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To cite this article: Hairu Li et al 2019 IOP Conf. Ser.: Earth Environ. Sci. 332 032043

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IOP Conf. Series: Earth and Environmental Science 332 (2019) 032043 doi:10.1088/1755-1315/332/3/032043

Intelligent prediction method of mechanical property based on hybrid driving of industrial data and mechanism model for high speed wire

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Abstract. For the high speed wire production process, a temperature field model and a strain field model were established. Based on the metallurgical mechanism model, the recrystallization and phase transition processes of the high speed wire rolling process were calculated, and the microstructure closely related to the mechanical property was obtained. Based on the combination with the actual production data, an artificial intelligence neural network architecture for predicting product property was established. Through the training of a large amount of data, the mapping relationship between process parameters and mechanical property was obtained, which has practical significance for the adjustment of actual chemical composition and process optimization.

1. Introduction

As the user's requirements for steel properties become more stringent, the range of product performance fluctuations is required to be small, which puts higher requirements on process parameters and control. Due to the large number of equipment required for the high-speed wire production process, the control parameters that affect the performance of the final product are complex. The establishment of a quantitative prediction system for high-speed wire with certain precision can adjust and control the chemical composition and various production conditions to quickly find the cause of product performance fluctuations [1].

Product property prediction technology is based on production data and physical metallurgy mechanism model, for various metallographic phenomena in hot rolling production, such as austenite recrystallization, austenite to ferrite, pearlite and bainite phase transformation, predict the microstructure and mechanical properties of the product after rolling, so as to achieve the control of product properties, quality and process optimization. The core models of performance prediction include temperature calculation model, stress-strain model, recrystallization kinetic model, microstructure evolution model and performance prediction model. Each model is interconnected and influenced, and it is a unified whole [2,3].

2. Analysis of Factors Affecting Wire Property

In the process of high-speed wire rolling, the factors affecting the properties of the rolled piece after rolling include the following aspects.



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(1) Influence of chemical composition of materials

High-speed wire covers a wide range of steel grades, including low-carbon steel, welding rod steel, high and medium carbon steel, steel curtain steel, cold heading steel and spring steel, etc. A corresponding mechanism model is applied to different ranges of chemical composition when developing the performance prediction model.

(2) Effect of rolling piece temperature during rolling

In hot rolling, the rolling piece has a heat transfer method such as convection, radiation and deformation heat, which causes a complicated change in the temperature and a large temperature gradient inside the rolled piece. The rolling piece temperature affects the deformation and the rolling force energy parameters by affecting the deformation resistance. In addition, the temperature affects the microstructure and properties.

(3) Effect of deformation degree during rolling

High-speed wire rolling is a groove rolling, and the deformation process is complicated. Due to the uneven deformation of the wire during the rolling process, residual stress and microstructure may be uneven, which may affect the occurrence of dynamic and static recrystallization, and affect the final mechanical properties.

(4) Effect of actual production process conditions

Including production site equipment layout, rolling speed system, groove setting, cooling and other process conditions.

3. Microstructure evolution mechanism model

3.1. Temperature field model

In the rolling process, the high-speed wire is in the box-type groove, and the subsequent groove is round-elliptical type. Due to the irregular shape of the wire in the deformation zone, the finite element method is used to divide the element into the cross-section of the deformation zone and use two-dimensional temperature field model is solved. The problem of solving the partial differential equations of two-dimensional heat conduction problems under given boundary conditions and initial conditions can be equivalently expressed by the Euler-Lagrange equation as the following functional minimum value problem.

$$I = \frac{1}{2} \iint_{D} \left[k \left(\left(\frac{\partial T}{\partial x} \right)^{2} + \left(\frac{\partial T}{\partial y} \right)^{2} \right) - 2 \left(q - \rho c \frac{\partial T}{\partial t} \right) \cdot T \right] dx dy + \frac{1}{2} \int_{S} h (T - T_{f})^{2} ds$$
(1)

in this, T_f is the temperature of the medium around the rolled piece.

In order to establish the finite element formula, the area under study needs to be divided into m elements with n nodes, as shown in figure 1. The rolling process is an unstable heat transfer process, and the temperature-to-time derivative can be replaced by a differential. The equation (2) for solving the temperature field is obtained after derivation.

$$\left(\left[K_T \right] + \frac{1}{\Delta t} \left[K_3 \right] \left\{ T \right\}_t \right) = \frac{1}{\Delta t} \left[K_3 \right] \left\{ T \right\}_{t - \Delta t} + \left\{ p \right\}$$
⁽²⁾

in the formula, $[K_T]$ is the temperature stiffness matrix, $[K_3]$ is the temperature-varying matrix, and $\{p\}$ is the internal heat source and the boundary condition correlation matrix.

For the field equipment layout, the finite element method is used to calculate the temperature change curve of the rolling process and the water cooling process for the finished product of φ 5.0mm as shown in figure 2. It can be seen from the figure that the temperature of the wire surface changes sharply during rolling and cooling, and the temperature of the core is relatively gentle. As the diameter of the rolling process decreases, the temperature difference between the surface and the core gradually approaches. The temperature distribution on the wire section can be obtained by calculating the temperature field, which provides data support for the calculation of the tissue evolution model.

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Figure 1. Element division.

Figure 2. Temperature curve of high speed wire rolling process.

3.2. Deformation analysis during rolling

High-speed wire rolling has many passes and complex deformation. The strain at different positions on the cross-section is different, this will lead to different recrystallization behaviours, and it is necessary to analyse the deformation process. Due to the symmetry of the cross-sectional shape of the wire, a quarter section similar to the temperature field calculation was selected for strain analysis.

The strain field is simulated by finite element software, and the calculation results of the study area are extracted, and the strain law of the rolled piece is comprehensively analysed. Considering that the strain change of the rolling piece is affected by factors such as stress, temperature and strain rate, the material properties adopt the Johnson-Cook constitutive equation. After the calculation is completed, the coordinates and strain values of each point can be extracted, and then the strain distribution bar graph as shown in figure 3 is drawn.



Figure 3. Different rolling pass strain distribution.

By comparing and analysing the strain distribution of the section, it is known that the strain distribution trends at different positions during the rolling process are different, which directly leads to the difference in austenite recrystallization behaviour. Combined with the calculation of the temperature field, it is possible to accurately calculate the recrystallization behaviour at different positions of the section.

3.3. Microstructure evolution model

During the rolling and cooling of high-speed wire rods, austenite will undergo dynamic recrystallization during the high-temperature rolling stage and static recrystallization will occur during the mill interval. During the cooling of the stelmor, austenite will undergo a continuous cooling transition to ferrite, pearlite and bainite. There are three forms of grain evolution during thermal

deformation, including dynamic recrystallization, static recrystallization and grain growth. The mathematical model describing the evolution process of the grain should contain the grain size model and the corresponding recrystallization kinetic model [4]. Using the temperature and strain results, the microstructure of the hot rolled product and the austenite size after rolling can be predicted by calculation. Dynamic recrystallized grain growth can be expressed by the equation (3).

$$d_{DG}^{2} = d_{D}^{2} + 3900 \cdot Ceq^{-1.43} \cdot \exp(-5380/T) \cdot t^{0.3}$$
(3)

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in the equation, d_D is the initial dynamic recrystallized grain size.

On the stelmor wind-cooled line, the wire will undergo a phase transformation from supercooled austenite to ferrite, pearlite and bainite. The austenite isothermal phase transformation kinetics can be described by the JMA equation. Using the classical nucleation and growth theory, the volume fraction and grain size of the transformed austenite into a new phase can be determined. The formula for calculating the phase transformation rate can be expressed by equation (4).

$$\frac{X}{X_{\text{max}}} = 1 - \exp\left(-\frac{1}{2.24}\left[\left(\frac{2.24}{\bar{d}_r}\right) \cdot q + 0.114 * (\Delta\varepsilon)^2\right] \cdot \left[1 + B \cdot (\Delta\varepsilon) \cdot k \cdot t^n\right]\right)$$
(4)

in it, k and n take corresponding values according to different phase change types.

The chemical composition and cooling rate directly affect the phase transformation process. In order to be able to describe the key influencing factors of the finished product properties, it is necessary to establish a calculation model of the phase fraction, ferrite grain size, pearlite interlayer spacing or cementite layer thickness with certain precision. The properties evaluation parameters after phase transformation are solved iteratively according to the cooling curve.

4. Properties prediction method based on industrial data

For the prediction method of the relationship between microstructure and mechanical properties, most of the classical research methods are based on production accumulation data and experimental data, and statistical regression methods are used to establish quantitative relationships. Since wire production is a complex system, the production process is constantly interfered by various random factors, and it is difficult to express it with accurate mathematical formulas [5,6]. Therefore, the results obtained by the traditional method are difficult to achieve the desired prediction effect.



Figure 4. High-speed wire properties prediction architecture.

The artificial intelligence neural network is an artificial intelligence pattern recognition method which is built by simulating the learning process of the brain nerve to the external environment. It has the function of adaptive learning and the complex nonlinearity of processing. Especially in recent years, the development of deep learning has gradually matured and has been successfully applied in the analysis and processing of industrial data [7]. With the improvement of deep neural network algorithms and the improvement of computer computing power, it can be formed in the training process. More data features, better fit training data, reduce the occurrence of under-fitting and overfitting.

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The neural network adopts the minimum mean square error learning method to complete the mapping of the input signal to the output signal during the process of minimizing the evaluation function. Properties data required for high speed wire includes tensile strength, area reduction and elongation. A large amount of properties sampling data is accumulated in the production database, which can be directly used as a training data sample of the neural network. The prediction architecture is shown in figure 4.

Through the training test of 3000 sets of data on the production site, the relative error between the output value of the sample and the output of the network is within 5%, which proves that the deep neural network has good prediction accuracy. Based on the established deep neural network architecture, this paper achieves high-precision prediction of high-speed wire properties, and the prediction results meet the optimization requirements of process control parameters.

5. Conclusion

(1) The calculation method of temperature and deformation of high-speed wire rolling process was established. Combined with the production process, the parameters determining product properties were calculated by mechanism model such as recrystallization kinetics model and tissue evolution, and the calculation results were verified by experimental means.

(2) The artificial neural network properties prediction architecture is designed. The chemical composition and mechanism model calculation results are used as the network input, and the properties evaluation is used as the network output. The mapping relationship between input and output is established through multiple hidden layers. After the neural network is trained in production data, the properties prediction of the product is realized. The test results of typical samples show that the prediction accuracy can meet the production requirements.

(3) Based on the development of high-speed wire intelligent prediction system driven by production data and mechanism model, the data depends on the key process parameters of the production process, and the prediction results directly reflect the influence of process setting on product properties. The system can achieve dynamic prediction and correction of product quality, optimize process design, and reduce properties fluctuations.

Acknowledgments

This work was supported by the national key research and development program of China (2017YFB0304203).

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