



## Research on the Design of Dual Intelligent Control System for Positive and Side Alignment of Machine Tool Guide Roller Straightening Technology

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**SUMMARY:** *This article aims to design a dual intelligent control system for straightening and side straightening of precision machine tool guides, in order to improve straightening accuracy and efficiency, and meet the high-precision requirements of precision machine tool guides. Firstly, based on the theory of elastic-plastic deformation, experimental research, and finite element simulation, the bending and rebound characteristics of precision machine tool guide rails are studied, and a mathematical analytical model of the relationship between guide rail rebound curvature and residual curvature is established. Secondly, using a deep neural network (DNN) algorithm model, a prediction model for the rebound amount of precision machine tool guide rails is established based on experimental data, and the relationship between loading stroke and rebound deflection is studied. Combined with the geometric motion model of precision machine tool guide rails, the influence of material characteristic parameters on rebound amount is studied. Finally, a precision machine tool guide rail straightening and side straightening automatic control system based on DNN algorithm was designed, and the feasibility of the model was verified through experiments. The experimental results show that when the lateral bending deformation of the precision machine tool guide rail is small, the straightening stroke calculated by the theoretical model is in good agreement with the finite element simulation and experimental results, with a maximum relative error within 10%. However, when the lateral bending deformation of the guide rail is large, there is a certain gap between the theoretical results and the finite element simulation and experimental results, and the relative error increases. The precision machine tool guide rail straightening and side straightening automatic control system based on DNN algorithm proposed in this article has good straightening effect when the lateral bending deformation of the guide rail is small.*

**KEYWORDS:** *machine tool guide rail; Roller straightening; Positive and lateral correction; Intelligent control; Deep neural network; Finite element simulation*

## 1 Introduction

The dual intelligent control system design of positive and side straightening for machine tool guide rail roller straightening technology is very valuable research. As is well known, precision

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machine tool guide rails are widely used in many high-precision industrial scenarios such as automation equipment. For a series of irregular cross-section precision machine tool guide rails, precision machine tool guide rails serve as a rolling guide, with steel balls rolling infinitely between the slider and the guide rail. The load platform can easily move linearly along the guide rail with high precision [1, 2]. Due to the low friction coefficient of rolling friction, the occurrence of ineffective motion is relatively reduced, making it easy to achieve micrometer level feed and positioning. Due to minimal wear during operation, the precision of precision machine tool guides must strictly meet the requirements when leaving the factory, and ensuring the flatness of precision machine tool guides is particularly important in precision machine tools and other equipment. However, a large number of precision machine tool guide rails often undergo bending or twisting deformation due to external forces, temperature changes, and internal force fluctuations during rolling, forging, extrusion, transportation, cooling, and various processing processes. Especially after heat treatment, in order to obtain high-precision machine tool guide rail products, they must be straightened and straightened to meet their flatness requirements. In addition, after a period of use, if the guide rails cannot meet the requirements due to bending deformation, they need to be repaired using straightening and straightening processes to extend their service life and achieve significant economic benefits [3].

Straightening technology is one of the important processes in the production of various metal strip profiles (bars) such as plates, wires, pipes, rods, and strips. Straightening "is a plastic processing method used to make bent sheets, profiles, pipes, and other workpieces into a straight state. It is often used in the production and repair of parts. In practical needs, according to the needs of the industry and processing objects, and due to the different types of materials, the required straightening methods are also different. Usually, straightening methods are mainly divided into [4]: pressure straightening method, parallel roller straightening method, inclined roller straightening method, hub straightening method, translational straightening method, stretching straightening method, bending straightening method, and other special straightening methods. The automatic straightening equipment developed based on these technologies includes: pressure straightening machine, roller straightening machine, stretching straightening machine, bending straightening machine, etc. According to whether it is heated or not, straightening can be divided into hot straightening and cold straightening. Generally, cold straightening technology is used, and the most commonly used cold straightening method is pressure straightening. Pressure straightening is a method of straightening bent parts by applying external static loads to cause reverse deformation [5]. It has the characteristics of high straightening force, high precision controllability, good flexibility, easy implementation, and applicability to complex parts. It can be widely used in the straightening process of large pipes, rods, asymmetric section profiles, guide rails, irregular surface long axis parts, and special steel. The process of pressure straightening is to support the two ends of the workpiece, and apply pressure through reverse straightening and side straightening in the middle of the workpiece bending, causing the workpiece to undergo reverse deformation. After removing the pressure, the workpiece undergoes some permanent plastic deformation and some elastic rebound. If the elastic recovery is exactly equal to the reverse deformation, the workpiece is straightened. Therefore, pressure straightening is also known as three-point straightening and side straightening [6]. With the development of the machinery industry, the production batches of various small and medium-sized strip parts are becoming larger and more diverse, and manual straightening is no longer sufficient to meet the production needs of machine tool parts. Therefore, automatic straightening technology has emerged. Automatic straightening technology is an advanced manufacturing technology that uses automatic straightening equipment to straighten various metal strip shaped parts such as shafts, pipes, and rods. It is an

important process in mechanical processing to ensure product quality and is widely used in mechanical manufacturing industries such as automobiles, machine tool equipment, engineering machinery, and military machinery.

With the development of automatic cold straightening technology, current research on pressure straightening technology mainly includes two aspects [7]: theoretical research on pressure straightening process and research and development of pressure straightening equipment; The precise control of straightening equipment requires the support of precise straightening process theory, therefore, conducting research on precision straightening process theory has become a key technology to achieve the numerical control, automation, and flexibility of straightening equipment. At present, most of the theoretical research on automatic straightening machines is limited to shaft parts, and there is relatively little research on parts with other cross-sectional shapes; Most of the theoretical models established in the research of straightening process are not precise due to the simplification of material stress models, heat treatment, geometry and other factors, and there are advantages and disadvantages in several methods for calculating important process parameters, but they have not been well considered in conjunction with the applicability of automatic straightening machines. Therefore, this study will focus on how to establish a more precise straightening mathematical model for irregular cross-section bars such as precision machine tool guides, and use deep learning algorithm models to accurately predict and calculate the straightening stroke, improve the practicality of theoretical models in automatic straightening machines, and enhance the work efficiency of automatic straightening machines.

## 2 Related research

For a long time, the implementation of pressure straightening technology has been mostly carried out by workers based on experience and estimation of straightening stroke, repeated measurement and trial calibration. This approach is not only inefficient and labor-intensive, but also difficult to ensure accuracy, and the working performance of the workpiece is also affected. The pressure straightening equipment used in the early days was either a manual screw press, a universal press, or a straightening machine modified from a press. With the development of technology and the needs of production, a specialized pressure straightening machine has been designed with the characteristics of small stroke and adjustable pivot position for straightening process. However, when using these devices, it is still necessary to estimate the straightening stroke based on experience, with a high proportion of manual labor, low efficiency, and difficulty in ensuring straightening accuracy [8].

With the development of automatic straightening technology, automatic straightening equipment can effectively improve product quality [9]. Developed countries attach great importance to the research of this technology and invest a large amount of manpower and material resources to carry out research work on this technology. Since the 1970s and 1980s, a few developed countries such as Italy, Germany, Japan, and the United States have successively developed fully automatic precision straightening machines with their own characteristics, such as the automatic straightening machines developed by Italy's GALDABINI company, Germany's MAE company, the United States' EITEL company, and Japan's Donghe Precision Machinery Co., Ltd; Due to the addition of detection devices, automatic feeding and retrieval devices, and computer control systems, the straightening efficiency and accuracy of the fully automatic straightening machine have been significantly improved, mainly manifested in automation, intelligence, high measurement accuracy, and fast production pace. All of these indicate that current research on campus technology is relatively complete in some developed countries, but due to technical confidentiality, there is limited information on campus

technology. The following are brief characteristics of the straightening processes of several straightening equipment abroad [10-12]:

The main features of the automatic straightening equipment straightening process of MAE Company in Germany are: 1) providing multiple sets of pressure points and support points, and the combination of pressure points and support points forms a three-point bending mechanical loading mode; 2) After each straightening is completed, the residual runout is detected in real-time online to determine and calculate whether to continue the straightening process. The calculation method for the straightening trip is a recursive algorithm, which needs to be gradually adjusted using certain optimization ideas; 3) The straightening process decision-making procedure adopts four different straightening strategies in sequence according to the different rough and fine machining processes; 4) The straightening action and straightening detection process can be coordinated and divided into four modes to improve efficiency. The idea of optimizing the straightening stroke proposed in the straightening process of this equipment is not found in other equipment straightening processes. But its calibration process is fixed, and the setting of more complex experience parameters still requires manual input, which requires high quality of workers.

The main characteristics of the automatic straightening equipment calibration process of EITEL Company in the United States are: 1) The adjustment and setting of straightening parameters are key factors in controlling the straightening process of the equipment. By adjusting the straightening parameters, the processing level during calibration can be improved. The adjustment of straightening parameters is carried out around each pressure point, and a fixed combination of pivot points is equipped for each pressure point. 2) Equipped with advanced crack detection devices, it can effectively control the phenomenon of workpiece fracture caused by excessive straightening stroke during straightening; 3) Provide 3 pressure points and 5 support points, but the control method is poor. A simple closed-loop feedback structure composed of detection sensors is used for a single straightening cycle; The outstanding advantage of this device is that it considers the idea that cracks are the cause of workpiece fracture, and can detect cracks in the straightening process in a timely manner and adjust the straightening stroke; However, all parameter settings need to be completed by experienced technicians and do not have intelligence.

The main characteristics of the straightening process of Japan Seiki Corporation's straightening machine are as follows: 1) The straightening object is targeted at shaft parts. The control system stores the deformation law of the shaft and parameters such as rebound after straightening into a database based on the different materials, diameters, and heat treatment processes of the shaft, and establishes an empirical database; 2) The maximum deformation detected by the system is compared with the empirical deformation of relevant parameters in the database, and the reasonable head stroke is determined based on the empirical data in the database, aiming to reduce the number of straightening times and obtain qualified products; The outstanding advantage of this device is its speed and convenience, but the determination of its straightening stroke relies entirely on interpolation comparison with empirical data in the database. It uses empirical data to judge the real-time monitoring situation and does not constitute a complete mathematical model of the straightening process, which has certain limitations.

Based on the analysis of the straightening process theory and control system of the three typical automatic straightening machines mentioned above, each has its own advantages and disadvantages, and they are all aimed at bar materials with regular cross-sectional shapes such as shafts and tubular parts. The corresponding control system and straightening strategy have not yet emerged, and there is no comprehensive and intelligent straightening decision process control system. Therefore, further research and exploration are needed to achieve true precision

and full automation. Current studies have shown that the development of automatic precision straightening equipment worldwide is showing the following trends: 1) complete series and complete variety specifications; 2) High travel accuracy, complete detection and display methods; 3) Developing towards numerical control, flexibility, and automation; 4) The scope of straightening technology is constantly expanding.

In recent years, China has also made progress in the research and production of precision and fully automatic straightening equipment [13]. For example, Hefei Forging Machine Tool Co., Ltd. and Hefei University of Technology have collaborated to develop the advanced YH40-25 fully automatic precision straightening hydraulic press; This equipment is a new and earliest domestically produced automatic straightening device that integrates electromechanical, hydraulic, detection, and computer functions. It has been appraised and reached the advanced level abroad, and can replace imports. Changchun Experimental Machinery Research Institute has also collaborated with Japanese companies to develop and produce the ASC series of automatic straightening machines, and independently developed the ASCI series. The straightening machine has an intelligent analysis and measurement system, programmable motor, electrical, mechanical, hydraulic, and air compression control technology. However, various devices still have problems such as a single processing object (mainly shaft parts) and the inability to integrate the straightening theoretical model well into the control system. To further expand the straightening range, ensure and improve the straightening accuracy in automatic straightening machines, and make the precise straightening model and accurate prediction of straightening stroke the current research focus.

### **3 Geometric model of precision machine tool guide rail motion**

As an important component of the linear feed module of machine tools, precision machine tool guide rails are composed of bed body, rolling guide rails, sliders, worktable and other components. For a single guide rail, double sliders are usually used to install and connect with the worktable. The schematic diagram of the machine tool guide rail is shown in Figure 1. The precision machine tool guide rail plays a guiding role on the moving parts of the machine tool, and its accuracy directly affects the accuracy of the relative motion between the moving parts of the machine tool, ultimately affecting the machining performance of the machine tool [14]. During the assembly process of the guide rail, it is necessary to repeatedly adjust and evaluate the connection positioning and fixation between the guide rail and the bed body. In the actual assembly process, the straightness of a single guide rail is usually measured and adjusted first, and used as the benchmark for subsequent accuracy indicators such as parallelism. Therefore, the straightness of the guide rail is an important indicator of machine tool accuracy and the main basis for machine tool assembly accuracy.



Figure 1: Schematic diagram of machine tool guide rail

According to the principles of motion geometry, there is a specific motion geometry relationship between the three elements of measuring the straightness of precision machine tool guide rails. For the general error motion of a ruler (worktable), there is a 6-degree-of-freedom error motion (three translations and three rotations), which can be measured using six displacement sensors [15]. The measured precision machine tool guide rail level moves with a spatial six degree of freedom error motion relative to the guide rail on the worktable. To investigate this error motion, a motion coordinate system  $\{O_m; i_m, j_m, k_m\}$  and a fixed coordinate system  $\{O_f; i_f, j_f, k_f\}$  are established on the level rail and guide rail (frame) respectively. For the convenience of subsequent calculations, the axes of sensors C1, C2, and C3 are parallel to the  $j_f$  axis of the fixed coordinate system, the axes of sensors C4 and C5 are parallel to the  $k_f$  axis of the fixed coordinate system, and the axis of sensor C6 is parallel to the  $i_f$  axis of the fixed coordinate system. To describe the position of the dynamic coordinate system on the ruler, the intersection points of the three planes of the ruler, vertex  $r_{0m} = (l, w, h)^T$ , is selected as the marker point to describe the position of the origin of the dynamic coordinate system in the ruler. The directions of the three axes of the dynamic coordinate system are perpendicular to the three planes of the ruler; According to the discussion in Chapter 2, the relationship between the moving coordinate system and the fixed coordinate system is as follows:

$$\begin{bmatrix} i_m & j_m & k_m & R_{Omf} \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} [M_{mf}] & R_{Omf} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_f & j_f & k_f & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where,  $R_{Om_f} = [x_{Om_f}, y_{Om_f}, z_{Om_f}]^T$  is the coordinate of the origin  $Om$  in a fixed coordinate system, representing the three degrees of freedom translation of the precision machine tool guide rail ruler;  $[M_{mf}(\alpha, \beta, \gamma)]$  is the rotation matrix of the moving coordinate system relative to the fixed coordinate system. To facilitate comparison with laser interferometer measurements, this rotation matrix is given in RPY angle form, and its expansion formula is:

$$[M_{mf}] = \begin{bmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \beta & 0 & \sin \beta \\ 0 & 1 & 0 \\ -\sin \beta & 0 & \cos \beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & -\sin \gamma \\ 0 & \sin \gamma & \cos \gamma \end{bmatrix} \quad (2)$$

The displacement vector  $R_{Om_f}$  and rotation matrix  $[M_{mf}(\alpha, \beta, \gamma)]$  at the origin of the dynamic coordinate system can fully describe the motion law of a rigid body in a fixed coordinate system. When the input parameters of the displacement vector and rotation matrix are discrete values, equation (1) describes the quasi-static displacement and discrete trajectory properties of the rigid body, corresponding to the measured motion of the three elements of precision machine tool guide rails.

For different measurement methods, the geometric elements of the measured precision machine tool guide rail correspond to points, lines, surfaces, and other geometric features on the measured object [16]. For the straightedge method measurement, the measured geometric element is the surface of the straightedge, which has a much higher geometric accuracy than the precision machine tool guide rail accuracy. It can be regarded as an ideal plane in the measurement, and its vector equation in the motion coordinate system is expressed as:

$$\Sigma_{pla} : (r_{Sm}(u, v) - r_{0m}) \cdot n_m = 0 \quad (3)$$

where,  $r_{0m} = (l, w, h)^T$  is a fixed point (intersection of three planes) on the measured plane,  $u$  and  $v$  are the parameters of the measured plane, and  $n_m$  is the unit normal vector of the measured plane.

Vector equations can be used to describe the geometric elements on the measured object in both moving and fixed coordinate systems. The choice of coordinate system depends on the coordinate system of the measured object. If the measured geometric elements are points, lines, or surfaces (including planes and surfaces), it depends on the measurement method. Under this measurement method, vector equation (3) corresponds to the measured object among the three elements.

According to the principle of sensor measurement, the sensor measurement vector is decomposed into the measurement reference quantity and measurement element loss of the sensor to determine the motion geometry significance of the sensor measurement data [17]. The positions and unit measurement directions of the six linear displacement sensors fixed on the rack are represented by the measurement reference vector  $R_{PC_j}$  and the measurement element vector  $L_{C_j}$ , respectively.  $\lambda_{C_j}$  is the measurement value of each sensor, and the subscript corresponds to the sensor number. The measurement values of each sensor actually reflect the position change of the intersection point between the surface of the ruler and the sensor reference line in the sensor measurement direction. The sensor measurement reference vector and the measurement element vector jointly describe the measurement data among the three elements of measurement.

Based on the motion geometry relationship that must be satisfied by the measured motion, measured geometric elements, and measurement data during the measurement process, a

motion geometry model can be established between the three measurement elements, namely the closed-loop vector basic equation for precision machine tool guide rail accuracy measurement:

$$\begin{cases} R_{PC_j} + \lambda_{C_j} L_{C_j} = R_{Omf} + [M_{mf}] r_{Sm123}; & j = 1, 2, 3 \\ R_{PC_j} + \lambda_{C_j} L_{C_j} = R_{Omf} + [M_{mf}] r_{Sm45}; & j = 4, 5 \\ R_{PC_j} + \lambda_{C_j} L_{C_j} = R_{Omf} + [M_{mf}] r_{Sm6}; & j = 6 \end{cases} \quad (4)$$

Equation (4) establishes the relationship between the three elements of precision machine tool guide rail measurement motion, measured geometric object, and measurement data based on the principles of motion geometry. The solution of the closed-loop vector basic equation can be divided into the following three situations [18, 19]: (1) Given the linear motion parameters of the precision machine tool guide rail and the measured geometric object equation, solve the theoretical measurement value of the sensor, compare the theoretical measurement value with the actual measurement value of the sensor to correct the sensor parameters, that is, the calibration of the sensor. (2) Given the linear motion parameters of precision machine tool guide rails and sensor measurement data, solving the equations of the measured geometric elements can obtain the surface shape and pose of the measured geometric object, that is, measuring the geometric error and installation error of the specimen. (3) Given the equations of the measured geometric object and the sensor measurement data, solving the linear motion parameters of the precision machine tool guide rail can obtain the six degree of freedom error motion parameters of the slider (worktable), namely the error motion measurement.

## 4 Prediction of guide rail straightening stroke based on DNN algorithm

### 4.1 Process description of precision machine tool guide rail straightening

After the precision machine tool guide rail undergoes deep neural network detection, if the measured straightness value is not qualified and the travel parameters are predicted, it enters the straightening process. This chapter will provide a detailed explanation of the straightening process. Due to the fact that the length of precision machine tool guide rails is generally five meters, and the maximum distance between the two support points in the straightening structure is over one meter, it is necessary to segment and straighten the precision machine tool guide rails according to the curvature of the curve. The so-called segmented straightening is to straighten the precision machine tool guide rail in sequence by dividing it into several pressure points, and the straightening process of each pressure point is similar to [20]. After all the pressure points have been straightened, the precision machine tool guide rail should be retested. If it fails, the straightening process should be restarted until the straightness of the precision machine tool guide rail passes the test. The process of straightening precision machine tool guide rails is shown in Figure 2.

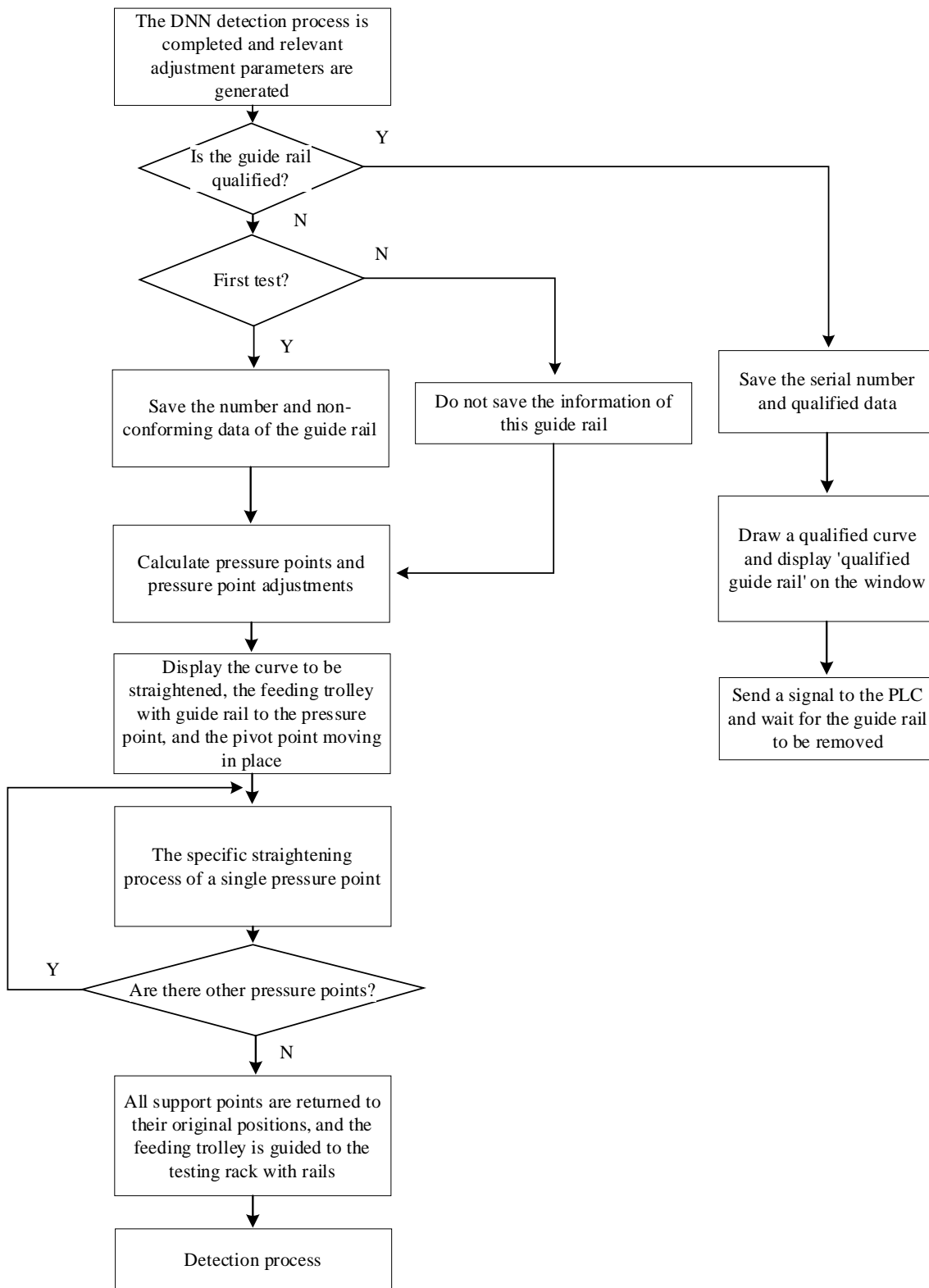


Figure 2: Precision Machine Tool Guide Straightening Process Diagram

After the precision machine tool guide rail inspection is completed, calculate the straightness error of the guide rail curve to determine whether the straightness of the guide rail is qualified. If it is qualified, save the number and qualified data of the guide rail to the database, draw a qualified curve on the main interface, display "guide rail qualified", and send a signal to

the PLC to wait for the guide rail to be removed; If the straightness is not up to standard, determine whether the first inspection is necessary. When it is the first inspection, the number and non-conforming data of the guide rail need to be saved. When it is not the first inspection, the information of the guide rail does not need to be saved. If the precision machine tool guide rail is not qualified, the unqualified data will be analyzed and calculated, and the deep neural network algorithm model will be used to predict the information of the pressure points, including position, span, number, etc. The pressure points will be adjusted according to the bending form of the precision machine tool guide rail curve and the actual straightness situation. Then, the pressure points will be straightened one by one. When each pressure point is straightened, the curve of the straightening part will be displayed (from the left pivot point to the pressure point, and then to the right pivot point). At this time, the feeding trolley will bring the guide rail to the corresponding pressure point position, and the pivot point will move to the position. After being ready, the straightening of a single pressure point will be carried out. After the current pressure point straightening is completed, it will be judged whether there are other pressure points. If there are, it will also be... Other pressure points need to be straightened, and after all pressure points are straightened, the fulcrum will return to its original position, The feeding trolley is equipped with a guide rail to the inspection rack for re inspection.

## 4.2 Hierarchical Structure of Deep Neural Networks

Deep neural network (DNN) is a key component of deep learning, consisting of multiple layers of neural networks that form a hierarchical structure [21, 22]. Each layer contains multiple neurons (or nodes), and these hierarchical structures allow the network to automatically extract and learn abstract features of data. The depth of deep neural networks comes from their multi-level structure, which allows them to better capture the complex relationships of data through the stacking of neurons. Figure 3 shows the typical structure of DNN.

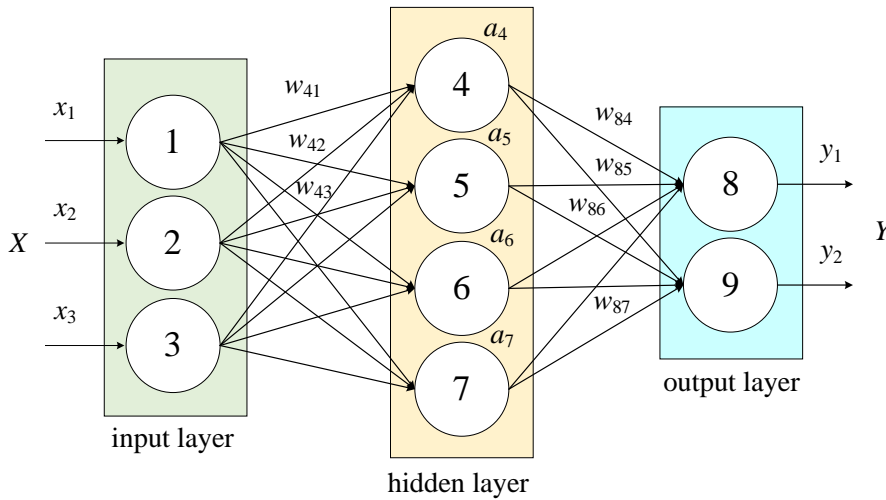


Figure 3: Typical structure of DNN

Parameter  $x_i (i=1, 2, \dots, m)$  serves as the input layer, taking raw data as input, with each input node corresponding to a feature quantity. In this article, voltage Euclidean distance is used to determine the topology structure. Each input node is the Euclidean distance between different node voltages, and the number of input layers depends on the total number of voltage Euclidean distances that can be obtained between different nodes.  $a_j (j=1, 2, \dots, n)$  and  $b_k (k=1, 2, \dots, s)$  are two hidden layers, and the number of hidden layers and neurons in each layer are selected according to the specific problem. Multiple hidden layers enable the network to solve more

complex problems, and each layer abstracts and transforms the input to gradually extract higher-level features. However, having too many hidden layers can lead to long computation time, wastage of computing resources, and overfitting issues.  $z_l(l=1,2,\dots,q)$  and  $h(z_l)(l=1,2,\dots,q)$  are output layers, and the number of output layers depends on the number of possible topological structures.  $z_l(l=1,2,\dots,q)$  is the network output function,  $h(z_l)(l=1,2,\dots,q)$  is the activation function, and the output result of the activation function is the probability of the corresponding topological structure.

### 4.3 Guide rail straightening DNN detection algorithm

Use the Xavier initialization method to initialize the weight matrix [23], and sample the elements of the weight matrix from a Gaussian distribution with zero mean. Taking the weight matrix  $W_1$  as an example, its variance  $Var(W_1)$  is:

$$Var(W_1) = \frac{2}{m+n} \quad (5)$$

where,  $m$  is the number of neurons in the previous layer;  $n$  is the number of neurons in the current layer.

Using the Xavier initialization method to make the output variance of each layer similar to the input variance, thereby avoiding gradient explosion or vanishing problems caused by gradients that are too large or too small. The magnitude of parameter updates for each layer will not differ too much, thus accelerating convergence.

Use Adam optimization algorithm to iteratively solve weights and biases [24, 25]. This method is a gradient based optimization algorithm that combines first-order moment estimation and second-order moment estimation of gradients to adaptively adjust the learning rate.

The specific calculation steps are as follows:

**Step 1:** Initialize parameters, initialize the first-order moment estimate  $u$  to zero; Initialize the second-order moment estimate  $v$  to zero.

**Step 2:** Calculate the gradient and calculate the gradient for each parameter to be solved based on the loss function  $c_{\text{loss}}$ .

**Step 3:** Update the first-order moment estimate  $u$  and second-order moment estimate  $v$ .

$$u_t = \beta_1 u_{t-1} + (1 - \beta_1) \nabla c_{\text{loss}} \quad (6)$$

$$v_t = \beta_2 v_{t-1} + (1 - \beta_2) (\nabla c_{\text{loss}})^2 \quad (7)$$

where,  $u_t$  is the first-order moment estimate of step  $t$ ;  $v_t$  is the second-order moment estimation of step  $t$ ;  $\beta_1$  and  $\beta_2$  are attenuation coefficients; The gradient of  $c_{\text{loss}}$  is  $\nabla c_{\text{loss}}$ .

**Step 4:** Revise the first-order moment estimation and second-order moment estimation.

$$\hat{u}_t = \frac{u_t}{1 - \beta_1^t} \quad (8)$$

$$\hat{v}_t = \frac{v_t}{1 - \beta_2^t} \quad (9)$$

where,  $\hat{u}_t$  is the first-order moment estimate of step  $t$ ;  $\hat{v}_t$  is the second-order moment estimation for step  $t$ .

**Step 5:** Update DNN model parameters.

$$\theta_t = \theta_{t-1} - \alpha \frac{\hat{u}_t}{\sqrt{\hat{v}_t + \varepsilon}} \quad (10)$$

where,  $\theta_t$  is the parameter to be calculated in step  $t$ ;  $\alpha$  is the learning rate, usually taken as 0.001;  $\varepsilon$  is a very small constant used to prevent zero division errors, usually taken as  $1 \times 10^{-8}$ , and its value does not affect accuracy and calculation time.

**Step 6:** Using the DNN model to predict the information of the straightening and side straightening pressure points of machine tool guide rails, including position, span, number, etc., and adjusting the pressure points based on the bending form of the precision machine tool guide rail curve and the actual straightness.

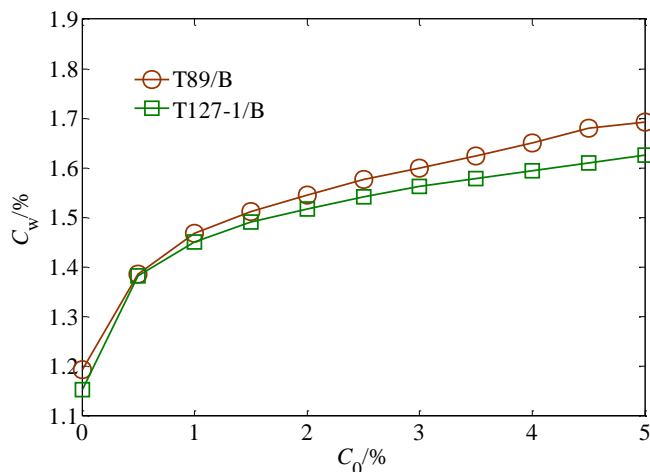
## 5 Experimental analyses

In order to better apply the precision machine tool guide rail straightening and side straightening technology based on the deep neural network prediction model mentioned above, the typical T89/B, T90/B, and T127-1/B series precision machine tool guide rail straightening and side straightening are taken as examples for model application. The cross-sectional dimensions and characteristic parameters of the three types of guide rails are shown in Table 1.

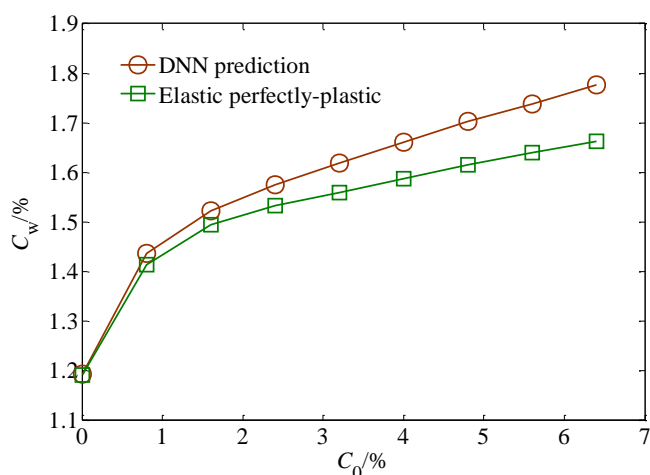
*Table 1: Sectional Dimensions and Characteristic Parameters*

Parameter	B1/mm	B2/mm	B3/mm	H/mm	H1/mm	H2/mm	Moment of inertia/cm <sup>4</sup>
T89/B	9.57	18.96	33.32	88.95	9.96	15.75	59.67
T90/B	9.94	22.78	41.93	89.94	9.93	15.38	102.13
T127-1/B	10.46	33.86	44.46	126.48	9.92	15.76	151.43

The elastic ultimate stress  $\sigma=250\text{MPa}$ , elastic modulus  $E=205150\text{MPa}$ , tangential modulus  $E'=3575\text{MPa}$ , and metal linear strengthening coefficient  $\psi=0.0169$  of the guide rail material can be obtained by substituting the cross-sectional dimensions and characteristic parameters of the three types of guide rails in Table 1, as well as the characteristic parameters of the guide rail material, into the straightening theoretical equation of the precision machine tool guide rail mentioned above. So, the relationship curves of these three typical precision machine tool guides can be obtained, as shown in Figure 4.



(a) T89/B, T127-1/B precision machine tool guide rail relationship curve



(b) Relationship curve of T90/B precision machine tool guide rail

Figure 4: Curve of curvature relationship for precision machine tool guide rail straightening

Figure 4 shows the relationship curves between the straightening and side straightening of three types of precision machine tool guides, T89/B, T90/B, and T127-1/B. Through this curve, the corresponding straightening and side straightening curvature ratios can be calculated based on the initial bending curvature ratio of the guide rail, which greatly facilitates the calculation of control parameters for the straightening and deformation of the guide rail. Among them, the curvature equations for straightening and side straightening in Figure 4a are based on a linear strengthening material model. When the material properties of the precision machine tool guide rail have high toughness, the linear strengthening coefficient AA in the bending moment equation and curvature equation of the straightening model can be transformed into an ideal elastic-plastic material guide rail straightening and side straightening model. For example, for T90/B type guide rails, let AA be used to obtain the straightening curvature equation and the relationship curve shown in Figure 4b. From this figure, it can be seen that when considering the metal strengthening effect during the straightening process, the reverse bending curvature of the precision machine tool guide rail with the same initial bending degree as the side straightening increases relative to the ideal elastic-plastic deformation. Moreover, as the straightening degree deepens, the influence of DNN prediction results on the straightening anti

bending ratio also deepens.

The theoretical model has more or less simplified the straightening process of guide rails, such as simplifying the guide rail section in the theoretical model and simplifying the guide rail material as bilinear follow-up strengthening material. However, the actual straightening process is more complex. Therefore, in order to verify the feasibility of the model, Table 2 shows the theoretical model, finite element simulation, and experimental straightening stroke data for a certain initial bending deformation during straightening. The deformation mode, load condition, and constraint mode of the guide rail under the three methods are the same as described above. The relative error refers to the error between the theoretical model, finite element simulation results, and experimental data.

According to Table 2, through comparative analysis of the theoretical model and application examples of the straightening process for precision machine tool guide rails, it can be seen that when the lateral bending deformation of the precision machine tool guide rail is small, the straightening stroke calculated by the theoretical model is in good agreement with the results obtained from finite element simulation and experiments, with a maximum relative error within 10%. The theoretical model of precision machine tool guide rail straightening has a good guiding role in guiding the lateral bending deformation straightening of the guide rail; When the lateral bending deformation of the guide rail is large, there is a certain gap between the theoretical results and the finite element simulation and experimental results, and the relative error increases. The main reasons for this are as follows:

1) The theoretical model is established based on the relevant assumptions of elastic-plastic mechanics, and its material stress-strain model is simplified as an ideal elastic-plastic or linear dynamic strengthening model, while the actual stress-strain state of precision machine tool guide rails is much more complex;

2) In order to establish a model for precision machine tool guide rail straightening and side straightening, the straightening process was simplified as the reverse bending of a simply supported beam. Therefore, the theoretical model did not consider the influence of the structural form of the straightening pressure head and support block on the straightening parameters, that is, did not take into account the contact nonlinearity problem during straightening.

3) The changes in the true elastic modulus, strengthening modulus, stress strengthening coefficient, elastic ultimate stress, and other parameters of precision machine tool guide materials also directly affect the calculation of straightening parameters.

Therefore, when applying the theoretical model of precision machine tool guide rail straightening and side straightening in practice, it is necessary to modify the model through a large number of experiments based on the actual stress-strain relationship and material mechanics parameters of the guide rail material during the actual straightening process, and considering the structural forms of the pressure head and support block during the straightening process. This is exactly what further research needs to be carried out.

*Table 2: Comparison and Validation of Theoretical Models*

Initial bending deformation/mm	Corresponding straightening stroke/mm				
	Theoretical model	Proposed method	Relative error/%	Finite element simulation	Relative error/%
0.950	1.876	1.966	-4.58	2.001	-6.25
1.454	2.414	2.547	-5.22	2.579	-6.40
1.741	2.715	2.944	-7.78	2.949	-7.93
2.154	3.147	3.460	-9.05	3.439	-8.49
2.527	3.547	3.836	-7.53	3.935	-9.86

## 6 Conclusion

### 6.1 Main tasks

The process of bending deformation straightening is the final step in the cutting process of precision machine tool guide rails, and it is also an inevitable link to improve the straightness of precision machine tool guide rails. The development of precision automatic straightening equipment will inevitably stimulate research on pressure straightening process theory, and the study of straightening process theory must start from the elastic-plastic bending rebound mechanism of the guide rail bending process. Therefore, this paper first systematically studied the bending and rebound characteristics of precision machine tool guide rails based on elastic-plastic theory, experimental research, finite element simulation and other methods. Then, based on this, the theory of precision machine tool guide rail straightening and side straightening process was explored, and a set of automatic control system for precision machine tool guide rail straightening and side straightening was designed based on deep neural network algorithm model. The main innovative work completed in this article is as follows:

(1) The material strengthening model and strengthening characteristic parameters have a significant impact on the calculation accuracy of the bending deformation of precision machine tool guide rails. Based on the theory of elastic-plastic bending, the bending deformation of reinforced metal precision machine tool guide rails was studied, and a mathematical analytical model of the relationship between guide rail rebound curvature and residual curvature was established. A three-point bending experiment of precision machine tool guide rails was designed on an electronic universal testing machine. By comparing the theoretical analysis results with experimental data, the influence of material strengthening models and changes in strengthening parameters on the calculation of guide rail bending deformation and high-precision straightening was explored.

(2) Based on experimental research on the bending deformation characteristics of precision machine tool guide rails, a deep neural network model was used as a medium to establish a prediction model for the rebound amount of precision machine tool guide rails based on experimental data. The relationship between loading stroke and rebound deflection under a certain initial deflection was studied. At the same time, the influence of material characteristic parameters on spring back was studied by combining the geometric motion model of precision machine tool guide rails. A material characteristic parameter prediction model was established through experimental data and deep neural network model data.

### 6.2 Research Prospects

The bending and deformation straightening of precision machine tool guide rails is a theoretical and practical research topic involving multiple disciplines such as materials, mechanics, machinery, and architecture. Although this article systematically studies the straightening of precision machine tool guide rails through theoretical models, deep neural network models, and experiments, scientific research is an endless and constantly developing work. Therefore, further research is still needed in the following areas:

(1) Research on the multi arc bending and straightening model of precision machine tool guide rails. Due to the fact that the length of precision machine tool guide rails is generally 3-5m and the longitudinal dimension is large, there are usually multiple bending deformations along the length direction of the guide rail. This article systematically studies the bending deformation of a single arc of precision machine tool guide rails, including positive and side straightening. The multiple arc bends of the guide rail are decomposed into a single arc and straightened separately. However, whether the single arc straightening has an impact on other

adjacent bending arc segments has not been studied yet. In order to improve the straightening efficiency, it is necessary to conduct research on the multi arc bending straightening model of precision machine tool guide rails.

(2) Establish a more accurate constitutive relationship for precision machine tool guide rail materials. The material constitutive relationship reflects the stress-strain relationship of the workpiece, and the accuracy of the guide rail straightening and side straightening models, as well as the deep neural network learning models, largely depends on the material constitutive relationship. Therefore, based on the load, stroke, and related constraints in the practice of guide rail bending straightening, a database of the actual stress-strain relationship of guide rail bending straightening should be established to reflect the material mechanical characteristic parameters of precision machine tool guide rail straightening.

(3) Research on the influence of the structural form of the straightening pressure head and support block on the straightening parameters of precision machine tool guide rails. In both the research of theoretical models for straightening, bending, and straightening, as well as the deep neural network learning analysis of guide rail bending and bending straightening, the loading load of precision machine tool guide rails is simplified as a concentrated load, and the support is simplified as a simply supported beam. However, in the practice of guide rail bending and bending straightening, the pressure head and support block in direct contact with the guide rail are not in point contact with the guide rail to be straightened. Therefore, the structural form of the straightening pressure head and support block will inevitably affect the straightening control parameters, and the degree of influence needs to be further explored.

(4) Research on the influence of straightening speed on the safety of precision machine tool guide rail straightening and the accuracy of straightening parameters. At present, both straightening theory and straightening experimental research are based on slow static loading conditions. In the practice of precision machine tool guide rail straightening, it is necessary to ensure a certain straightening effect and a faster straightening speed. Therefore, the size of the straightening rate will inevitably affect the safety and reliability of straightening and the accuracy of guide rail straightening control parameters. Therefore, it is necessary to study the reliability of guide rail straightening at different straightening rates and compare the accuracy of straightening control parameters at different straightening rates.

## Author's Profile

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