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Research on the Cause and Control Method of Edge Warping Defect during Hot Finishing Rolling

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Abstract: Different from the cross-section profile defects caused by uneven roll wear or external forces during hot finishing rolling, the edge warping defect often occurs and has special local characteristics. However, the cause and control method of edge warping are still unclear. By superposition calculating the roll shape, it is found that the high-order comprehensive roll gap contour formed by the superposition of the bathtub-shaped roll thermal contour and parabolic original roll shape is the main cause of strip edge warping. To ensure that the comprehensive roll gap contour is parabolic rather than the original roll shape, the target curve of the comprehensive roll contour in the form of a parabola is determined according to the amplitude of the middle position of the comprehensive roll contour of the last strip in a standard rolling unit, and then subtract the thermal contour curve of the last strip to obtain the desired curve of the antithermal original roll shape. In theory and application, the optimization of the original roll shape can effectively avoid the occurrence of edge warping defect.

Keywords: edge warping; cause; control method; roll shape optimization; hot rolling

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1. Introduction

Strip steel is one of the most widely used products in construction, automobile, aerospace, and other fields. Some high-strength steels, such as dual-phase (DP) steel and transformation induced plasticity (TRIP) steel, are applied in the automotive industry to lighten parts and improve crash resistance [1]. Some more advanced steels, such as medium-Mn steel, still in development, will soon emerge on the market [2]. There are many indicators to evaluate strip steel, such as size, flatness, and mechanical properties [3]. Among them, the cross-sectional profile is a key factor for hot-rolled strip, which directly affects product quality and production stability [4]. The existing control model and roll shape technology are almost developed around this index [5].

Although the theory and technology for strip cross-section profile control have experienced decades of development, as the rolling mill is becoming wider, the strip width is becoming wider, and the strip thickness is becoming thinner, some cross-sectional profile defects are still difficult problems in actual production, such as the well-known crown, edge drop, high spot, and especially edge warping defect (see Figure 1; the edge thickness at the strip edge is larger than that inside the edge).

In terms of crown control, many prediction models are developed by the elastoplastic deformation theory and data-driven method, the crown allocation strategies are implemented, and the proper roll shapes are designed for multiple stands to obtain the target exit strip crown and perfect flatness. Zhao [6] established a high-precision shape control model by the mechanism of strip shape forming and the deformation of a roll system, in which special concentration is placed on the effect of roll wear, roll thermal expansion, metal transverse flow, and stress release on the shape. Li [7] established a high-precision prediction model of a strip crown to improve the accuracy of the traditional models, in which the evaluation coefficient that represents the influence of a single factor on a strip crown and the correction coefficient that represents the interaction effects of each other are introduced together. Li [8] adopted the data-driven method to improve the crown accuracy of hot-rolled strips, in which three novel strip crown prediction models using the well-performing and efficient tree-based ensemble learning algorithms, respectively, including Random Forest (RF), eXtreme Gradient Boosting (XGBoost), and Light Gradient Boosting Machine (LightGBM), are developed, and the impact levels of each input variable on the strip crown are measured.

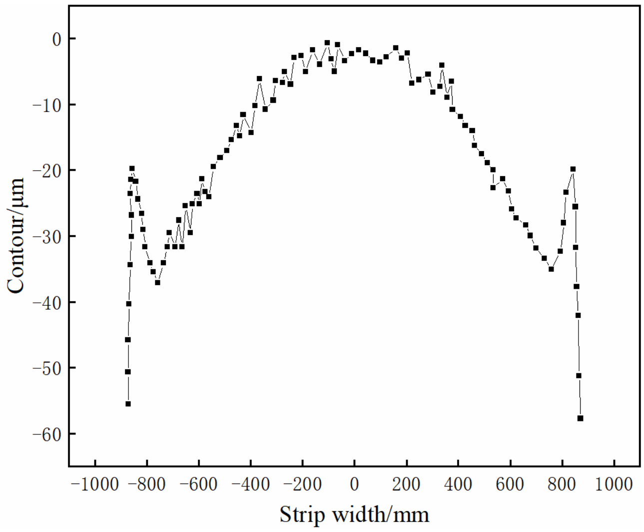

Figure 1. The measured edge warping defect of strip after the last finishing mill.

In terms of edge drop that increases the transverse thickness difference, the combined actions of a shape model and roll shape are required to solve this problem since the edge drop is related to profile inheritance, roll flattening, roll wear, transverse temperature distribution, etc. It is worth mentioning that the work roll shape with a taper is the key of the solution. He [9,10] designed the high-precision cross-section control technology from rough rolling to finishing rolling, in which the varying contact backup roll technology and optimization of load distribution in the roughing stand is adopted to improve the profile of the transfer bar, and the approximate rectangular section of a hot strip is obtained by the high-precision shape setting and control model, symmetrical variable taper work roll technology, and smart shifting technology in the downstream stands. Li [11] studied the effect of temperature drop in the edge of an electrical steel strip on the profile of the strip. When the electrical steel strip is in a single-phase state, the strip edge temperature drop can reduce the strip crown. When the electrical steel strip is in a two-phase state, the strip edge temperature drop can lead to a larger strip crown.

In terms of high spot, most studies focus on the optimization of a roll shifting strategy since the high spot is closely related to the uneven roll wear. Shang [12] improved the continuously variable crown (CVC) work roll contour and proposed the relevant constraint conditions under CVC cyclical shifting mode, which resulted in the crown control ability being stronger, the work roll wear being more uniform, and the strip cross-section shape being better. Yao [13] proposed a keep-smooth shifting strategy of the taper roll to achieve a smooth roll wear contour, which is helpful to alleviate the high spot and extend the rolling length of a schedule. Cao [14] established the work roll wear prediction model and thermal roll contour model and a 3D finite element model of roll stacks and a strip by using the MATLAB and ABAQUS software, and developed a variable stroke and step (VSS) shifting strategy based on the exponentially damped sinusoid function to obtain the smooth work roll wear contours.

Different from the above cross-section profile defects with relatively mature solutions, there is little research on the edge warping defect that often occurs in a wide rolling mill. Yamaguchi [15] adopted a periodically jumping roll shift pattern to improve the profile defect that the edge thickness at the strip edge is larger than that inside the edge. However, the improvement effect is greatly affected by the shift stroke, and the jumping shift pattern will reduce the uniformity of roll wear.

Although local warping at the strip edges leads one to suspect uneven roll wear, from the actual tracking result, the edge warping defect appeared from the beginning of rolling. Figure 1 shows the profile of the 12th strip in a rolling unit. At this moment, the roll thermal crown almost increases to the equilibrium state, but the roll wear is still small. Furthermore, the high spot always appears in the middle and late stage of the rolling unit, and the peak of the high spot formed by uneven roll wear is usually located at the position of 100 to 200 mm from the strip edge [16,17]. Therefore, the high spot and the edge warping do not belong to the same defect through the comparison of contour shape features (see Figure 2). The roll deflection caused by the rolling force or bending force will only cause the overall bending of the roll and will not cause local sharp changes. Therefore, it is worth studying how the edge warping defects are formed and how to eliminate it.

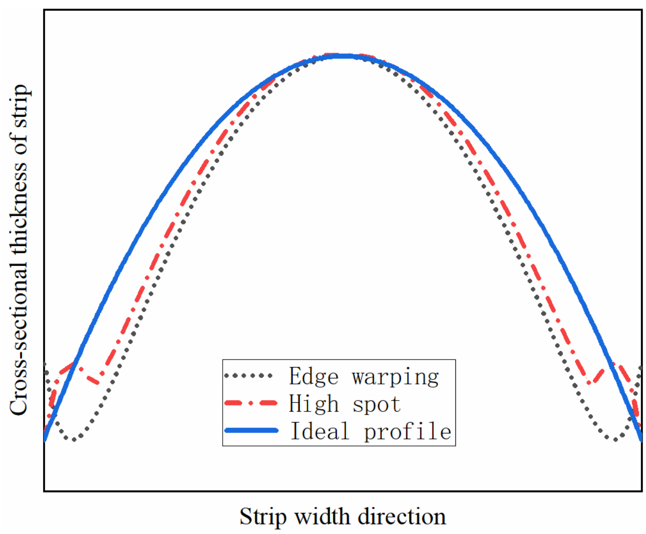

Figure 2. Typical strip profile defects and ideal strip profile.

Although it is well known that the comprehensive roll shape is obtained by the superposition of the original roll shape, roll thermal contour, and roll wear, most of the original roll shape (also called grinding roll shape) designs do not fully consider what the final superimposed comprehensive roll shape is after rolling multiple strips. Therefore, we can try to analyze the cause of edge warping defect from the change of the comprehensive roll shape used on the hot finishing mill. On the one side, the most used work roll shapes currently are the parabolic roll shape and CVC roll shape [18], in which CVC can be shifted to change the contour of the roll gap. It is worth noting that the roll gap contour formed by different roll shifting positions of CVC is still parabolic. That is to say that the roll gap contours formed by the mainstream original roll shapes are all parabolic. On the other side, the roll gap contour formed by the roll thermal expansion is not parabolic. Chen [19] established a finite difference method to simulate the roll temperature and thermal crown, and the lateral distribution of the roll surface temperature and roll thermal crown after rolling each strip within a rolling period was obtained. Jiang [20] adopted the data-driven method to improve the accuracy of the model. It can be seen from their research that the roll gap contour formed by the roll thermal expansion shows a bathtub form during rolling, which is almost flat in the middle position of the contact with the strip, while a steep drop will occur at the edge position of the contact with the strip, which is caused by the rapid transition of the roll temperature. Finally, a new question is what will happen when these two roll gap contours are superimposed. Obviously, the superposition result of the parabolic original roll gap contour and the bathtub-shaped thermal roll gap contour is a high-order curve, which may be responsible for the edge warping problem and needs to be focused on.

In this paper, the cause of strip edge warping is explored by superposition calculating and analyzing the roll shape. According to the forming mechanism of the defect, the original roll shape is redesigned to improve the final comprehensive roll contour and successfully eliminate most edge warping defects in practical terms.

2. Establishment of Roll Thermal Expansion Model

In order to calculate the effect of the thermal expansion of a work roll on a strip profile, it is necessary to establish a roll thermal expansion model [15,19]. The roll thermal expansion model is closely related to the temperature distribution of the work roll. Since the temperature of the roll is almost axis-symmetrically distributed, the temperature change along the circumference of the roll is ignored, and the roll temperature field model is simplified into a 2D model. Based on Fourier's law, the differential equations for describing the heat transfer process are established considering the contact heat transfer with the plate, backup roll and bear, and convective heat transfer with the coolant and the air (see Figure 3). The heat transfer coefficients for different boundary conditions are shown in Table 1. Then the roll is discretized into meshes, and the established differential equation at each node is transformed into a difference form. The temperature field can be obtained by solving the equations using the forward elimination and backward substitution method.

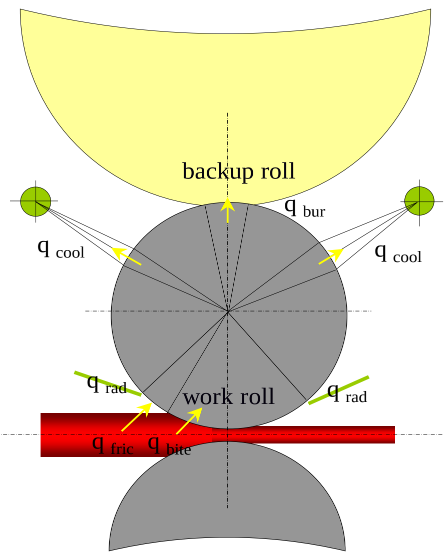

Figure 3. Diagram of boundary conditions of heat transfer of work roll.

Table 1. Heat transfer coefficients for different boundary conditions.

Heat Transfer Coefficient (HTC)	Values
HTC between work roll and air	$30\ W/(m^2 \times K)$
HTC between work roll and coolant	$2000\ W/(m^2 \times K)$
HTC between work roll and plate	$150\ W/(m^2 \times K)$
HTC between work roll and bearing	$250\ W/(m^2 \times K)$
HTC between work roll and backup roll	$100\ W/(m^2 \times K)$

The amount of thermal expansion at different positions along the axial direction can be calculated according to the calculated temperature distribution. The calculation equation is as follows [15,19]:

$$u(x) = \frac{4(1+\nu)\beta}{R}\int_{0}^{R}[T(x,r) - T_0]rdr \tag{1}$$

where $u(x)$ is the thermal expansion per diameter at the axial position x. ν is Poisson's ratio. β is the thermal expansion coefficient. R is the radius of the work roll. $T(x,r)$ is the temperature at the axial position x and at the radial position r. T_0 is the initial temperature of the roll, °C.

3. Comprehensive Roll Gap Contour Based on the Parabolic Original Roll Shape

Taking a 2550 mm hot rolling mill belong to Delong Co., Ltd. located in Liyang of China as an example, considering that the last mill stand has a direct influence on the cross-sectional profile of a strip, the last mill stand is selected for calculation. This mill stand adopts the work roll shape curve in the form of a parabola. The roll parameters of the rolling mill are shown in Table 2. Although the cyclic reciprocating roll shifting strategy usually used can reduce the thermal expansion of the roll and change the distribution and amplitude of the thermal contour to some extent, the change is limited because the temperature transfer inside the roll is relatively slow. Therefore, in this paper, the "worst" working condition of continuous rolling of multiple identical strips without roll shifting is taken as the simulation object, and the rolling parameters of 60 identical strips are shown in Table 3. The evolution process of the comprehensive roll contour after the superposition of the original roll shape and the thermal contour in the rolling unit is calculated (see Figure 4; #N represents the Nth strip in the rolling unit).

Table 2. Roll parameters of rolling mill.

Rolling Parameters	Values
Length of work roll body	2850 mm
Diameter of work roll body	664.7 mm
Length of work roll neck	665 mm
Diameter of work roll neck	508.5 mm
Parabolic original roll shape	−280 µm

Table 3. Rolling parameters of 60 identical strips.

Rolling Parameters	Values
Strip width	2040 mm
Entry thickness	5.61 mm
Exit thickness	4.97 mm
Rolling speed	6.8 m/s
Shifting position	0 mm
Rolling temperature	970 °C
Rolling time of each strip	50 s
Rolling gap time between strips	30 s
Air temperature	25 °C
Initial temperature of the roll	25 °C
Coolant temperature	30 °C
Bearing temperature	50 °C

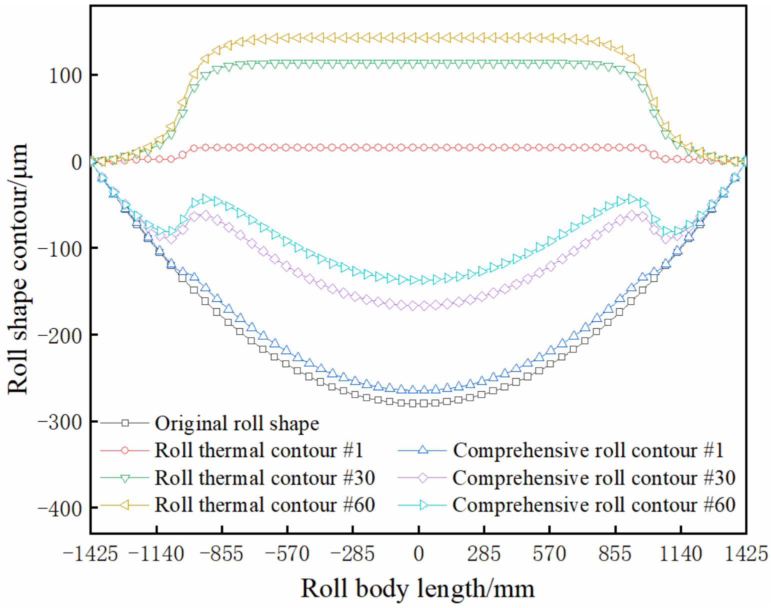

Figure 4. The evolution of roll thermal contour and comprehensive roll contour based on the parabolic original roll shape.

It can be seen from Figure 4 that when the original roll shape is a parabolic curve, the comprehensive roll contour at the beginning of rolling is almost parabolic. As the number of rolled strips increases, the roll thermal expansion increases, and the comprehensive roll contour becomes a complex high-order curve. At the same time, the roll gap contour within the strip width is gradually changed from a parabola form to an edge warping form (see Figure 5a).

To quantify the change of gap contour for the strip, the difference between the thickness of the strip edge and the thickness of the lowest point of the contour curve is defined as the edge warping height. It can be seen that the edge warping height increases gradually with the rolling process, especially at the early stage of rolling, which is consistent with the "fast first and then slow" growth rule of thermal contour (see Figure 5b).

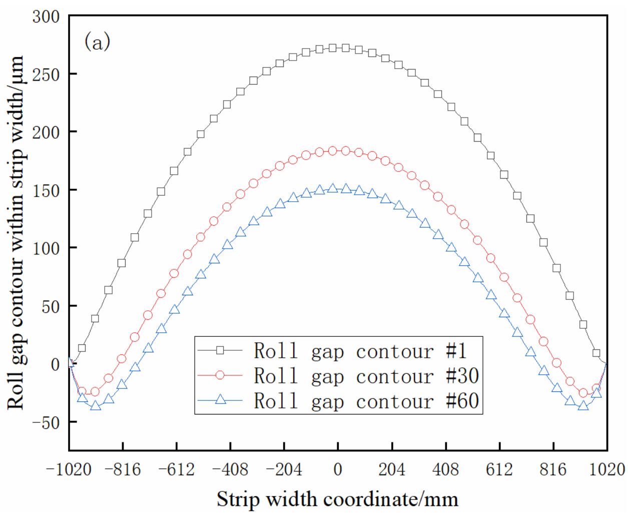

Figure 5. *Cont.*

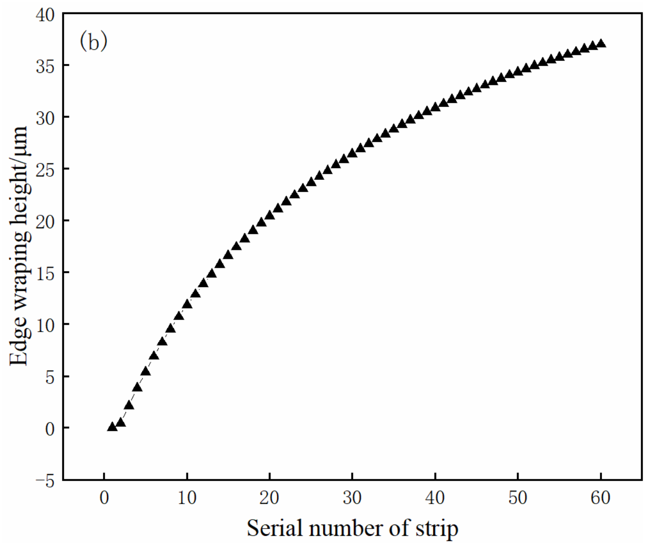

Figure 5. Roll gap contour within strip width. (**a**) The evolution of roll gap contour within strip width based on the parabolic original roll shape. (**b**) The evolution of edge warping height within the rolling unit.

4. Design of Antithermal Original Roll Shape

In order to overcome the edge warping caused by roll thermal expansion, the antithermal original roll shape is designed.

First, the target curve of the comprehensive roll contour in the form of a parabola is determined according to the amplitude of the comprehensive roll contour of the last strip. In detail, three key points of the comprehensive roll contour of the last strip are extracted, including the starting point, the middle point, and the end point. The target curve expression of the new comprehensive roll contour is shown in Equation (2). The coordinate values of three key points are substituted into the expression to obtain the coefficients.

$$y = ax^2 + bx + c \tag{2}$$

Then subtract the thermal contour curve of the last strip from the target parabolic curve of the comprehensive roll contour to obtain the desired curve of the antithermal original roll shape (see Figure 6; it simply means Curve ③ = Curve ①–Curve ②). The purpose of this is to ensure that the comprehensive roll contour is parabolic rather than the original roll shape.

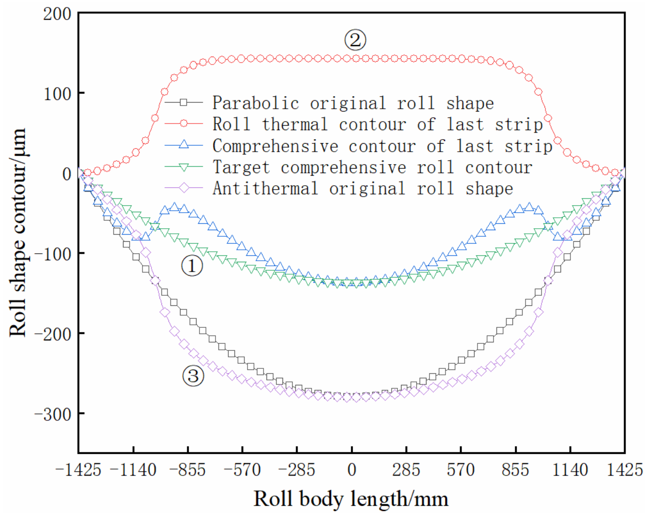

Figure 6. Design route of antithermal original roll shape.

5. Comprehensive Roll Gap Contour Based on Antithermal Original Roll Shape

After using the antithermal original roll shape, at the early stage of rolling, the roll thermal expansion is small, and the comprehensive roll contour is similar to the original roll shape, showing the shape of "bathtub". With the increase in the roll thermal expansion, the shape of the comprehensive roll contour is becoming closer to a standard parabola (see Figure 7).

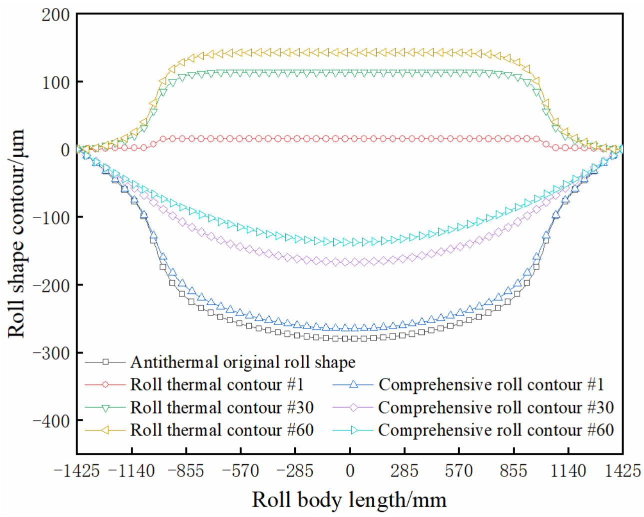

Figure 7. The evolution of roll thermal contour and comprehensive roll contour based on the antithermal original roll shape.

In the range of the strip width, the comprehensive roll gap contour is kept in parabola form from the beginning to the end of the whole rolling unit, and the edge warping height is always zero, which can effectively avoid the occurrence of edge warping (see Figure 8). The reason for this good effect is that the contour and evolution of the roll thermal expansion are taken into account when formulating the target curve of a comprehensive roll contour. The undesired change of the roll shape in the rolling process is offset in advance.

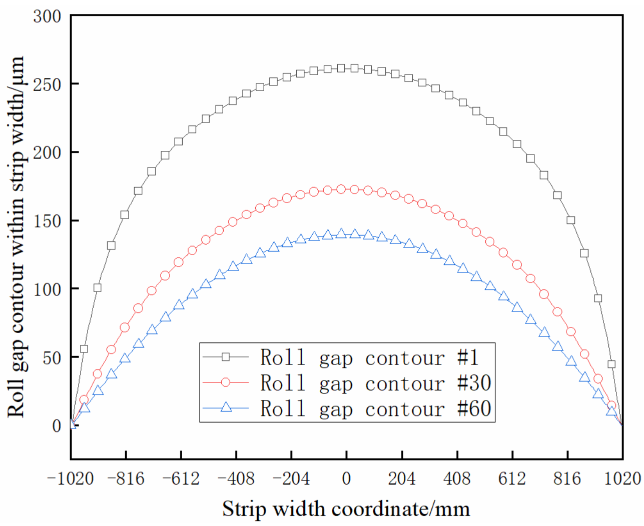

Figure 8. The evolution of the roll gap contour within strip width based on the antithermal original roll shape.

Furthermore, the roll shape of each finishing mill stand can be designed according to the proposed method, which is more conducive to ensuring a good profile of the final product. After application in practical production, the numbers of coils of which edge warping height ≥ 10 µm for 1 month before and after the original roll shape optimization are compared (see Figure 9). It can be seen that the strip cross-sectional profile has been significantly improved, and good profiles can also be obtained for the wide-width strips above 2000 mm, which are prone to edge warping.

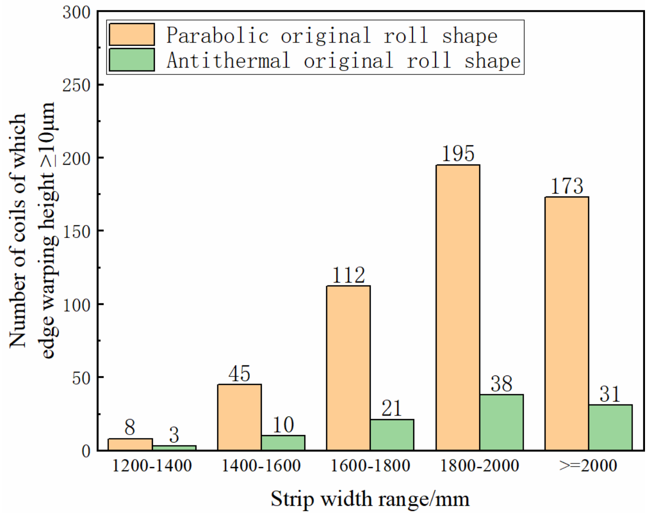

Figure 9. The improvement effect of edge warping defect.

6. Conclusions

1. The high-order comprehensive roll gap contour formed by the superposition of a bathtub-shaped roll thermal contour and parabolic original roll shape is the main cause of edge warping.
2. The edge warping defect is eliminated by optimizing the original roll shape, which is obtained by the difference between the target parabolic comprehensive roll contour and the bathtub-shaped thermal contour. The improvement effect has been verified in practice.

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