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Study on the Effect of Continuous Annealing Process on Mechanical Properties of Cold Rolled Strip Steel

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abstract

The aim of this study is to investigate the influence of each parameter on the mechanical properties of strip steel in the continuous annealing process of cold rolled strip steel. The influence of each parameter on the hardness of strip steel was systematically analysed by collecting the specification data, process parameters and performance index data of the strip steel products, and applying descriptive statistical analysis, Spearman correlation coefficient analysis, random forest regression and factor analysis. The results show that carbon content, quenching furnace temperature, homogenising furnace temperature and fast cooling furnace temperature are the key factors affecting the hardness of strip steel. Among them, carbon content and quenching furnace temperature showed a significant positive correlation with hardness, while the average heating furnace temperature and fast cooling furnace temperature showed a significant negative correlation with hardness. These findings provide an important theoretical basis for optimising the production process of cold rolled strip steel, which helps to improve the product quality and the economic benefits of enterprises.

Keywords: Cold Rolled Strip Steel; Continuous Annealing; Mechanical Properties; Process Parameters; Correlation Analysis; Random Forests

1 | Introduction

Cold rolled strip is a high value-added product of steel enterprises, in practice, the strip after cold rolling needs to be continuously annealed to eliminate the internal stress and improve the mechanical properties of cold rolled strip. The process flow of continuous annealing is shown in Fig. which usually includes the stages of heating, holding, slow cooling, fast cooling, over-ageing, quenching, etc. 1,[1], as shown in Fig. 1.

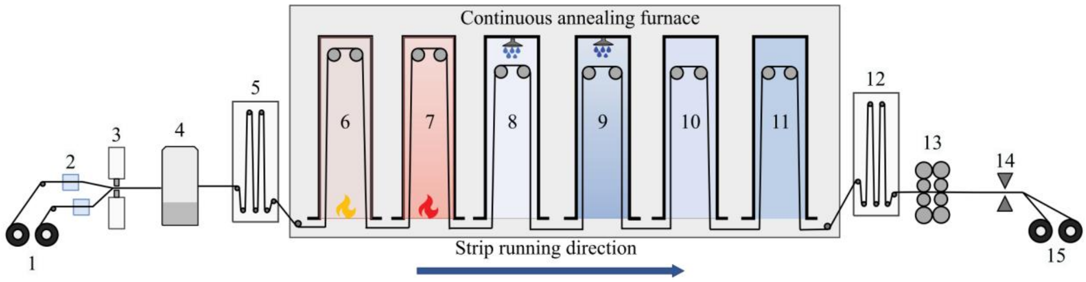

Figure 1 Process flow of continuous annealing process in cold rolling mills

Firstly, the strip is heated to a specified temperature in a heating furnace, and then held in an even-heat furnace to ensure that the temperature inside and outside the strip is the same; then the strip passes through the stages of slow-cooling furnace, fast-cooling furnace, over-ageing furnace, and quenching furnace in order to achieve the recrystallisation of the internal metal organisation and to achieve the required mechanical properties [2]. After the treatment is completed, the plate and coil will be tested offline for mechanical properties through the laboratory, and if the properties are not up to the standard, it will cause economic losses. Therefore, performance testing of strip is essential to optimise the quality of steel products.

2 | Literature Review

Due to the complex characteristics of the metallurgical industrial process, as well as equipment, technology, processing materials and cost and other factors, researchers or field operators are difficult to carry out a variety of experiments directly in the actual production line, people can not carry out in-depth research on complex objects (such as strip tension). In view of the system simulation technology has the characteristics of safety, economy and foresight [3], the use of simulation system can not only in-depth understanding and mastery of the dynamic characteristics of a variety of complex objects, but also for fault diagnosis and a variety of advanced control technology experiments, so the simulation system has been widely used in the metallurgical industry [4].

Regarding the research on dynamic modelling and simulation technology for the metallurgical industry, in the 1950s, the literature [5,6] firstly carried out simulation studies on the continuous rolling process to analyze the effects of small external disturbances on plate thickness and tension; the latter used the dynamic tension equation and thickness delay as the basis of computation and theory, and studied the change of tension and thickness of the strip between the racks in the continuous rolling process when a certain rack was affected by external disturbances. Later, Japanese scholars began the study of rolling process simulation and optimal control methods, in which the research work of Hiroshi Suzuki, Masamasa Kamada, etc. laid the foundation for this field, and analysed the dynamic characteristics of the continuous rolling process [7].Andreas Kugi et al. considered the influence of hydraulic servo mechanism, and established the corresponding system model, but the model will be considered as an external force of the rolling force, and there is no systematic model for the influence of the dynamic characteristics of the rolling process. However, the model considered the rolling force as an external force and did not systematically analyse the influence of the dynamic characteristics of the rolling process [8]. Literature [9] for the hot rolling mill to establish the seat model and rolling process model, considering the influence of the hydraulic system, the strip convexity and tension dynamic behaviour of the simulation. Literature [10] established a theoretical model of dynamic strip wearing process and simulated the strip wearing process of cold continuous rolling.

3| Effect of Parameters on Mechanical Properties of Strip Steel

3.1 Descriptive Analysis Based on Numerical Features of the Data

We help to determine those parameters that have an important influence on the mechanical properties of the strip based on the given specification data, process parameters and performance index data of the strip product. Firstly, we need to describe the distribution pattern of each performance parameter, and in this paper, we introduce mean, maximum, minimum, median, index difference, skewness coefficient and kurtosis coefficient to describe the statistical data.

(1) Skewness Factor

The skewness coefficient is a statistical measure used to describe the degree of skewness of a data distribution. It measures the symmetry of the data distribution with respect to the mean. If the data distribution is symmetrical, then the skewness coefficient is zero. The formula for calculating the skewness coefficient is:

$$S_k = \frac{n}{(n-1)(n-2)} \sum_{i=1}^{n} \left(\frac{x_i - \mu}{\sigma}\right)^3 = E\left[\left(\frac{X-\mu}{\sigma}\right)^3\right] = \frac{\mu^3}{\sigma^3}$$

Where n is the sample size, S_k is the skewness coefficient, $E(X)$ is the mean and μ^3 is the third order centre distance.

(2) Kurtosis Coefficient

Kurtosis is a statistical measure used to describe the steepness of a data distribution. It measures the thickness of the tails and the sharpness of the peaks of a data distribution. The kurtosis coefficient is calculated by the formula:

$$K_u = \frac{n(n+1)}{(n-1)(n-2)(n-3)} \sum_{i=1}^{n} \left(\frac{x_i - \mu}{\mu}\right)^4 - \frac{3(n-1)^2}{(n-2)(n-3)} = E\left[\left(\frac{X-\mu}{\sigma}\right)^4\right] = \frac{\mu^4}{\sigma^4}$$

where is the kurtosis coefficient of K_u and μ^4 is the fourth order centre distance.

(3) Indicator Solving

The statistical indicators for solving the given specification data, process parameters and performance index data of the strip products using MATLAB , as shown in Table 1 below.

Table 1 The Performance Parameter Index

norm	**Strip thickness**	**Strip width**	**carbon content**	**silicon content**	**Strip speed**	**Furnace temperature**	**Furnace temperature**	**Retarder temperature**	**Over-aging furnace temperature**	**Fast cooling furnace temperature**	**Hardening furnace temperature**	**Levelling machine tension**	**durometer**
minimum value	8020	180	218	4	481	673	619.5	573.5	312	40	28	1962.36	540
maximum values	9570	234	540	17	679	812.6	725	720.5	416.5	72	55	2852.45	660
average value	8600.59	204.04	381.74	8.98	614.68	720.35	649.18	623.8	354.48	59.93	41.8	2361.46	597.12
median	8470	202	387	9	629	718.8	644	618.5	352.25	57	42	2339.89	600
skewness	0.89	0.79	-0.61	0.75	-0.86	0.76	1.88	0.97	0.92	-0.02	-0.05	0.52	-0.76
kurtosis	3.22	3.4	3.61	3.73	2.98	4.94	5.99	3.73	4.01	1.29	2.65	3.31	3.13
(statistics) standard deviation	341.44	12.84	53.05	2.39	41.89	19.15	19.85	29.06	16.18	9.35	4.48	163.82	20.07

Overall, the variables in this data set show different characteristics in terms of skewness and kurtosis, with some variables such as homogeniser temperature and heating furnace temperature showing significant right skewness and peaks, while others such as carbon content and hardness show left skewness. The kurtosis of most of the variables is higher than 3, indicating a generally steeper distribution.

3.2 Judging the Correlation between Each Performance Index and Hardness Based on Spearman's Correlation Coefficient

Correlation analysis is to analyse the degree of correlation between the specification data, process parameters and performance index data of the given strip product. From the probability density distribution of each performance indicator in the figure above, it can be seen that some of the parameters do not satisfy the normal distribution, so we use Spearman's correlation coefficient to carry out the analysis. The final results are shown in Figure 2.

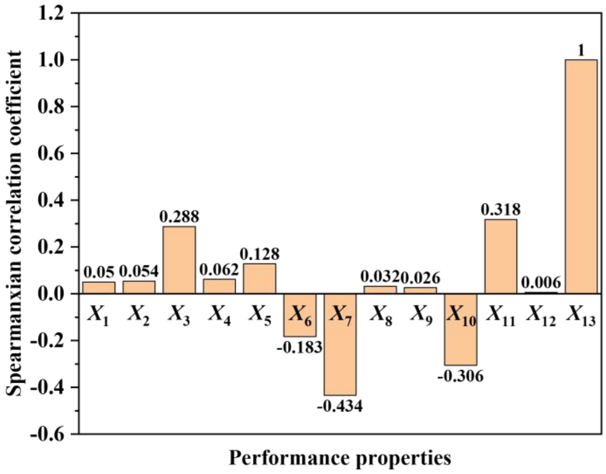

Figure 2 Spearman's Correlation Coefficient of Each Performance Attribute with Hardness

It can be analysed from the above charts that carbon content (0.288), strip speed (0.128), quenching furnace temperature (0.318) and hardness have a significant positive correlation; mean heat furnace temperature (-0.434), fast cooling furnace temperature (-0.306) and hardness have a significant negative correlation; and the strip thickness, strip width, silicon content, slow cooling furnace temperature, over-ageing furnace temperature, the tension of the flattening machine There is almost no correlation with the hardness, so the carbon contentparameters of have an important influence on the mechanical properties of the strip X_3, quenching furnace temperature X_{11}, homogenising furnace temperature X_7, fast cooling furnace temperature X_{10}.

3.3 Random Forest back Calculation of Eigenvalue Importance

The principle of Random Forest regression for calculating feature importance is based on the information gain that comes from using features for segmentation in decision trees.

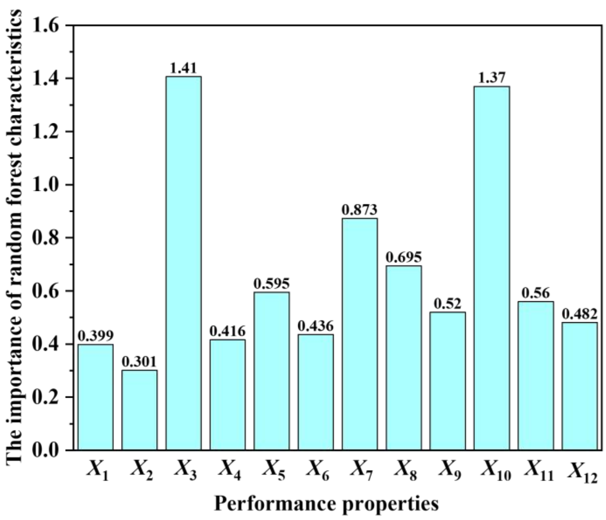

Figure 3 Characteristic Importance of Random Forests

From the analysed results in , it can be seen that the temperature of the fast cooling furnace and the carbon content are the two most important factors affecting the mechanical properties of the strip during the production process. Therefore, field operators should pay special attention to the control of these two parameters in the production. In addition, the temperature of slow cooling furnace, the temperature of uniform heating furnace and the tension of levelling machine also need to be controlled accurately to ensure the stability of the mechanical properties of the strip. In conclusion, the analysis of the importance of each process parameter can provide guidance for the optimisation of the production process and quality control, which can help to improve the stability of the quality of the strip products and the economic benefits of the enterprise.Fig. 3

3.4 Factor Analyses to Determine the Influence of Performance Parameters

Assume that the specification data, process parameters and performance index data for the 12 given strip products $X_i(i = 1,2,\cdots,12)$ can be expressed as:

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_{12} \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_{12} \end{bmatrix} + \begin{bmatrix} \alpha_{11} & \alpha_{21} & \cdots & \alpha_{15} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{25} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{12,1} & \alpha_{12,2} & \cdots & \alpha_{12,5} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_5 \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_{12} \end{bmatrix}$$

Where F_1, F_2, F_3, F_4, F_5 is the common factor we set and unobservable, their coefficients are called loading factors. And it is satisfied:

$$E(F) = 0, E(\varepsilon) = 0, Cov(F) = I_m$$

$$D(\varepsilon) = Cov(\varepsilon) = diag(\sigma_1{}^2, \sigma_1{}^2, \cdots, \sigma_1{}^2), Cov(F, \varepsilon) = 0$$

For the loading matrix of the two factors

$$\Lambda = (\alpha_{ij})_{12\times2}, i = 1,2,\cdots,12, j = 1,2$$

Taking orthogonal matrices

$$T = \begin{bmatrix} \cos\emptyset & -\sin\emptyset \\ \sin\emptyset & -\cos\emptyset \end{bmatrix}$$

Calculate the variance of the loadings for each factor, determine the rotation matrix by maximising the objective function, and finally calculate the rotated factor loading matrix.

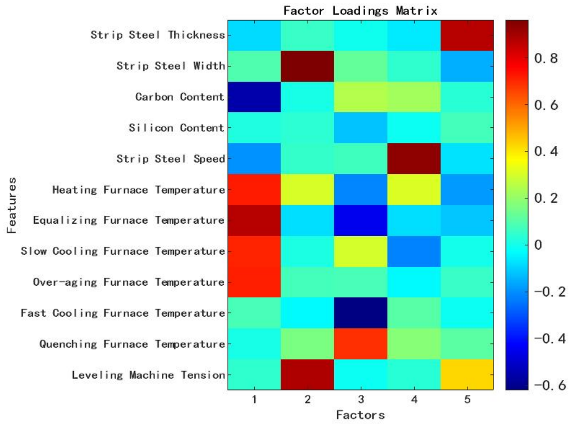

Figure 4 Coefficient Load Matrix

According to our results, strip thickness, strip width, silicon content and carbon content are the key specification parameters. Strip speed, furnace temperatures at each stage (heating furnace, uniform heat furnace, slow cooling furnace, fast cooling furnace, over-aging furnace, quenching furnace) and levelling machine tension are key process parameters. These parameters have a significant effect on the hardness of the strip and can be adjusted by the operator to optimise the mechanical properties of the strip and the production process.

4| Online Inspection Model for Strip Steel Product Quality

We build a data-driven online inspection model for strip steel product quality to ensure to help field operators monitor and analyse the performance of this online monitoring model. First, we divide the given data into two parts: training set and test set, then use CNN neural network regression algorithm and multivariate quadratic regression algorithm in the field of machine learning regression to train and predict other performance parameters as independent variables and hardness parameter as variable, and finally analyse and evaluate the performance of the online monitoring model based on the parameters of the test set.CNN is a deep learning model that is particularly good at processing local patterns in image and time-series data, automatically learning features of input data through a combination of convolutional, pooling and fully connected layers.

Input: Specification data, process parameters and performance indicators of the given strip product;
Output: Predicted values of hardness parameters.

For the evaluation of CNN models, MSE (Mean Square Error), RMSE (Root Mean Square Error), MAE (Mean Absolute Error), MAPE (Mean Absolute Percentage Error), and R^2 to measure the prediction accuracy and stability of the model on the training, cross-validation, and test sets are included.

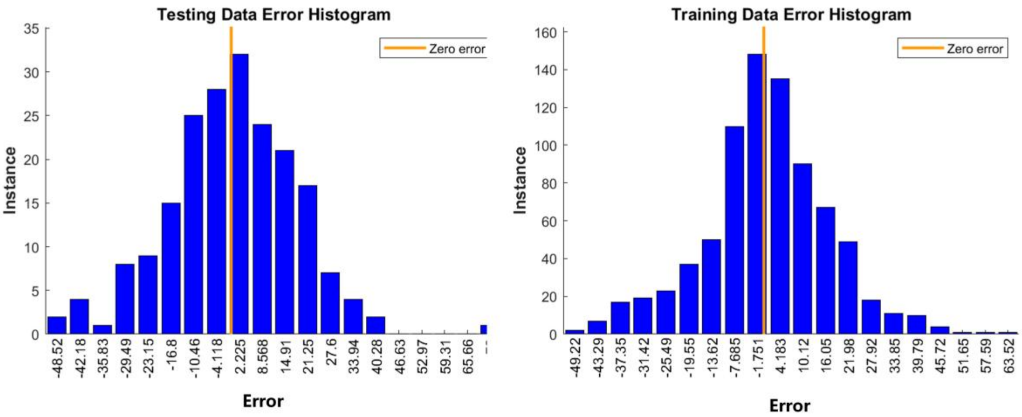

Figure 5 Histogram of test set vs. training set error

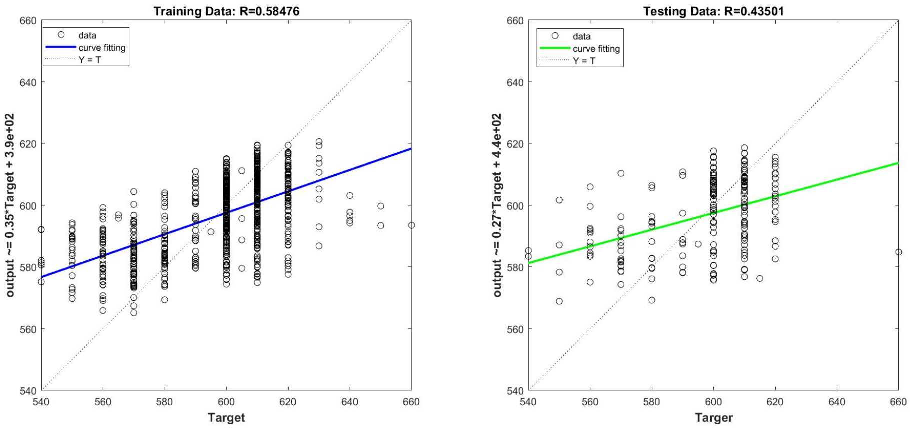

Figure 6 Regression Plots of the Training and Test Sets

Table 2 Model Evaluation Results

	MSE	RMSE	MAE	MAPE	R^2
Training Set	377.056	19.418	15.149	2.547	0.062
Cross Validation Set	395.32	19.875	15.514	2.607	0.016
Test Set	377.913	19.44	15.373	2.586	0.064

From the results of MSE, RMSE, MAE and MAPE, the performance of the model on the training set, cross-validation set and test set is very consistent, which indicates that the model has good stability and consistency. CNNs can automatically learn local features in the input data and gradually extract and combine them from low-level features to high-level features in a hierarchical way, so they perform particularly well in data processing with spatial or temporal features.

5| Conclusion

In this study, the effects of various parameters on the mechanical properties of strip steel in the continuous annealing process of cold rolled strip steel were systematically investigated through the comprehensive use of descriptive statistical analysis, Spearman's correlation coefficient analysis, random forest regression and factor analysis. The results show that carbon content, quenching furnace temperature, uniform heating furnace temperature and fast cooling furnace temperature are the key factors affecting the hardness of strip steel. Among them, carbon content and quenching furnace temperature were significantly positively correlated with hardness, while the average heating furnace temperature and fast cooling furnace temperature were significantly negatively correlated with hardness. These findings provide an important theoretical basis for optimising the production process of cold rolled strip steel, which helps to improve the product quality and the economic benefits of enterprises.

However, this study is mainly based on the analysis of historical data and lacks real-time monitoring and adjustment of dynamic changes in the actual production process. Secondly, although key influencing factors were identified, the interaction mechanism between these factors has not been explored in depth. In addition, the relatively limited sample size of the study may affect the generalisability and reliability of the results. Future studies should further expand the sample size, adopt more advanced data collection and analysis techniques, and study in depth the interactions among process parameters and the dynamic optimisation strategies in actual production, in order to better guide industrial production practices. In terms of quality control in other industrial fields, the specification data and process parameters of strip steel can be replaced with the product characteristics and process parameters of the corresponding fields, so as to solve the problem of product quality monitoring and optimisation in this field.

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