Optimization of continuous variable crown work roll shifting strategy using k-nearest neighbors algorithm for hot strip rolling mill

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Abstract
Appropriate work roll shifting strategy in the finishing hot strip mill can make roll wear uniform and contour smooth. To eliminate the problem of roll shifting position duplication due to available roll shifting strategy, the optimized work roll shifting strategy is proposed in the hot strip rolling mill with continuous variable crown work rolls, using the k-nearest neighbors algorithm. The self-perpetuating parameter is used to describe the concentrated wear of the work roll. The position repeated parameter is put forward to evaluate the roll shifting position history. The relationship between concentrated shifting positions and uneven roll wear is analyzed based on in-site data collected in a hot strip rolling mill. The program of optimization strategy is coded using language C. Off-line simulation is made to obtain optimized shifting positions using the program. The comparison between in-site engineering data and optimized shifting positions has been assessed using the scatter diagram and kernel density estimation. Comparison results show that the new strategy can solve the problem of shifting position duplication well. A simplified method is established to make it easy to apply the strategy to online applications, and the in-site application shows that the optimization strategy has an excellent practical effect.

Keywords
hot strip, k-NN algorithm, online application, optimization, roll shifting strategy

JEL Classification
Industrial engineering

1 | INTRODUCTION
Roll wear reduction is an effective way to save production costs and increase the productivity of the hot strip rolling mill. The continuous variable crown (CVC) roll wear is a seriously concerned since this technology has been used widely. Using CVC technology, the variable roll gap crown can be obtained by the artful roll shifting mechanism.
As an innovative technology to improve product quality, increase productivity, and reduce costs, CVC technology has been one of the critical parts of schedule free rolling (SFR). During the rolling process of the first several strips after work roll change, the roll gap can be well compensated using CVC technology. Otherwise, the formation process of the work roll thermal crown would alter the roll gap profile quickly. When the rolling conditions such as thermal crown reach a dynamic equilibrium, the rolling process enters a relatively steady stage. Then the purpose of roll shifting turns to smooth roll wear in the axial direction besides the primary function of changing the roll gap. Considering the strip shape control ability of the rolling mill, the roll gap is not decided by a single factor. Elastic deformation of rolls, thermal expansion, roll wear, and the original grinding shape compose the roll gap profile together. Therefore, many roll shifting positions are competent for the roll gap profile requirement. Without advanced active provoking, under relatively stable rolling conditions, the searching process of the optimized shifting position is stalled when the shape setup model finds a temporarily proper shifting position. As a result, the shifting position is kept constant for a long time for many strips’ sequential rolling. Sometimes, based on in-site experience, the roll shifting positions and bending force may be set to be fixed value by operators before a better plan is put forward.

CVC technology is one of the widely used roll shifting technologies. Many research works have been conducted on roll contour curve design, shifting strategy optimization, and new kinds of work roll with shifting function. Xu et al. introduced a method to design the CVC-Plus work roll curve. Karandaev et al. verified that the roll changing period was improved due to the decrease of friction forces in the axial direction. Linghu et al. developed a 3D elastic-plastic finite element method (FEM) model of cold strip rolling for a 6-high CVC mill. Since the linear relationship between shifting position and equivalent roll gap crown, the negative effect on the roll gap is more obvious when CVC work roll is used in cyclical shifting mode. To meet the requirement of schedule-free rolling for wide nonoriented electrical steel production with a large number of the same width strips, Cao et al. studied the asymmetry self-compensating work rolls (ASR) shifting strategies for different rolling schedules. To enhance the shape control capability of ultra-wide hot strip mills, a linearly variable crown (LVC) work roll was developed by He et al. Besides the research on work roll, the backup roll contour was also concerned. Sun et al. proposed the varying contact length backup roll (VCR) technology in a hot strip mill to increase the transverse stiffness of loaded gap, reinforce the control effect of roll bending, and improve the contact force distribution between backup roll and work roll. Some researches were carried out using the FEM model. Shang et al. established a 3D FEM model of roll stacks for an 1800 mm CSP hot rolling mill and determined the working principle for the CVC cyclical shifting mode. The problem of roll uneven wear in certain CSP mills was resolved by using cyclical shifting. To avoid severe local wear, Kong et al. presented a variable step cyclical shifting strategy with a general work roll contour.

However, besides roll wear, another main target of rolling process control, the strip profile and flatness, should be paid enough attention to. Besides the physical process, it is complicated for the shape setup model to meet the targets because of the calculation process itself. A more convenient shifting strategy should be built to resolve both the two problems, roll wear and strip shape control.

In this article, data analysis and intelligent methods are used to achieve the target of avoiding roll shifting position concentration. Meanwhile, the shape control function in hot rolling strip mill with CVC work roll is considered.

2 WORK ROLL WEAR ANALYSIS

First, an investigation should be made about specific relationships between work roll shifting position and roll wear. The profile of steel can be approximately regarded as a mirror image of the work roll gap profile in the hot strip rolling mill. Anything that changes roll diameter in a local area can cause an unexpected effect on rolled strip profile. If the roll wear is uneven in the axial direction, the contour of the roll gap is irregular, so the product quality is declined and roll changing periods are affected. The reason and phenomenon of roll wear are complicated. Friction between work roll and steel proceeds the rolling course, however, it also inevitably causes the loss of roll mass. Aware of the importance of roll wear in the hot rolling process, some researchers have tried to find the essential principle, effective factors, and the method to control roll wear. Some kinds of experiential equations to describe and calculate the wear of work roll were presented and discussed by Lenard.

According to previous studies, lots of factors such as rolling force, the hardness of roll and steel, temperature, accumulative rolling length, and strip steering are dominant practical factors of work roll wear. John et al. built a roll wear
prediction model for finishing stands of hot strip mill. Byon et al.25 performed a single-stand reversible pilot groove rolling test as well as a rolling test in an actual rod mill, and the effect factors were studied. Liu et al.26 developed a model of work roll wear in hot strip mills. Because of the high hardness, low temperature, and high pressure, the position corresponding to the steel edge got more severe roll wear than other parts. If the same product width is maintained for a long time, the steel edge contacts the same roll position and generates a pit on the work roll surface. The roll wear curve along with the steel width covered area of the lower work roll of F2 stand is shown in Figure 1. At the same time, Figure 1 contains the original CVC roll curve and the self-perpetuating parameter (SPP) curve, shown in different line types.

As an example of roll wear, the real measured diameter curve of the “offline” work roll gets a “pit” at the relative roll barrel length of −0.2 to −0.3. For the convenience of data collection as well as representativeness, the data are collected from the F2 stand of an in-site hot strip rolling mill. The F2 stand belongs to a 1780 mm hot strip product line with a 4-high reversible roughing mill and 7-stand 4-high finishing mills. The work rolls of F1, F2, F3, and F4 are CVC work rolls with diameters of 760–850 mm, length of 2080 mm, and shifting ranges of ±120 mm.

For the data from the grinding machine, the measuring deviation shall be considered. The trend of data should be focused on instead of the value of the data themselves.

The roll wear is severe in areas where the strip is tightly pressed with work roll. Since enough attention has been paid to strip quality, the work rolls are usually changed before strip shape defects occur. So, the pit shape of the roll wear curve where edges of the strip always pass frequently is not very obvious. However, there are still three pits from the left to the right, at about −0.2, 0.19, and 0.34 of relative roll barrel length, respectively, in addition to slight fluctuations of the other parts of roll wear. In view of the real work roll surface, the sharp radius change in Figure 1 between −0.12 and 0.12 of relative roll barrel length is not real since the corresponding area of roll surface is smooth.

The SPP is proposed to depict the roll wear, as shown in Equation (1). A bigger SPP stands for the more severe roll wear along with the work roll’s axial direction.

\[ \lambda = \frac{\omega}{L} \times 100\% , \]  

where \( \lambda \) is the SPP, \( \omega \) is roll wear, which is the value to characterize the difference between grinding roll diameter and the current diameter, \( L \) is the length of the roll barrel.

The width distribution of rolled strips during the work roll changing period is shown in Figure 2. Allowing for the actual requirement of products, rolling scheduling is not easy to follow the optimal routine. Therefore, to avoid strip profile problems, the wider strips are tried to be arranged to be rolled before the narrower ones. When high-precision width control technology27,28 is applied in modern hot rolling strip mills, the target width can be regarded as the actual width. Besides width deviation, the offset from the rolling centerline can make the roll wear at the location where contacts the strip edge wear more seriously. Jiang and Tieu29 researched the mechanics of thin strip steering. Okada et al.30 built a strip steering control system, which was successfully applied to an actual plant. Zhao et al.31 made a

**Figure 1** Roll wear curve of lower work roll of F2 stand
FIGURE 2  Strip width during one single roll changing period of the work

3D numerical simulation of the aluminum strip steering process under asymmetric variations in hot rolling. Furu-moto et al.\textsuperscript{32} tried to reduce off-centering at the tail end in hot rolling. Based on in-site application, usually, the offset is at least about 20 mm, or a little more. The offset was eliminated or decreased by the operator during the rolling process.

The CVC work rolls are used in stand F1, F2, F3, and F4 with roll shifting function as well as common rolls with Sine function curves for the other three stands. For all the four stands with CVC technology, the shifting positions are variable in specific ranges but keep almost constant after the first three pieces of steel rolling.

In this article, the position repeated parameter (PRP) is used to describe the probability density of the work roll shifting position. The concept of PRP is shown in Equation (2).

\[ r = \frac{p}{n} \times 100\%, \]

where \( r \) is the PRP, \( p \) is the number of consecutive repeated data in shifting position record file. If the difference between two adjacent shifting positions is less than 3 mm, and the difference between the two adjacent steel widths is less than 20 mm, the two shifting positions can be considered the same. \( n \) is the total rolled strip number in the changing period of the work roll.

Besides uncertain factors such as strip steering and measurement errors, strip width and work roll shifting positions are related to the contact area between strips and the work roll surface, where roll wear occurs. The PRP represents the fraction of real contacting mileage of a certain area on the roll surface in the total rolling mileage within the roll changing period, and the rolling mileage is one of the important factors to calculate roll wear.

The PRP of work roll shifting positions of finishing stands in one single roll changing period rolls are listed in Table 1.

According to the data in Figure 1 and Table 1, the wear of the work roll presents its complexity: the PRP of about 1500 mm width strips are higher than 35%, but the SPP does not present a state conform with it, only small peaks according to the strip’s edge of 1500 mm can be seen from the SPP curve. This may be related to the hardness of steel, strip steering, and other factors. However, the rolling of strips with a width of 1260 mm leaves a noticeable mark on the roll surface, especially at the strip edges, corresponding to positions with a relative roll barrel length of \(-0.23\) to \(-0.19\) and \(0.35\)–\(0.37\). The SPP is higher than 10%, which means the roll wear is greater than 0.22 mm. Furthermore, the PRP of the 1260 mm strip width of F2 stand is 20%, the shifting position with the 20% PRP is 100 mm, this conforms to the state of the offline roll curve and the curve of SPP. Although the process of roll wear cannot be accurately recorded and all the rolled strips affect the roll wear during the work roll changing period, the strips with a width of 1260 mm contribute significantly to the roll wear of the corresponding part.

To avoid a high SPP peak arising in narrow areas, the PRP must be small. Based on strip shape theory and considering effective factors of roll wear, work roll shifting strategy can be available for improving the PRP. To overcome the inherent difficulties of the shape control mathematic model, an intelligent method should be used to build a kind of novel work roll shifting strategy based on in-site data analysis and using data classification algorithms.
TABLE 1  PRPs of work roll shifting positions of finishing mill stands

| Stand no. | Steel width (mm) | Shifting position (mm) | PRP (%) |
|-----------|------------------|------------------------|---------|
| F1        | 1220             | 30                     | 14      |
|           | 1220             | -80                    | 6       |
|           | 1260             | 100                    | 26      |
|           | 1470             | 100                    | 7       |
|           | 1510             | 100                    | 24      |
|           | 1510             | 50                     | 10      |
|           | Others           |                        | 13      |
| F2        | 1220             | 50                     | 14      |
|           | 1220             | -50                    | 6       |
|           | 1260             | 100                    | 20      |
|           | 1470             | 100                    | 7       |
|           | 1510             | 100                    | 25      |
|           | 1510             | 50                     | 10      |
|           | Others           |                        | 18      |
| F3        | 1220             | 80                     | 23      |
|           | 1250             | 113                    | 11      |
|           | 1250             | 96                     | 6       |
|           | 1510             | 100                    | 36      |
|           | Others           |                        | 24      |
| F4        | 1220             | 80                     | 23      |
|           | 1250             | 95                     | 17      |
|           | 1250             | 95                     | 6       |
|           | 1510             | 100                    | 36      |
|           | Others           |                        | 18      |

3  Optimization Strategy of Shifting Position

The primary target of the shape setup model is to reasonably arrange the difference between the unit crown of slab and strip product using all available shape control actuators without breaking the critical buckling condition. Considering the complex rolling circumstances, such as the large width/thickness ratio, it is difficult for the setup model to perform the primary setup task. Based on a specific algorithm, the shifting position which is offered by the shape setup model may be the best choice. When the rolling condition reaches its equilibrium, the setup model keeps this position constant until the “cat ear” is generated before the work roll is changed.

The task of the online setup model is to design a proper unit crown curve that can content the unit error between the slab and the strip product. The unit crown curve is preferably monotonically rising or decreasing from the first to the last active stand, but small fluctuations can also occur. Due to different rolling conditions, the unit crown curves can be various and different. As a setup result of the model, shifting positions is one of the actuators to fulfill the unit crown curve as well as the bending force, rolling force, and other processing parameters. The roll gap change caused by roll shifting can be compensated by other flatness control mechanisms, which can be accomplished automatically when the setup model detects a shifting position change. Therefore, the roll shifting position offered by the shape setup model is not unique, which provides an opportunity to reduce PRP by further optimization of the roll shifting strategy. The optimized shifting positions should meet some conditions, and these conditions should be satisfied at the same time:
The new position should be different, and the bending force is enough to compensate for the roll gap, as well as the PRP is not be increased. Additionally, the shifting position must satisfy the requirement of distance and velocity, as shown in Equation (3).

$$l_{\text{max}} = \min (v_{\text{cyc}} \times t, s_{\text{lim}}),$$  \hspace{1cm} (3)$$

where $i$ is the stand number of finishing mill, $l_{\text{max}}$ is the maximum shifting distance of stand $i$, $v_{\text{cyc}}$ is the shifting speed of stand $i$, $t$ is the time needed for the strip from the current position to F1 entrance, $s_{\text{lim}}$ is the physical limit of work roll shifting of stand $i$.

Based on in-site collected data, an available algorithm is needed to generate a new work roll shifting position. Usually, rolling parameters such as reduction schedule, rolling speed, strip temperature, rolling force, and bending forces are calculated as the initial strip rolling schedule. As shown in Figure 3, when a new testing data record is input, the optimization is started. First, historical data are checked whether the new input shifting position repeats the previous data. If the shifting position of the testing sample is reduplicative, a new shift position should be created using the program developed in this article. Under this condition, as shown in Figure 4, the answer to “optimizing” is “yes,” then the optimization process begins.

The k-nearest neighbors (k-NN) algorithm is used to retrieve from a constructed training data set. The attributes for retrieving and classifying are composed of strip target thickness, width, and the rolling force of the first four stands. The shifting positions of the first four stands are the retrieving results shown as selected vectors. The selected
FIGURE 5  Shifting position of finishing stands of the training set

vectors offer several optional shifting positions and the range of shifting positions. According to the range of shifting positions, following the principle that all already used positions should be avoided, a new shifting position is to be created. First, a random shifting position is generated in the given range offered by the selected vectors. Second, if the new position can make PRP increasing in the work roll period, a new random shifting position is created, and the iteration is ended when every condition is satisfied. The newly generated shifting position is saved to the historical data file.

Sixty-two records of online in-site engineering data are selected to compose the training set. The range of strip target thickness is from 1.8 to 9.6 mm, the range of strip width is from 1240 to 1521 mm, the range of the rolling force is shown in Figure 4, the shifting position ranges of F1, F2, F3, and F4 are shown in Figure 5.

The range of strip target thickness, width, and rolling force of finishing stands cover most of the usually rolled products with a good quality of flatness as well as other quality indexes. The training set needs to be updated continuously with newly evaluated engineering records.

The k-NN algorithm is used to find the nearest neighbors of the input sample in training set by the Euclidean distances of thickness, width, and the rolling force of the first four stands of the finishing mill. Since the similar records number is 4 when the training set is built, the parameter $k$ is set as 4, too, to avoid overfitting and underfitting. The k-NN is a kind of nonparametric method used for classification and regression. The input consists of the $k$ closest training examples in the feature space. The output depends on whether k-NN is applied for classification or regression. Due to its simplicity, nearest neighbors have been successfully used in a large number of classification and regression problems, including handwritten digits and satellite image scenes. Being a nonparametric method, it is often successful in classification situations where the decision boundary is very irregular. The program is coded using C language under Visual Studio 2010 circumstance and ready for function testing.

4  |  NEW SHIFTING POSITION AND DISCUSSION

4.1  |  Offline optimization results

Eighty-seven rolled strips in one work roll changing period in the engineering log are selected to build a testing set. The 87 strips have already been rolled one by one, and the work roll shifting positions are recorded in the engineering log file. The distribution of shifting positions and PRPs is shown in Table 1.

The original shifting positions of F1, F2, F3, and F4 are shown in Figure 6. The curves of shifting positions present as some horizontal line segments in these figures. At the same time, the optimized shifting positions of F1–F4 stands are presented as a scatter plot, as shown in Figure 6. The unit crown curves in the finishing mill will change with the shifting positions if the compensation offered by the bending force is not enough to maintain the original roll gap. In the online model, if the target of profile and flatness control cannot be fulfilled, the optimization process will not be accomplished.
Kernel density estimation (KDE) is a nonparametric way to estimate the probability density function of a random variable. KDEs are closely related to histograms but can be endowed with properties such as smoothness or continuity by using a suitable kernel.\textsuperscript{35} KDE with Gaussian kernel is used to analyze the new shifting positions distribution, as shown in Figure 7. The bandwidth of the kernel is a free parameter that exhibits a strong influence on the resulting estimate. The bandwidth reflects the overall flatness of the KDE curve. More significant bandwidth causes a flatter overall curve of KDE. Smaller bandwidth makes the overall curve of KDE steeper. Based on the data, the bandwidth is selected for F1 16.5144, F2 8.1014, F3 8.7246, and F4 9.0342, respectively.

4.2 \hspace{1em} Training set building

The optimized strategy generates new shifting positions in the range of upper and lower limits offered by the training set. All data included in the limits are reliable and have been proved in an online rolling mill. The training set is built before the optimization work, and the new shifting positions should not be generated beyond the initial training set range. So, the training set needs a kind of mechanism to make it suitable for the continually changing rolling condition. Simulation is an effective way to obtain available rolling parameters and build the training set. Simulative work is often carried out using software, such as finite element method software\textsuperscript{36} and influence function method software.\textsuperscript{37}

4.3 \hspace{1em} Time consuming

The optimized strategy of roll shifting is based on the reference value contributed by the strip shape setup model. The setup model should finish the mission before the strip enters the finishing mill, and the optimization work should be carried out online. Therefore, the time for the optimization process is crucial, and it should be accomplished as soon as possible. A personal computer (PC) is used to carry out the testing calculation. The performance parameters of the PC are Intel Core i7-6700 CPU @ 3.40 GHz and 16.6 GB RAM.
The maximum time for the calculation is 0.153 s, and the minimum time is less than 0.001 s, the average is 0.81 s. Time elapsed for every strip and the full calculation time is shown in Figure 8. If the same types of records already exist, the time would elapse longer to avoid existing samples.

A more efficient algorithm is necessary to save CPU resources of online process control computers to make this strategy appreciate online use.

5 | **ONLINE APPLICATION**

Safety and efficiency are essential for the online control model in a hot rolling strip mill besides accuracy. For the shifting position optimization strategy, which is developed in this article, the calculation time is the bottleneck. Therefore,
the method should be simplified to save time. Selected vectors are generated using the training data set by the k-NN algorithm offline. The upper limit and lower limit of optional shifting positions are offered to the online program. It is easy for the online program to generate a random number between the limits to avoid needless duplication. After the new shifting position is created, it is checked whether duplicate. If the new position is duplicate and the number of the cycle does not exceed the limit, the iteration is started again. The simplified optimization process is shown in Figure 9.

The simplifying makes the program running faster and be suitable for online applications. It was embedded in the online setup model program of the 1780 mm hot rolling strip product line.

The work roll shifting positions optimized by the online optimization strategy are shown in Figure 10.

For the last 16 pieces of steel, in order to meet the work convenience requirements of specific products, the operator keeps the shifting positions of the first four stands unchanged, as shown in Figure 10.

As for the other 48 strips, the work roll shifting positions are kept moving and avoiding duplication as far as possible using the online optimization program. Although some duplications exist, the PRP of the four stands of the 48 strips is 8.3%, 2.0%, 6.3%, 2.0%, respectively. At the same time, there are no other adverse effects reported, and the crown and flatness control is normal.
The online setup model has the function of calculating bending force after the optimization. The box plots of renewed bending force reference values are shown in Figure 11. The bending forces of the first four stands are scattered in available ranges of 0–2300 kN.

6 | CONCLUSIONS

1. Considering both roll shape control and roll wear, an effective optimizing strategy of work roll shifting was built for CVC hot rolling mill. The online application shows that the optimizing strategy can eliminate shifting positions duplication, and the data statistics method is conducive to improving roll shifting control.
2. Time elapsed for every calculation of the optimization of roll shifting position was evaluated. For saving time, a simplified algorithm was applied online. Efficient algorithms and intelligent training set building methods should be proposed in the future.

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