operation.

To remove these issues, the present study proposes a novel optimization method for the structural parameters of the straightening machine. According to the small deformation and large deformation theory, the large diameter rollers are arranged in the front and the small diameter rollers are arranged in the rear. Then, the influence of each structural parameter on the straightening accuracy is explored, and the optimal value of each parameter is preliminarily calculated.

The traditional single variable algorithm was summarized from the practice of mass production and design, which lacks theoretical basis. Moreover, the structural parameters of straightening machine are coupled with each other, and the results obtained by the single variable algorithm are easy to fall into the local optimal solution. Therefore, it is necessary to design a new structural parameter optimization method. Based on the above issues, all parameters are studied as a whole in this paper. The links between the parameters are fully considered to achieve an overall optimum. Then, the PSO algorithm was selected in this work.

With the goal of minimizing contact stress fluctuations, PSO is used to optimize multiple structural parameters. In addition, a pair of large-diameter pinch rollers are added on the entrance side of the straightening machine to improve the biting condition. The results show that the structural parameters of the straightening machine obtained by the PSO algorithm make the straightening effect better than the traditional single variable algorithm.

The rest of this paper is organized as follows: Section 2 introduces the calculation process of some structural parameters and determines the value range. Section 3 introduces the PSO algorithm solving process. Section 4 describes the proposed model in detail. Especially the design of the objective function. Section 5 is the experiment, the theoretical values of the straightening force determined by the PSO algorithm was compared with the test values. Finally, Section 6 summarizes the full research.

2. Structural Parameter Calculation and Process Parameter Setting of the Straightening Machine

Through the analysis of the structure of the variable roller spacing straightening machine, it can be seen that the processing accuracy of the straightening machine is mainly affected by the roller number, roller diameter, and roller spacing (The steel bar type straightened in this paper is HRB400E with a diameter of 12 mm. And the initial curvature ratio is 5). The traditional single variable algorithm is used to calculate the optimal value of each parameter separately.

2.1. Calculation of the Roller Number. The roller number is one of the most basic parameters of the steel bar straightening machine, and reasonable roller number has an important influence on the effect of steel bar straightening. The straightening principle are as follows: The reverse curvature ratio formed by the straightening roller offsets the initial curvature ratio C_o of the steel bar and the spring-back curvature ratio C_f so that the residual curvature ratio C_c of the steel bar is close to 0 so as to achieve the purpose of straightening [11]. In this paper, the large deformation theory is used in the front roller group, and the small deformation theory is used in the rear roller group. The steps for calculating the roller number in the small deformation theory are as follows: first, the relationship between the initial curvature ratio C_o of the steel bar and the reverse curvature ratio C_w is calculated. Then, the residual curvature ratio C_c in the process of steel bar straightening is calculated from the reverse curvature ratio C_w as shown in the following formula:

$$
\begin{aligned}
C_w &= \frac{4}{\pi}\left\{\frac{1}{3}\left[2.5-\frac{1}{(C_0+C_w)^2}\right]\times\left[1-\frac{1}{(C_0+C_w)^2}\right]^{(1/2)}+\frac{(C_0+C_w)}{2}\arcsin\left(\frac{1}{(C_w+C_0)}\right)\right\},\\
C_c &= C_w - C_f.
\end{aligned}
\tag{1}
$$

According to this method, the number of straightening rollers can be calculated quantitatively [12]. Figure 1 is the schematic diagram of the straightening process of the variable roller spacing straightening machine.

After 10 times of straightening, the residual curvature ratio of the steel bar is 0.0184, and the residual deflection is 0.744 mm/m less than 1 mm/m, which meets the requirements of the straightening accuracy. However, in the actual production and operation, the reduction of each straightening roller will be affected by factors such as the reduction device and the size of roller. In order to reduce the error between the actual processing and theoretical calculation, 1–2 additional rollers are often added.

Table 1 shows the residual curvature ratio of the steel bars at each roller during the straightening process. As shown in the table, when the number of straightening rollers is 11, 12, and 13, which can all meet the processing requirements, but the straightening accuracy of the 13-roller straightening machine is higher. Its residual deflection of the steel bar after straightening is 0.642 mm/m.

2.2. Calculation of the Roller Diameter

2.2.1. Calculation of the Roller Diameter Range. The main function of the straightening roller is to make the piece obtain the required reverse curvature for straightening. In addition, the biting conditions of the piece at the entrance and the contact strength of the straightening roller must also be considered. The reverse curvature required for straightening is much greater than the elastic limit curvature A_t. The increasing multiple of A_w is related to the raw material and cross-section shape of the piece. The reverse curvature ratio C_w is equal to the compressive reverse curvature A_w divided by the elastic limit curvature A_t. The reciprocal of A_w is the radius of the straightening roller. The radius of the straightening roller is shown in the following formula:

$$
\begin{aligned}
R &= \frac{1}{A_w}\\
&= \frac{1}{C_w A_t}\\
&= \frac{EH}{2\sigma_t C_w},
\end{aligned}
\tag{2}
$$

where E is the elastic modulus, MPa; H is the material diameter, mm; and σ_t is the elastic limit, MPa.

The diameter of the straightening roller can be formulated by the following equation:

$$
\begin{aligned}
D &= 2R\\
&= \frac{EH}{\sigma_t C_w}.
\end{aligned}
\tag{3}
$$

In order to obtain the optimal roller diameter value, the roller diameter per unit thickness $d_H = D/H$ is taken as the measurement standard. The hierarchy of the roller diameter selection is shown in Figure 2. It can be seen from the figure that the green part is the ideal area. Thus, the selection of the optimal value of the roller diameter should consider the following aspects:

(1) *Workpiece Material.* The higher the strength of the straightening workpiece, the larger the value of C_w. However, the actual investigation found that when the thickness of the workpiece $H < 0.5$ mm, the value of the roller diameter D will be very small. Too small roller diameter does not have enough strength to resist the impact but also brings difficulties to the structure arrangement.

(2) The contact strength of the straightening roller. When the height of the piece is larger than the width, the pressure may cause the plastic deformation and even fatigue erosion on the surface of the piece. Therefore, the straightening model can be simplified as a cylinder and a plane, and the contact stress can be calculated to limit the roller diameter. The formula is as follows:

$$
\sigma_{\max} = 0.418\sqrt{\frac{FE}{BR}},
\tag{4}
$$

where F is the maximum straightening force, $F = (8\overline{M}_{\max}M_t/p)$, $P = 1.15D$, $M_t = (BH^2\sigma_t/6)$, $F_y = N_y + P_y = N\cos\alpha + \mu P\sin\alpha$; B is the contact width between the workpiece and the roller surface;

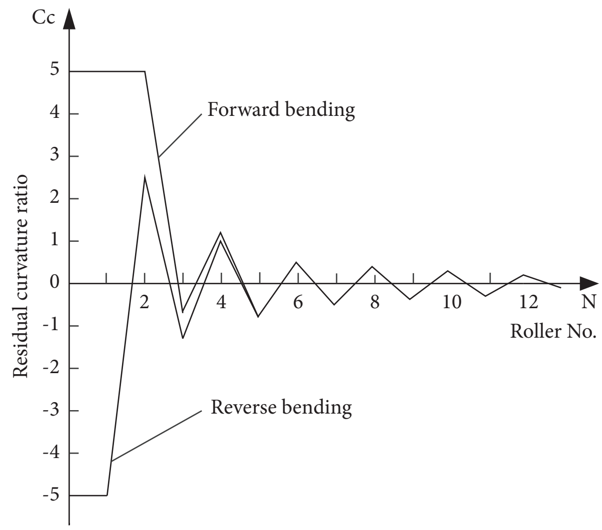


Figure 1: Straightening process of the variable roller spacing straightening machine.

Table 1: Residual curvature ratio of the steel bar at each roller.

Roller no.	1	2	3	4	5	6	7	8	9	10	11	12	13
C_w	0	4	4	3.5	3	1.601	1.386	1.29	1.23	1.203	1.179	1.158	1.142
$C_{c\,\min}$	−5	2.313	2.313	1.831	1.343	0	0	0	0	0	0	0	0
$C_{c\,\max}$	5	5	2.328	1.832	1.343	0.214	0.093	0.050	0.030	0.025	0.018	0.014	0.011

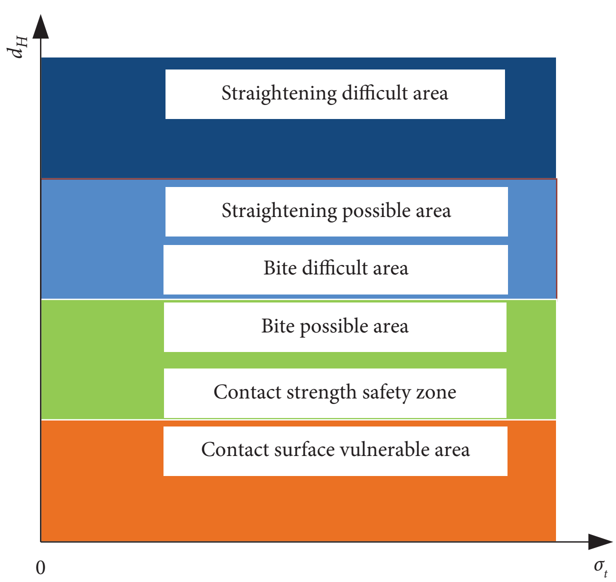


Figure 2: The hierarchy of roller diameter selection.

E is the elastic modulus, $E = 206$ GPa; and R is the radius of the roller, $D = 2R$.

Finally, $d_H = (D_{\min}/H) = (176/\sqrt{\sigma_t})$.

(3) *Biting Condition*. The biting model of the steel bar is shown in Figure 3. The condition that the steel bar enters the straightening roller smoothly is as follows:

$$F_x + P_x > N_x, \tag{5}$$

where F_x is the propulsive force of the lower roller, P_x is the horizontal component of the friction force, and N_x is the resistance in the horizontal direction.

According to the force balance, the vertical component is as follows:

$$\begin{aligned} F_y &= N_y + P_y \\ &= N\cos\alpha + \mu P\sin\alpha, \end{aligned} \tag{6}$$

where N_y is the resistance in the vertical direction, P_y is the vertical component of the friction force, α is the bite angle, and μ is the friction coefficient of the contact surface.

It can be seen from Figure 3, $F_x = \mu F_y$, $P = \mu$N, $P_x = \mu N\cos\alpha$, $N_x = N\sin\alpha$. In summary, the biting conditions are as follows:

$$\mu F_y + \mu N\cos\alpha > N\sin\alpha. \tag{7}$$

Substituting equation (6) into equation (7), we get the following formula:

$$2\mu\cos\alpha + \left(\mu^2 - 1\right)\sin\alpha > 0, \tag{8}$$

where μ is the sliding friction coefficient between the straightening roller surface and the surface of the steel bar, $\mu = 0.2$.

It can be seen from the geometric relationship of the model in Figure 2, $\cos\alpha = (R - e)/R$; $\sin\alpha = (2Re - e2)\ 1/2/R$; e is the reduction of the upper straightening rollers, $e = 3.3485\sigma_t R2/EH$, mm.

Substituting the above data into equation (8), we get

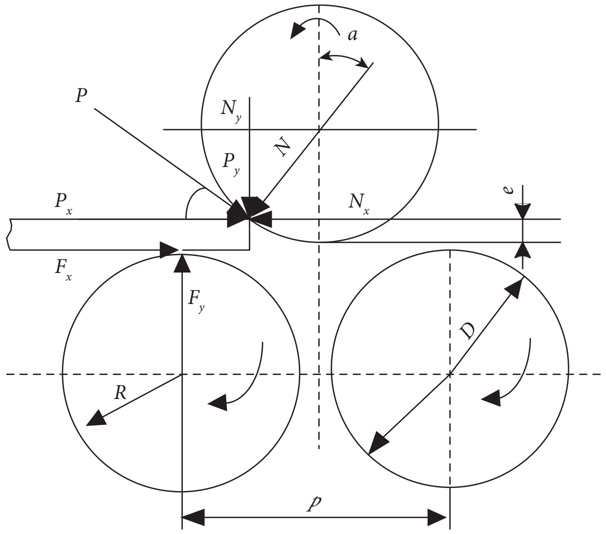


Figure 3: The steel bar biting model.

$$R^2 - 13.52Re + 6.76e^2 > 0. \quad (9)$$

Solving the equation yields the following results:

$$\begin{aligned} R_{\max} &= 0.0225\frac{EH}{\sigma_t}, \\ D_{\max} &= 2R_{\max} \\ &= 0.045\frac{EH}{\sigma_t}, \\ d_H &= \frac{D_{\max}}{H} \\ &= \frac{9270}{\sigma_t}. \end{aligned} \quad (10)$$

In summary, through the theoretical calculation, it is finally calculated that the roller diameter of the straightening roller ranges from 112 to 185 mm.

2.2.2. Preliminary Selection of the Roller Diameter. Through the transient analysis module of the ANSYS workbench, the optimal solution of the roll diameter is obtained. The simulation model before straightening is shown in Figure 4. Because the main purpose of the simulation is to demonstrate the straightening process and analyze the straightening results, according to the contact relationship between the straightening roller and the steel bar, the model is simplified to the straightening roller and the steel bar, and the straightening roller is regarded as centrally symmetrical [13]. In order to reduce the number of grids in the model and speed up the calculation time, the solid roller can be simplified into a hollow roller. Moreover, in order to be more consistent with the actual situation, the average grid density in the overall model should be less than 0.4.

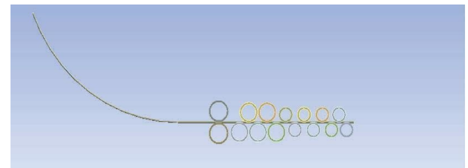


Figure 4: The model before straightening.

Choosing 15 points in the bending section of the steel bar, the average residual deflection of the rear roller group with different diameters are shown in Table 2.

It can be seen from Table 2 that when the diameter of the rear roller group is 125 mm, the straightening effect is the best. The average residual deflection of the steel bar is 0.643 mm/m, which is less than the deflection value required by the straightening standard and consistent with the theoretical calculation. The straightening effect is shown in Figure 5. The figure shows the straightness of the steel bar after the straightening process and the contact stress change of the steel bar passing through the traction roller and front roller group during the straightening process.

2.3. Calculation of the Roller Spacing

2.3.1. Calculation of the Roller Spacing Range. During the process of the steel bar straightening, the reverse curvature must be greater than or equal to the sum of the maximum initial curvature A_0 and the spring-back curvature A_f. The formula is $A_0' = A_0 + A_f$. Among them, A_0' is the curvature change of the straightening roller and steel bar during the straightening process [14].

According to $A_0' = (1/2)(D + d)$, we can get the result from the following equation:

$$\begin{aligned} D_{\max} &= 2\left(A_0 + A_f\right) - d \\ &= \frac{2EI}{M_s} - d, \end{aligned} \quad (11)$$

where I is the inertia moment of steel bar, d is the diameter of the steel bar, and M_s is the plastic moment of the steel bar.

In conclusion, the maximum roller spacing between straightening rollers is as follows:

$$t_{\max} = \frac{2EI}{M_s} - d. \quad (12)$$

In addition, biting conditions should be taken into account. The limit formula of the maximum roller spacing is as follows:

$$t_{\max} = \frac{\beta Ed}{19.2\sigma_s}, \quad (13)$$

where β is the ratio of the straightening roller diameter to the roller spacing.

Moreover, the minimum roller spacing of straightening machine should also be considered. The straightening roller and the steel bar will be elastically deformed due to the extrusion pressure, forming a local surface contact during

Table 2: The average residual deflection of the rear roller group.

Diameter of rear roller group (mm)	Average residual deflection (mm/m)
115	0.7479
120	0.694
125	0.643
130	0.665

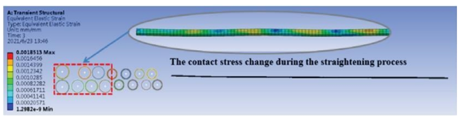


Figure 5: The straightening effect of the rear roller group with a diameter of 125 mm.

the straightening process. If the straightening roller spacing is too small, it may cause excessive local pressure on the surface of the steel bar, which will not only increase the wear of the roller surface but also bring scratches or even indentations to the surface of the steel bar.

Let $P_{\max}$ be the maximum contact stress experienced by the straightening roller. The formula for the maximum contact stress is as follows:

$$P_{\max} = \sqrt{\frac{F_{\max}}{\pi d R\left(\left(1-\mu_1^2/E_1\right)+\left(1-\mu_2^2/E_2\right)\right)}} \leq [P], \tag{14}$$

where μ_1 and μ_2 are the friction coefficients between the steel bar and the roller, $\mu_1 = \mu_2 = 0.2$; d is the diameter of the steel bar, mm; $[P]$ is the maximum allowable stress, $[P] = 2\sigma_s$; and $F_{\max}$ is the maximum straightening force of the straightening roller, N.

The maximum straightening force formula is as follows:

$$F_{\max} = \frac{8}{t}\left[\left(3-k_{o\min}^2\right)\frac{1-\eta}{2}+\frac{\eta}{k_{o\min}}\right]W\sigma_s, \tag{15}$$

where $k_{0\max}$ is the minimum elasticity and thickness coefficient, $k_{0\max} = 0.3$; W is the elastic section coefficient of the steel bar, mm^3; and η is the enhancement coefficient of the steel bar, $\eta = 0.1$.

In summary, the minimum value of the roller spacing t is expressed as follows:

$$t_{\min} \geq 7.15d. \tag{16}$$

Finally, through theoretical calculations, the range of roller spacing is 86–178 mm.

2.3.2. Preliminary Selection of the Roller Spacing. The extrusion pressure of the straightening roller can be calculated by the straightening moment. The straightening model is simplified as a beam which is subjected to a number of concentrated loads, and the straightening force of the straightening roller on the steel bar is equivalent to the concentrated load. The extrusion pressure of the steel bar at each straightening roller can be calculated by the bending moment value. The value of the bending moment is related to the initial curvature and reverse curvature, but it is difficult to calculate accurately [15]. Therefore, under the premise, error is allowed, the bending moment of the steel bar at each roller can be simplified as follows:

(1) The pure plastic deformation of the steel bar occurs at the second, third, fourth, and fifth straightening rollers, which is $M_2 = M_3 = M_4 = M_5 = M_s$.
(2) The steel bar at the 10th, 11th, and 12th straightening rollers can be equivalently regarded as the pure elastic deformation, which is $M_{10} = M_{11} = M_{12} = M_w$.
(3) Except for the first and the 13th rollers, the bending moment of the steel bar at the rest of the straightening rollers is half of the sum of M_s and M_w, which is $M_6 = M_7 = M_8 = M_9 = M_a = 1/2\ (M_s + M_w)$.

Among them, the plastic bending moment formula on the steel bar is $M_s = \sigma_s S$; the elastic bending moment formula is $M_w = \sigma_s W$; the plastic section coefficient is $S = d^3/6$; and the elastic section coefficient is $W = (\pi d^3/32)$.

The straightening force of each straightening roller to the steel bar is shown in the following formula:

$$\begin{aligned}
F_1 &= \frac{2}{t}M_2,\\
F_2 &= \frac{2}{t}\left(2M_2+M_3\right),\\
F_3 &= \frac{2}{t}\left(M_2+2M_3+M_4\right),\\
&\vdots\\
F_i &= \frac{2}{t}\left(M_{i-1}+2M_i+M_{i+1}\right),\\
&\vdots\\
F_{n-2} &= \frac{2}{t}\left(M_{n-3}+2M_{n-2}+M_{n-1}\right),\\
F_{n-1} &= \frac{2}{t}\left(2M_{n-1}+M_{n-2}\right),\\
F_n &= \frac{2}{t}M_{n-1},
\end{aligned} \tag{17}$$

where F_i ($i = 1,2, \ldots, n$) is the extrusion pressure at each straightening roller, N; M_i is the bending moment of the steel bar at each straightening roller, kN·m.

According to the configuration principle of the roller spacing mentioned above, the roller spacing at the entrance is relatively small. The roller spacing in the middle part is relatively large, and the arrangement of the roller spacing at the exit is symmetrical with that at the entrance. This structure can avoid the collision and ensure the steel bar bite in smoothly. Therefore, the corresponding equality and inequality constraints are established.

Firstly, in order to minimize the total straightening force, the equality constraints are established. It is as follows:

$$\begin{aligned} h_1 &= x_1 - x_2 = 0,\\ h_2 &= x_3 - x_4 = 0,\\ h_3 &= x_5 - x_6 = 0,\\ h_4 &= x_7 - x_8 = 0,\\ h_5 &= x_9 - x_{10} = 0,\\ h_6 &= x_{11} - x_{12} = 0, \end{aligned} \tag{18}$$

where x_i ($i = 1,2, \ldots, 12$) is the roller spacing, h_i ($i = 1,2, \ldots, 12$) is the equation number.

$$\begin{aligned} g_1(\vec{x}) &= x_3 - x_1 \geq 0,\\ g_2(\vec{x}) &= x_1 - x_{11} \geq 0,\\ g_3(\vec{x}) &= x_3 - x_{11} \geq 0,\\ g_4(\vec{x}) &= x_1 - 43 \geq 0,\\ g_5(\vec{x}) &= 89 - x_1 \geq 0,\\ g_6(\vec{x}) &= x_3 - 43 \geq 0,\\ g_7(\vec{x}) &= 89 - x_3 \geq 0,\\ g_8(\vec{x}) &= x_5 - 43 \geq 0,\\ g_9(\vec{x}) &= 89 - x_5 \geq 0,\\ g_{10}(\vec{x}) &= x_7 - 43 \geq 0,\\ g_{11}(\vec{x}) &= 89 - x_7 \geq 0,\\ g_{12}(\vec{x}) &= x_9 - 43 \geq 0,\\ g_{13}(\vec{x}) &= 89 - x_9 \geq 0,\\ g_{14}(\vec{x}) &= x_{11} - 43 \geq 0,\\ g_{15}(\vec{x}) &= 89 - x_{11} \geq 0,\\ g_{16}(\vec{x}) &= 1010 - x_1 - x_2 - x_3 - x_4 - x_5\\ &\quad - x_6 - x_7 - x_8 - x_9 - x_{10} - x_{11} - x_{12} \geq 0, \end{aligned} \tag{19}$$

where x_i ($i = 1,2, \ldots, 12$) is the roller spacing number and g_i ($i = 1,2, \ldots, 12$) is the equation number.

Then, the inequality constraints are established to limit the range of the roller spacing, as shown in equation (19). The fminco function in MATLAB is used to optimize the roller spacing of the variable roller spacing straightening machine. The final roller spacing is shown in Table 3.

Table 3: Roller spacing optimization results.

No.	1	2	3	4	5	6	7	8	9	10	11	12
Roller spacing (mm)	87	87	89	89	89	89	89	89	80	80	67	67

3. PSO Algorithm Solving Process

The PSO algorithm originated from the study of predation behavior of birds. A random search algorithm based on the group cooperation developed by simulating the migration and gathering behavior of birds in the process of predation [16]. According to the information exchange and sharing between individuals in the population, the flight direction of the individuals in the population is constantly updated and toward the optimization goal. Since the particles in the PSO algorithm only contain speed and position information, it is necessary to gradually move towards the global optimal solution by continuously updating the speed and position of the particles themselves [17]. Jian proposed a new PSO-ARS optimization algorithm. This algorithm extends the local search strategy to the PSO algorithm. In PSO-ARS, some of the best particles are selected for the region search at the end of each generation. This strategy can give particles more chances to find better solutions and speed up the convergence. In addition, each particle has its own region radius, which is adaptively controlled in the evolution process to make the region more suitable for searching [18]. Li proposed a new parallel PSO algorithm. The algorithm is based on LPSO of ring topology, and each particle consists its own neighborhood and its left and right particles. In this way, the particle is guided by the best information of the neighborhood of the three particles (including itself). When all the neighbors of a particle (including itself) have completed their evolutionary operations, the particle can obtain enough guidance information, move to the next generation in advance, and accelerate the evolution process [19]. Xia proposed a triple archive PSO algorithm (TAPSO), which divides the particles in the population into three types, and then selects appropriate samples and designs effective learning models for the particles [20]. Wang proposed a dynamic swarm learning distributed PSO algorithm for the large-scale optimization. The whole population is divided into multiple populations. These populations co-evolve through the master-slave multipopulation distributed model to form a distributed PSO (DPSO) and enhance the diversity of algorithms. In addition, DPSO adopts the dynamic group learning strategy to balance diversity and convergence [21].

Because PSO variants have achieved satisfactory results in various fields, it is worth trying to solve the problem of overall parameter optimization of the steel bar straightener by using them in the future work. The structural parameter optimization of the steel bar straightening machine using PSO algorithm is a typical multiobjective optimization problem [22]. In order to understand the flow of the PSO algorithm more intuitively, the specific execution steps of PSO in the context of the optimized problem is shown in Figure 6.

The specific solution process is as follows.

There are N particles in the D-dimensional space. The position of the particle i is as follows:

$$x_i = \left(x_i^{(0)}, x_i^{(1)}, x_i^{(2)}, x_i^{(3)} \cdots x_i^{(n)}\right). \tag{20}$$

The speed of the particle i is as follows:

$$v_i = \left(v_i^{(0)}, v_i^{(1)}, v_i^{(2)}, v_i^{(3)} \cdots v_i^{(n)}\right). \tag{21}$$

The best individual position that the particle i has experienced is as follows:

$$p\mathrm{best}_i = \left(p_{i1}, p_{i2}, \ldots p_{in}, \right). \tag{22}$$

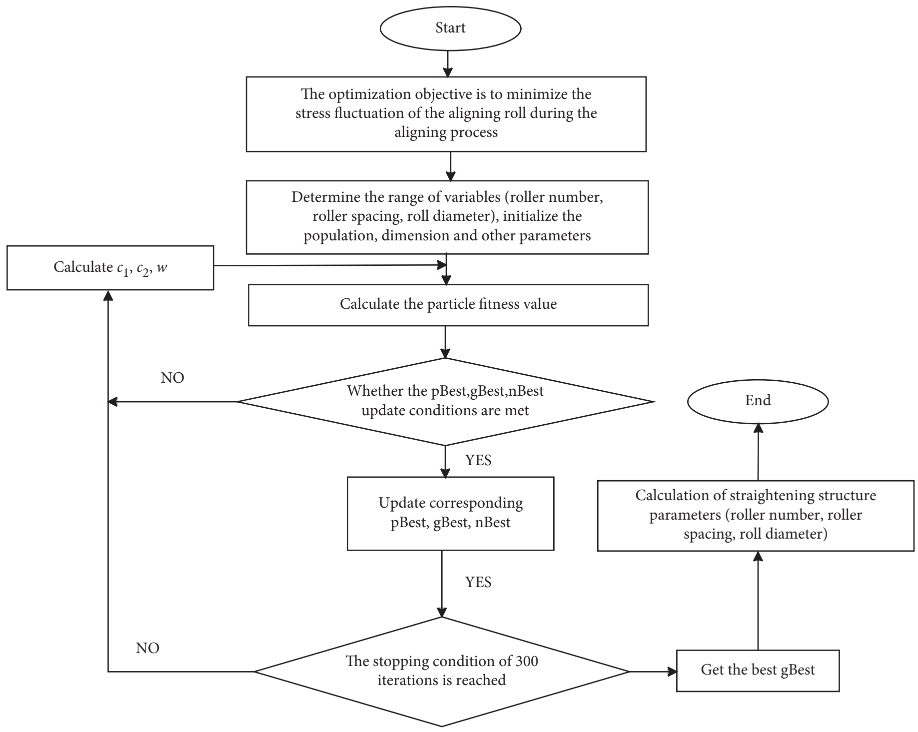


Figure 6: The flow chart of the PSO algorithm.

The best positions experienced in the particle swarm are as follows:

$$gbest = (g_1, g_2, \ldots g_n). \tag{23}$$

Among them, the position change range in the $d(1 \leq d \leq D)$ dimension is limited to $[x_{\min}, x_{\max}]$, and the speed change range is limited to $[v_{\min}, v_{\max}]$ (in the iteration, if the value of x exceeds the maximum and minimum values, the value of x and v become the boundary value).

The d-dimensional speed update formula of the particle i is as follows:

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 \left(pbest_i - x^t\right) + c_2 r_2 \left(gbest - x^t\right). \tag{24}$$

The d-dimensional position update formula of the particle i is as follows:

$$x_i^{t+1} = x_i^t + v_i^{t+1}, \tag{25}$$

where v_i^t is the speed of the particle at time t and x_i^t is the position of the particle at time t; c and r are the acceleration constant and the maximum step length of the adjustment learning, respectively; r_1 and r_2 are random numbers between (0, 1); the inertia weight coefficient ω is used to adjust the particles in the population to maintain the current speed influence weight. According to the actual experience, the value of ω is generally selected from 0.12 to 0.90.

4. Structural Parameters Optimization Based on the PSO Algorithm

The traditional single variable algorithm is summarized from the practice of mass production and design, which lacks theoretical basis. Moreover, the structural parameters of the straightening machine are coupled with each other, and the results obtained by the single variable algorithm are easy to fall into local optimal solution. Therefore, it is necessary to design a new structural parameter optimization method. Based on the above issues, all parameters are studied as a whole in this paper. The links between the parameters are fully considered to achieve an overall optimum.

4.1. Objective Function Design. In the optimization design, it is a key step to determine the objective function correctly. The determination of the objective function is directly related to the optimization results and the amount of calculation. Through the analysis of the production process and structure of the steel bar straightening machine, it can be seen that the great difference of the contact stress between the rollers is the main reason for the uneven wear of the rollers and the influence on the machining accuracy. The processing of the steel bar straightening machine involves many structural parameters, among which the roller number, roller diameter, and roller spacing are the main parameters that affect the straightening machine. Therefore, the contact stress of each straightening roller is adjusted by the structural parameters such as roller number, roller diameter, and roller spacing so that the contact stress of each straightening roller is close to each other.

According to the structural characteristics of the variable roller spacing steel bar straightening machine, the roller diameter and roller spacing of the front and rear roller groups of the straightening machine are different, so the front and rear roller groups should be optimized separately.

In order to design an ideal objective function, the following aspects should be considered for the steel bar straightening machine:

(1) Reduce the fluctuation of the contact stress between the straightening rollers
(2) Improve the processing accuracy of the straightening machine
(3) Reduce the total straightening force of the straightening machine
(4) Minimize the energy consumption and equipment wear

Based on the above considerations, the following objective function is designed:

$$\text{FITNESS} = \sqrt{\sum_{i=1}^{11}\left[\sigma_i^2 - \left(\frac{\sum_{i=1}^{11}\sigma_i}{11}\right)^2\right]^2}, \tag{26}$$

where σ is the contact stress, Pa.

Among them, the formula for calculating the contact stress σ is as follows:

$$\sigma = 0.418\sqrt{\frac{F_i E}{BR_i}}, \tag{27}$$

where E is the elastic modulus of the steel bar, $E = 206000$ MPa. B is the contact width between the steel bar and the straightening roller, mm. R_i is the straightening roller radius, mm. F_i is the straightening force at each roller.

4.2. Optimization Range of Structural Parameters. According to the analysis of the structure of the variable roller spacing straightening machine, the contact stress fluctuation of the straightening roller is mainly affected by the roller number, roller spacing, and roller diameter. The calculation process of the roller number has been analyzed and explained in detail in the previous section. For HRB400E type steel bar with initial curvature of 5 and the diameter of 12 mm, when the roller number is 11, it has reached the industry standard of the straightening accuracy. However, in order to reduce the influence of the reduction error on the straightening accuracy, the method of increasing the number of rollers (1–2 straightening rollers) is often used. Among them, the number of the front roller group is 5, and the number of straightening rollers in the rear roller group is obtained by subtracting the number of straightening rollers in the front roller group from the total number of straightening rollers.

Furthermore, for the roller diameter of the straightening roller, the value range is determined by the following conditions: (1) The strength of the straightening piece. (2) The contact strength of the straightening roller. (3) The biting condition of the straightening piece on the entrance side of the straightening machine. The calculation process of the roller diameter has been analyzed and explained in detail in the previous section. It is calculated that the roller diameter range of the straightening roller is 112–185 mm. In order to compare with the straightening effect obtained by the single variable algorithm, the roller diameter range of the front roller group is now set to 160–185 mm, and the roller diameter range of the rear roller group is set to 112–130 mm.

Moreover, the range of the straightening roller spacing is affected by the following three points: (1) The effect of the straightening accuracy. (2) The biting conditions of the piece on the entrance side of the straightening system. (3) The surface of the straightening roller. In addition, the empirical coefficient also affects the range of roller spacing. When the straightening machine adopts the method of collective downward pressing of the upper roller, $a = 1.1$. When the straightening machine adopts the independent downward pressing method of the upper roller, $a = 1.2$. Because the latter is chosen in this paper, the roller spacing range on the same side is set to 43–108 mm. However, since the minimum radius of the roller diameter of the front roller set is 80 mm, the range of the roller spacing of the front roller group is finally 80–108 mm. In summary, the optimization range of the structural parameters of the variable roller spacing steel bar straightening machine is finally shown in Table 4.

4.3. Structural Parameter Optimization Results and Analysis. According to the optimization objective function and the structural parameter optimization range of the variable roller spacing straightening machine, the parameters setting of the PSO algorithm are completed. The fitness value of the different roller number was calculated by MATLAB software. The iterative process of the objective function is shown in Figure 7.

It can be seen that for 11-roller straightening machine, the objective function starts to converge after about 120 iterations, and its best fitness value is $8.8914e-6$. For 12-roller straightening machine, the objective function starts to converge after about 95 iterations, and its best fitness value is $8.1712e-7$. For 13-roller straightening machine, the objective function begins to converge after about 80 iterations, and its best fitness value is $2.5987e-7$. From the results of all the cases, when the roller number of the straightening machine is 13, the results are better than the other two results. In summary, the number of straightening rollers is set to 13 optimally.

Figure 8 shows the comparison before and after the optimization of the straightening force of the second, fourth, tenth, and twelfth rollers. Compared with the straightening force before optimization, it can be seen that the fluctuation of the straightening force is more stable, and the fluctuation range does not change much, which is in line with the optimization goal. The total straightening force obtained by the single variable algorithm is about $49773N$, and the total straightening force optimized by the PSO algorithm is about $41686N$, which is a relative decrease of 16.25%. Furthermore, the fluctuation of the straightening force of the rollers is shown in Figure 9. It can be seen that the fluctuation range of the straightening force is changed from −4.86%, 5.93% to −4.19%, 4.2%, and the maximum variance is reduced from 102.81 to 58.124 after optimization.

Table 4: The optimization range of the structure parameter of the variable roller spacing straightening machine.

Roller spacing (mm)	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	
Upper limit	108	108	108	108	108	89	89	89	89	89	89	89	
Lower limit	80	80	80	80	80	56	56	56	56	56	56	56	
Roller diameter (mm)	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}
Upper limit	185	185	185	185	185	130	130	130	130	130	130	130	130
Lower limit	160	160	160	160	160	112	112	112	112	112	112	112	112

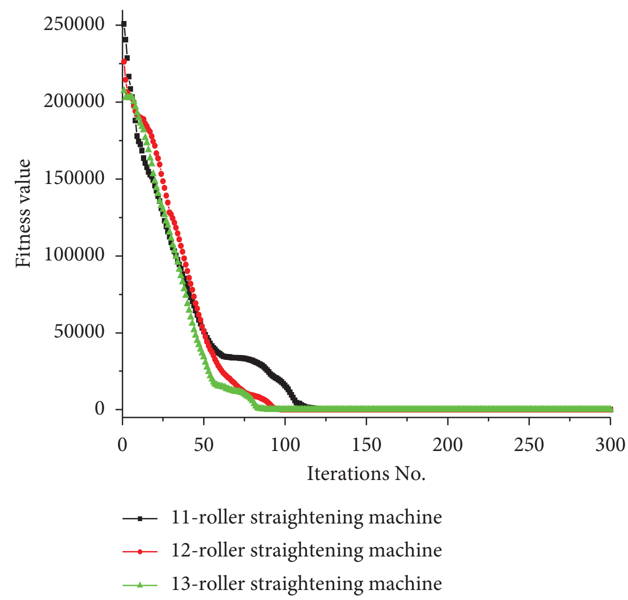
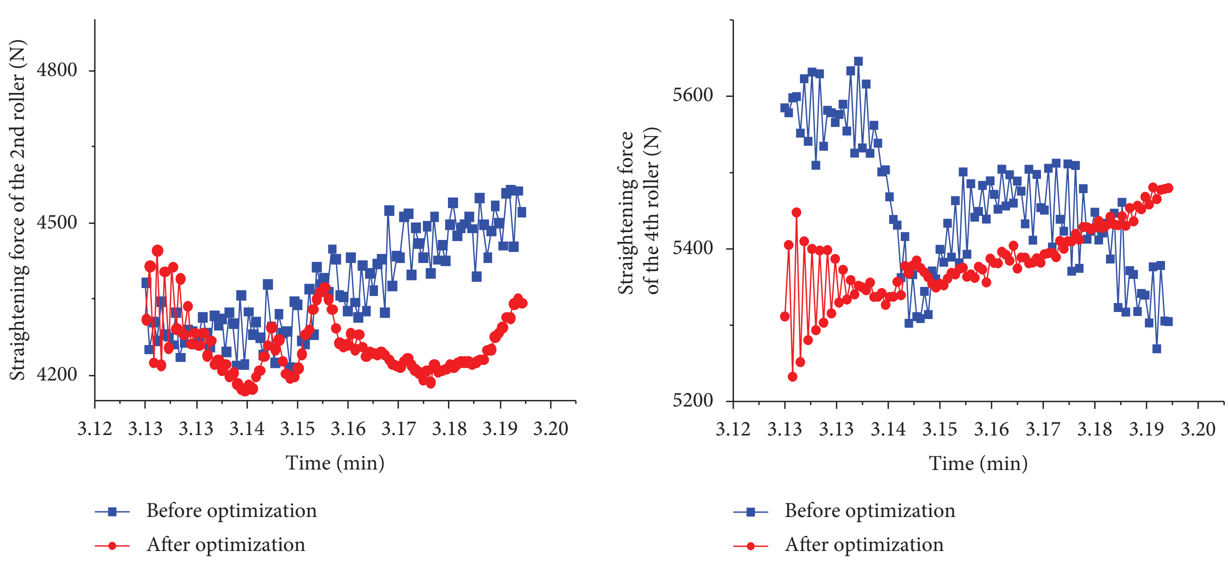


Figure 7: The iterative process of the objective function.



(a) (b)

Figure 8: Continued.

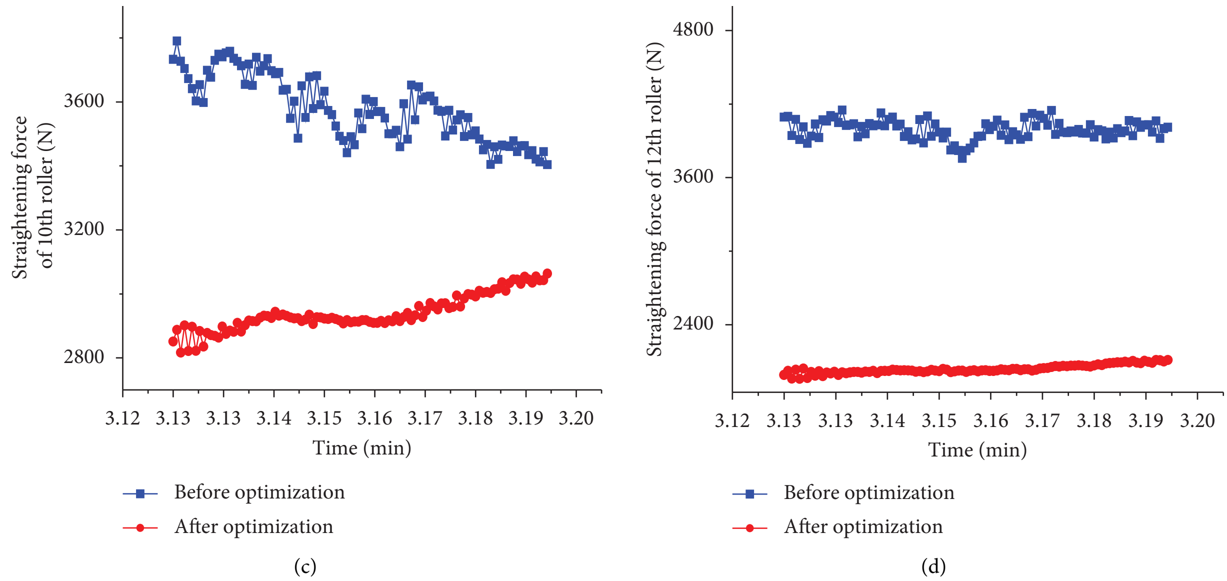


Figure 8: The comparison of the straightening force of each roller before and after the optimization. (a) Straightening force change of the second roller. (b) Straightening force change of the fourth roller. (c) Straightening force change of the tenth roller. (d) Straightening force change of the twelfth roller.

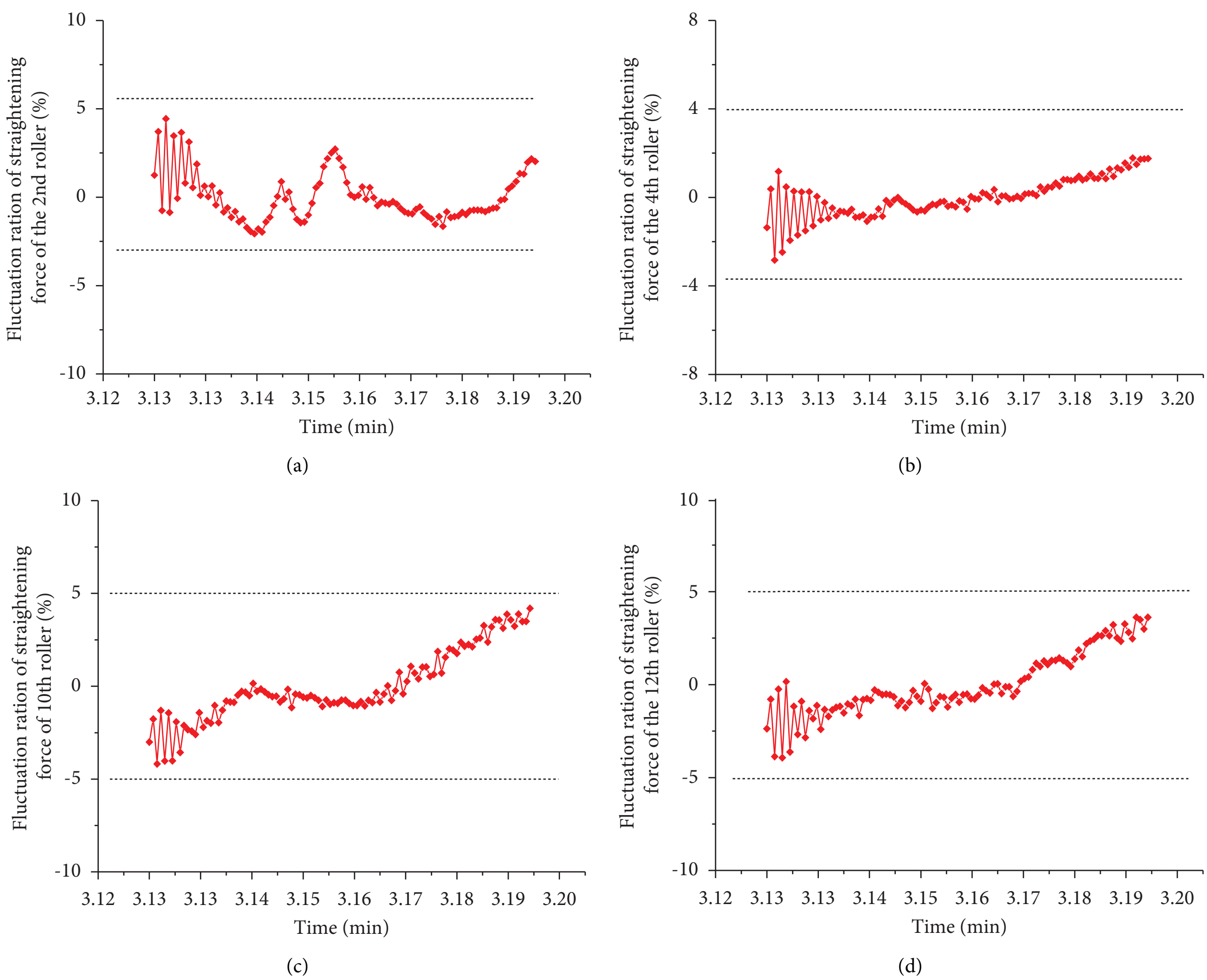


Figure 9: The fluctuation ration of the straightening force of each roller. (a) The fluctuation ration of the second roller. (b) The fluctuation ration of the fourth roller. (c) The fluctuation ration of the tenth roller. (d) The fluctuation ration of the twelfth roller.

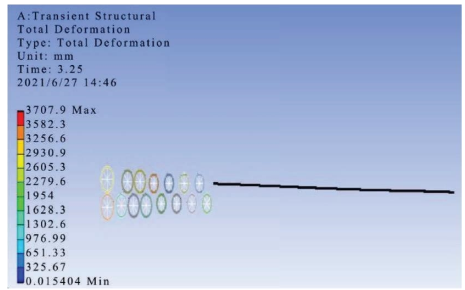


FIGURE 10: Straightening effect drawing.

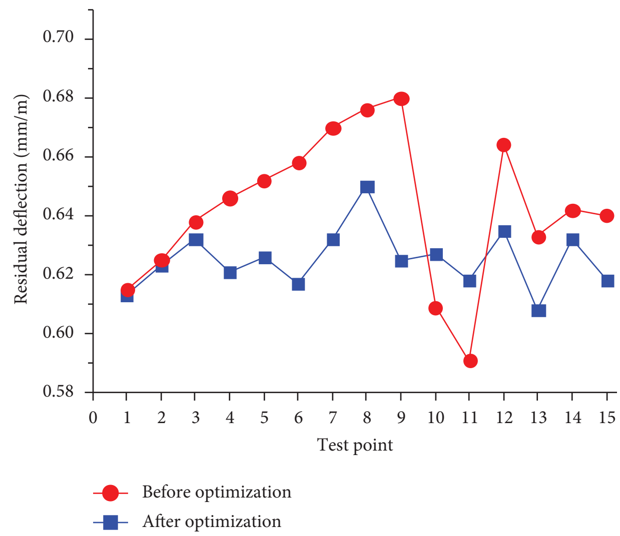


FIGURE 11: 15 points residual deflection before and after the optimization.

TABLE 5: The optimization results of the structure parameters of the variable roller spacing straightening machine.

Roller spacing (mm)	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	
Value	87	87	88	88	108	108	108	108	108	108	107	107	
Roller diameter (mm)	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}	D_{12}	D_{13}
Value	160	160	160	160	160	130	130	130	130	130	130	130	130

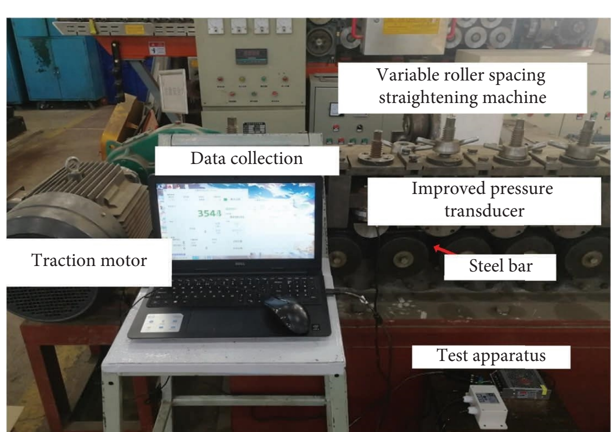


FIGURE 12: The steel bar straightening machine module.

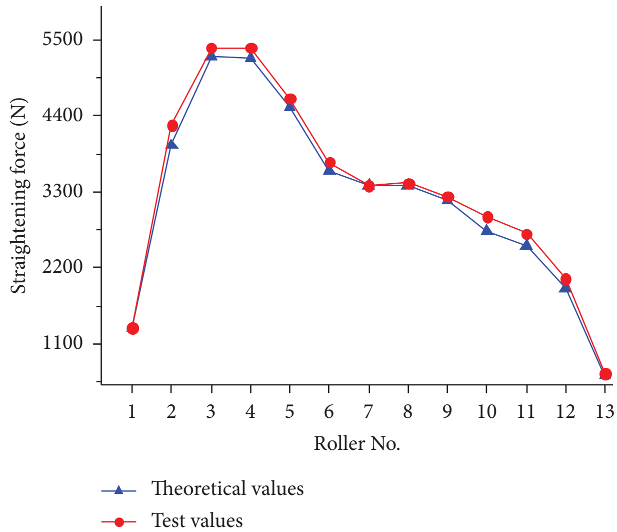


Figure 13: The comparison of the test values and theoretical values of the straightening force.

The straightening effect optimized by the particle swarm algorithm is shown in Figure 10. We randomly select 15 points on the surface of the steel bar and check the deformation of each point, whose values can be used as the residual deflection. The residual deflection of 15 points on the steel bar is shown in Figure 11. Compared with the single variable algorithm, the average residual deflection of the steel bar optimized by the PSO algorithm decreased from 0.643 mm/m to 0.625 mm/m, which was a relative decrease of 2.88%. It is proved that using the PSO algorithm to optimize the structural parameters of the straightening machine is better for reducing the fluctuation of the straightening force and improving the straightening accuracy. The structural parameters of the variable roller spacing straightening machine optimized by the PSO algorithm are shown in Table 5.

5. Experiment

In order to verify the straightening effect of the straightening machine after PSO algorithm optimization, a prototype was used to measure the straightening force at each straightening roller. This experiment was completed in the straightening machine module workshop of a certain factory, as shown in Figure 12. The test prototype is composed of a traction motor, traction part, straightening part, and improved indenter. The line speed of the straightening machine was set to 1.2 m/s. A data acquisition device was used to collect the straightening force of each straightening roller in real time.

In order to obtain the straightening force of each roller after the optimization by the PSO algorithm, the experiment changed the straightening rollers to semicircular indenters. A pressure weighing sensor was equipped under the indenter to achieve static measurement. Firstly, the indenter position was adjusted by the calculated reduction amount. Secondly, the data were collected through the pressure sensor. Finally, the data were transformed by the 485 conversion module and then sent back to the computer to obtain the values of the straightening force of each straightening roller under different reductions.

The test values and theoretical values are shown in Figure 13. It can be seen that the theoretical values of the straightening force determined by the PSO algorithm was near the test values, and the error is within the allowable range. Results showed that the proposed method could improve the machining accuracy of the steel bar straightening machine effectively.

6. Conclusion

In this paper, the PSO algorithm was used to optimize the structural parameters of the steel bar straightening machine. First, the main parameters that affect the accuracy of the straightening machine were comprehensively analyzed, and the optimization range of each parameter was determined. Second, in order to minimize the fluctuation of the contact stress, the objective function was established by fitting the roller spacing, roller diameter, roller number, and so on. Then, the structure parameters of the straightening machine are optimized by using the PSO algorithm in MATLAB software. Finally, the proposed structural optimization method was verified in practice and compared with the single variable algorithm. The main findings of the present study are as follows:

(1) Wear and deformation are the main failure forms of the straightening roller. In this paper, the elastic-plastic straightening theory based on the large and small deformations is used to design the structure of the variable roller spacing straightening machine, which balances the relationship between the strength and stiffness of the straightening roller.

(2) Under the same conditions, it is not right that the smaller the roller diameter of the rear roller group, the better the straightening effect of steel bars taking the residual deflection as an indicator.

(3) The PSO algorithm can effectively avoid falling into the local optimal solution. Compared with the single variable algorithm, the PSO algorithm performs better in finding the optimal solution. It was found that the straightness of the steel bar is increased by 2.88%, and the total straightening force is reduced by 16.25%, compared with the single variable algorithm. The fluctuation of the straightening force is greatly reduced.

(4) In this paper, the PSO algorithm is successfully applied to the research on the structural parameter optimization of the straightening machine, which provides a good theoretical analysis method for the nonlinear constrained optimization problem.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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