Effect of Phase Transformation and Latent Heat on Hot Rolling Deformation Behavior of Non-oriented Electrical Steel

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(Received on November 9, 2016; accepted on January 19, 2017; J-STAGE Advance published date: April 4, 2017)

In order to make up for the deficiency of the traditional austenite deformation resistance model and the existing rolling theory in the gage and shape control of hot rolled non-oriented electrical steel, the mathematical models related to phase transformation are established by regression analysis and then written to be ABAQUS subroutines, which are subsequently embedded into the heat transfer model and rolls-strip coupling model. The finite element models are used to accurately predict the transverse distribution of the temperature field and phase field, and analyze the effect of phase transformation and latent heat on the total roll force, distribution of per unit roll force and roll gap profile. The transverse transformation difference is induced by the temperature difference along strip width direction. The latent heat contributes to the uniformity of temperature field and phase field. The total roll force and center gage are reduced due to the phase transformation, but the adjustment of roll force on the crown is enhanced and the rolling pressure spikes are eliminated due to the appearance of ferrite phase in the edge of strip. The roll force distribution and roll gap profile are weakly dependent on the latent heat, but primarily influenced by the transformation.

KEY WORDS: non-oriented electrical steel; hot strip mills; phase transformation; latent heat; ABAQUS secondary development.

1. Introduction

Non-oriented electrical steel is a kind of high value-added and high quality steel product. In addition to the requirements of magnetic properties of low iron loss and high magnetic induction, the gage and shape of strips as the most important indicator of dimensional precision have been paid more and more attention by producers and users.1–4) The hot rolling production process of non-oriented electrical steel is almost the same as the carbon steel, but because of the particularity of material composition and rolling schedule related to product performance, which results in the beginning temperature of transformation is between the entrance temperature and finishing rolling temperature, the multiphase rolling is inevitable during hot finishing rolling,5) as shown in Fig. 1. Along rolling direction, the upstream stands locate in the austenite region, the middlestream stands drop into dual-phase region, and the downstream stands reach the ferrite region. Furthermore, due to the obvious temperature difference along strip width direction, the time of dropping into dual-phase region of middle section is different from that of edge section. And also because the heat dissipation area and cooling rate in two sections are different during finishing rolling process, the non-uniform transverse microstructure distribution is caused ultimately. It can be found from the transverse microstructure distribution in each phase regions that in austenite or ferrite phase region the phase type is single phase, while in dual-phase region, the middle section is usually austenite or austenite-ferrite mixed structure and the edge section is usually austenite-ferrite mixed structure, even ferrite structure. The transverse difference of temperature and microstructure will together contribute to the uneven distribution of deformation resistance of material. Due to the high temperature deformation characteristics in dual-phase region is opposite to the austenite or ferrite single phase region,6) and the latent heat is released simultaneously with the phase transformation, the accuracy of roll force prediction is decreased by using the traditional austenitic rolling model in which the influences of microstructure difference and latent heat are neglected, which will cause thickness oversize or abnormal wave and seriously affect the product quality and stability during hot rolling process of non-oriented electrical steel.7)

In order to make clear the influence of phase transformation on hot rolling deformation behavior, the researchers have studied from three aspects: deformation resistance model, effect of phase transformation on rolling deformation and effect of latent heat due to phase transformation. On the aspect of deformation resistance model, the models
for austenite region, ferrite region and dual-phase region are established respectively by regression analysis of the experimental data. C. S. Li et al. determined the critical transformation temperature range of non-oriented electrical steel adopting CCT experiment, and described the deformation resistance of three phase regions adopting the traditional model, of which coefficients are obtained by regression analysis of the hot compression test data. The similar method was employed by S. Z. Wang et al. to analyze the effect of deformation temperature, strain and strain rate on the deformation resistance. Y. Dong et al. completed the division of different phases according to temperature and subsequently established the constitutive model respectively for single phase regions of austenite and ferrite by the Arrhenius model. It can be seen from previous research results that the existing deformation resistance models of non-oriented electrical steel are essentially statistical models, which typically adopt the functions consisting of macro deformation factors and simply couple or equivalently deal with each effect, so that the influence of microstructure evolution on the macro mechanical properties cannot be reflected. Furthermore, the deformation resistance in dual-phase region is closely related with the transformed fraction that vary nonlinearly with time and temperature. However the existing models without microstructure information only use temperature to approximately express this relationship, which will be incapable to accurately represent the nonlinear variation characteristics and cause inaccurate results. Therefore, it is necessary to establish a deformation mechanism model, which is based on accurate prediction of the proportion fraction of each phase under various cooling conditions at any time, to calculate the deformation resistance in different phase regions, especially in dual-phase region. On the aspect of effect of phase transformation on rolling deformation, the related theoretical research is less, and it is still a hot spot and difficult point in controlled rolling of non-oriented electrical steel. Y. Saito divided the strip into two single phase regions along width direction, it is difficult to determine the boundaries of two phase regions and the “phase step” is inconsistent with actual smooth distribution. It is necessary to accurately predict the transverse microstructure distribution under different conditions, and establish the coupled Thermal-Transformation-Mechanical rolling model including the effect of phase transformation. On the aspect of effect of latent heat due to phase transformation, the researchers mostly focus on the effect of latent heat on the temperature and residual stress in the laminar cooling process after rolling. However, the quantification of latent heat between finishing mill stands and the effect of latent heat on followed hot rolling deformation are rarely reported, which restrict the further improvement of accuracy of gage and shape control.

It is obvious that the knowledge and quantitative analysis for the evolution law and softening mechanism of γ-α transformation during finishing rolling process are still incomplete. The existing rolling theory is difficult to meet the requirements of gage and shape control during same width rolling and cross rolling of non-oriented electrical steel. To solve this problem, on the one hand, it is necessary to establish the deformation resistance model of non-oriented electrical steel in different phase regions and with various proportion fraction to make up the deficiency of traditional deformation resistance model. On the other hand, it is necessary to study the effect of transverse difference of temperature and microstructure and the latent heat due to transformation on the hot rolling deformation to broaden the application range of the existing rolling theory under complex deformation conditions.

In the present study, the mathematical models related to phase transformation are established by regression analysis
and then written to be ABAQUS subroutines, which are subsequently embedded into the heat transfer model and rolls-strip coupling model. The models can accurately predict the transverse distribution of the temperature field and phase field, and the calculated results are fitted into mathematical functions as the state variables, and then taken into followed rolling deformation to further analyze the effect of transverse differences of temperature and microstructure on the total roll force, distribution of per unit roll force and roll gap profile. The new coupled Thermal-Transformation-Mechanical rolling model can make up the deficiency of the existing rolling models, reveal the effect of phase transformation on hot rolling deformation behavior, and lay a theoretical foundation for the further development of accurate prediction model of hot rolled non-oriented electrical steel.

2. Mathematical Model Related to Transformation

In order to quantify the transformation process and latent heat of non-oriented electrical steel and obtain the deformation resistance in each phase region, the transformation kinetics model, latent heat model and high-temperature deformation constitutive models based on dislocation density theory are established respectively by thermal dilatometric tests, DSC thermal analysis test and hot compression experiments, which lay the foundation for the secondary development of ABAQUS subroutines to represent the effect of phase transformation.

2.1. Transformation Kinetics Model

In order to describe the transformation process and accurately predict the proportion fraction of each phase at a given cooling condition at any time, it is necessary to establish the transformation kinetics model for non-oriented electrical steel. There are four steps: ① The critical transformation temperature range was determined by continuous-cooling test CCT at an extremely low cooling rate. ② According to the critical transformation temperature range, TTT tests were designed and isothermal transformation kinetics model was formulated by fitting the measured data. ③ In combination with the Additivity Principle, continuous-cooling transformation kinetics model was established. ④ Model validation.

In detail, firstly, the cylindrical specimen of 4 mm in diameter and 10 mm in height was taken for test by dilatometer DIL805A. The specimen was austenitized by heating to 1120°C and holding for 10 min, and subsequently cooled to room temperature at a rate of 0.05°C/s. The chemical composition of the non-oriented electrical steel from which the test specimens were machined is listed in Table 1. From the Dilatometer-Temperature curve of CCT, The Ar3s and Ar3f, which correspond to the separation points between transformed fraction and time was obtained by normalizing the Dilatometer-Temperature curves. The Avrami equation was employed to characterize the isothermal transformation kinetics as shown by Eq. (1).\(^\text{16}\) Equation (2) was derived by using logarithm on both sides of Eq. (1). The parameters \(n\) and \(k\) at different temperatures were obtained from a least-squares fit to the plot of \(\ln[1/(1-X)]-\ln r\) as shown in Fig. 3. It can be seen that \(n\) is effectively independent of the temperature and the average value is 1.6. \(\ln k\) is almost linearly varying with temperature and the expression of \(k\) was derived as Eq. (3) after regression. By substituting \(n\) and \(k\) for Eq. (1), the isothermal transformation kinetics model of non-oriented electrical steel was finally derived as Eq. (4).

\[
X(t) = 1 - \exp\left(-kt^n\right) \quad (1)
\]

\[
\ln \ln \left[\frac{1}{1-X}\right] = n \ln t + \ln k \quad (2)
\]

\[
k(T) = \exp(-0.103T + 96.989) \quad (3)
\]

\[
X(t) = 1 - \exp\left(-\exp\left(-0.103T + 96.989\right)t^6\right) \quad (4)
\]

| Chemical composition of non-oriented electrical steel tested (mass%). |
|------------------|---|---|---|---|---|
| C                | Si | Mn | P  | S  |
| 0.0031           | 0.77 | 0.25 | 0.02 | 0.005 |

Fig. 2. Dilatometer-Temperature curve of CCT.

Fig. 3. \(n\) and \(\ln k\) at different temperatures.
Thirdly, based on the isothermal transformation kinetics model and in combination with the Additivity Principle, the transformed fraction in the continuous-cooling transformation process at any time \( t_{i+1} \) was expressed by Eq. (5).

\[
X(t_{i+1}) = 1 - \exp \left[ -k_i \left( t_{i+1} - t_i \right)^n \right] \tag{5}
\]

where \( t_i \) is given as follow, \( k_i \) and \( n_i \) are the reaction rate and Avrami exponent at the temperature \( T_i \), respectively.

\[
t_i = \frac{\ln \left( 1 - X(t_i) \right)}{k_i} \tag{6}
\]

Finally, in order to validate the model proposed, a verification test was designed by cooling the specimen from austenitized temperature 1 120°C to room temperature at a rate of 10°C/s. It can be seen from Fig. 4 that the calculated results are fairly close to the measured results and the square value of the correlation coefficient \( R^2 \) is 0.968. Thus the validity of the model is confirmed to be adequate.

2.2. Latent Heat Model

The latent heat is released simultaneously with the phase transformation, which will affect the temperature distribution of strip between finishing mill stands, and in turn affect the amount of transformation. Therefore, it is necessary to quantify the latent heat due to transformation by the experiment, and establish the corresponding mathematical model. The cylindrical specimen of 4 mm in diameter and 0.5 mm in height was taken for test by thermal analyzer SDT Q600. The specimen was austenitized by heating to 1 200°C at a rate of 10°C/min, and subsequently cooled to 900°C at the same rate. By analyzing the automatically recorded DSC curve as shown in Fig. 5, the specific enthalpy of non-oriented electrical steel is identified as 25.25 J/g, which is the specific enthalpy of non-oriented electrical steel was established as Eq. (8)

\[
\sigma = \left( \left( \alpha \mu b \right)^2 h \sigma / s \left[ 1 - e^{-\beta / T} \right] + \sigma_0 e^{-\beta / T} \right)^{1/2} \tag{8}
\]

where \( \sigma \) is the material constant, \( \mu \) is the modulus of rigidity, and \( b \) is the Burgers vector, \( \sigma_0 \) is the yield stress, \( \alpha \) is the deformation resistance, \( h \) is the hardening coefficient representing growth rate of dislocation density, \( s \) is the softening coefficient representing decreasing rate of dislocation density.

The hot compression experiments were conducted in a wide temperature range from austenite to ferrite by Gleeble 3500. Three austenite temperatures (1 000°C, 1 050°C, 1 100°C), three ferrite temperatures (800°C, 850°C, 900°C) and one dual-phase temperatures (950°C) are selected. Strain and strain rate are respectively 0.7 and 10 s\(^{-1}\). By the regression analysis of experimental data, the characteristic parameters of deformation resistance model for austenite and ferrite phase regions are shown in Eqs. (9) and (10), respectively.

\[
\begin{align*}
\sigma_A &= \left( \left( \alpha_A \mu b \right)^2 h_A \sigma / s_A \left[ 1 - e^{-\beta / T} \right] + \sigma_0 e^{-\beta / T} \right)^{1/2} \\
&= 1.97 \\
\sigma_0 (T) &= -2.00 \times 10^{-5} T^2 + 2.24 \times 10^{-2} T + 33.66 \tag{9} \\
h_A (T) &= -1.11 \times 10^{-7} T^2 + 2.077 \times 10^{-5} T - 860.10 \\
s_A (T) &= 3.80 \times 10^{-5} T^2 + 6.50 \times 10^{-3} T + 2.74
\end{align*}
\]
For the calculation of deformation resistance in dual-phase region, firstly the transformed fraction is calculated by the transformation kinetics equations, which is taken as weight coefficient to mix the two phases. Meanwhile, the softening effect of dynamic transformation restoration is also considered.20,21) The expression is as follow:

\[
\sigma = (1-\beta)\left[\sigma_A (1-X) + \sigma_C X\right]
\]

where \(\beta\) is the softening factor representing the softening effect of dynamic transformation restoration, \(X\) is the transformed fraction. As is known, it is difficult to accurately describe the complex coupling relationship between dynamic transformation restoration and hot deformation by mathematical formula. Thus by the regression analysis of measured stress-strain data, the variation trend of softening factor \(\beta\) with strain \(\varepsilon\) was obtained. It can be seen from Fig. 6 that with the increase of deformation, the softening effect is obviously enhanced in the beginning, and then tends to be stable until the hardening effect of plastic deformation is balanced. According to the characteristic of the curve, the softening factor \(\beta\) is expressed by exponential function as follow:

\[
\beta = 0.294 \left( e^{-0.097\varepsilon} - e^{-0.396\varepsilon} \right)
\]

3. Thermal-Transformation-Mechanical Coupling Model

3.1. Model Simplification

According to the characteristic of temperature drop during finishing rolling process of non-oriented electrical steel, the model is simplified as follows:

(1) The period of strip in the roll gap is very short and the amount of phase transformation is relatively small. Furthermore, the temperature drop due to heat transfer between strip and rolls will be partially or fully compensated by the temperature rise due to plastic deformation of strip. Therefore, the variation of temperature and microstructure in the roll gap is not considered.

(2) Because the length of strip is far greater than the width and thickness, and the temperature control technology along strip length direction is mature which makes the temperature fluctuation controlled within 10°C,22) so the heat transfer along length direction can be ignored. Furthermore, the strip is thin during finishing rolling, the rate of heat transfer along thickness direction is fast and temperature difference between the top/bottom surface and the central part is small. Therefore, the slightly uneven temperature along strip thickness direction is ignored. Therefore, only the obvious difference along the transverse direction is considered.

3.2. Initial Temperature and Boundary Conditions

Based on an actual working condition from industrial mills and using the two-dimensional alternating difference method,22,23) the magnitude and distribution of temperature field of strip at the exit of the finishing mill stands were calculated. The temperature distribution of center layer of cross section of strip at F3 mill stand exit is shown in Fig. 7(a). It can be seen that the temperature of middle and edge of strip are respectively 995.2°C and 965.3°C. The edge of strip is very close to the critical transformation point. In other words, the edge of strip will transform from austenite to ferrite firstly, and the middle of strip will not change because its temperature is higher than the critical transformation temperature. Thus there will be an obvi-
ous transverse microstructure difference at the entrance of next stand and the strip will be rolled in the dual-phase region at F4 mill stand. The above results coincide with the actual position of phase transformation and abnormal wave observed in Ref. 7). Therefore, in this study the temperature distribution of strip at F3 mill stand exit is selected as the initial temperature field and subsequently the rolling process at F4 mill stand is simulated, which can most unlimitedly reflect the effect of transverse microstructure difference on the hot rolling deformation.

In order to avoid the excessive speed of phase transformation affecting the stability of rolling, the cooling water between finishing stands is always switched off. The strip between finishing mill stands is generally under air cooling, and there are two kinds of heat transfer forms: radiation and convection. In this study, the equivalent heat flux is proposed to represent the combined effect of radiation and convection. The emissivity and convection coefficient between strip and air are referred to Ref. 24). The magnitude and distribution of equivalent heat flux are obtained by conversion as shown in Fig. 7(b). It can be seen that the absolute value of equivalent heat flux in the edge of strip is larger than in the middle due to the larger heat transfer area in the edge.

The key rolling parameters of F4 mill stand are shown in Table 2.3.3. Finite Element Coupling Model

After simplifying model in front, the Thermal-Transformation-Mechanical coupling model can be decomposed into two parts, as shown in Fig. 8. One is interstand model to calculate temperature, transformed fraction and latent heat of strip between mill stands. The other one is rolling model considering the effect of temperature and microstructure in the roll gap. The temperature field and phase field calculated by the interstand model are fitted into mathematical functions as the state variables, and then transferred to the rolling model to realize the coupling solution of interstand and roll gap, microstructure evolution and macro hot deformation. The basic models, including heat transfer model and rolls-strip coupling model, are realized by the conventional finite element method. The other models related to phase transformation are achieved by user subroutines.

3.3.1. Basic Finite Element Model

Heat transfer model for strip between mill stands is shown in Fig. 9(a). The width and thickness of strip were respectively 1250 mm and 10.66 mm. The strip was divided into four layers along thickness direction and the mesh size along length direction and width direction were respectively 2.5 mm and 4 mm. The analysis type of “heat transfer, implicit” was adopted. The element type was C3D8. The initial temperature field was set up in the initial step. The cooling boundary conditions were applied to all nodes in the form of load functions.

According to symmetry, the 1/4 rolls-strip coupling model was established, as shown in Fig. 9(b). The analysis

### Table 2. Key rolling parameters of F4 mill stand.

<table>
<thead>
<tr>
<th>Entry thickness/mm</th>
<th>Exit thickness/mm</th>
<th>Bending force/kN</th>
<th>Front tension/MPa</th>
<th>Back tension/MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.66</td>
<td>6.6</td>
<td>1200</td>
<td>12</td>
<td>8</td>
</tr>
</tbody>
</table>

![Fig. 8. Thermal-Transformation-Mechanical coupling model.](image)

![Fig. 9. Basic finite element model. (a) Interstand heat transfer model. (b) Rolls-strip coupling model.](image)
type was “dynamic, explicit”. Rollers were elastic and strip was elastic-plastic. The mesh size of strip was same as the previous model. The element type was C3D8I. The contact surfaces of backup rolls and work rolls, work rolls and strip were specially refined to improve the accuracy of simulation results. The discrete rigid sheets were created and tied to the roller ends to simulate the rotation of rollers. The smooth loading curve was adopted to make all the contact steadily built, and then the stable rolling was carried out.

3.3.2. Subroutine Secondary Development

The subroutines applied in the interstand model are described as follows:

SDVINI: initial subroutine, which is used to initialize the proportion fraction of austenite and ferrite.

KINETICS: transformation kinetics subroutine, which is programmed according to the front transformation kinetics models, is used to calculate the transformed fraction and transition rate at a given cooling condition at any time.

HETVAL: latent heat subroutine, which is programmed according to the front latent heat model, is used to quantify the latent heat due to transformation and realize the coupling of temperature field and phase field. The transition rate for the calculation is acquired by the subroutine KINETICS presented above.

The subroutines applied in the rolling model are described as follow:

VUMAT: elastoplastic constitutive subroutine, which is used to describe the stress-strain relation of the material and obtain the new value of stress and strain after a strain increment is given.

TRANSFER: state variables transfer subroutine, which can transfer the state variables of temperature field and phase field from the interstand model to the rolling model at the first incremental step, is used to provide the initial state of strip for rolling.

HARDSUB: deformation resistance subroutine, which is programmed according to the front deformation resistance models, is used to calculate the deformation resistance of material under different phase regions, temperatures and proportion fraction.

4. Results and Discussion

In order to accurately predict the distribution of phase field, reflect the coupling relationship between temperature field and phase field under the influence of latent heat, and comparatively analyze the effect of transformation and latent heat on hot rolling deformation, three typical simulation conditions are designed, as shown in Table 3.

### Table 3. Typical simulation conditions.

<table>
<thead>
<tr>
<th>Simplified symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Without transformation (pure austenite)</td>
</tr>
<tr>
<td>A+F</td>
<td>Transformation considering variation of phase structure</td>
</tr>
<tr>
<td>A+F+Heat</td>
<td>Transformation considering variation of phase structure and latent heat</td>
</tr>
</tbody>
</table>

Figure 10(a) shows the effect of latent heat on the temperature field. The temperature of whole strip decrease during air cooling between mill stands. Because the contact area between the edge section and air is larger than the middle section, so the temperature drop in the edge is larger. Without taking into account the effect of the latent heat, the maximum temperature difference along strip width direction increases from 29.90°C to 40.17°C. However, when the effect of the latent heat is considered, the thermal energy compensated by latent heat slows down the rate of temperature drop in the edge. The inhomogeneity of transverse temperature is improved and the maximum temperature difference decreases to 24.38°C.

Figure 10(b) shows the effect of latent heat on the phase field. Because the initial temperature in the edge of strip is lower, the phase transformation will occur with a priority. And the closer to the edge, the faster the cooling rate, the greater the temperature drop, the longer the period of transformation, and the larger the transformed fraction. The temperature in the middle of strip maintains above the criti-
cal transformation temperature, so the transformed fraction is zero and the phase type remains austenite in the middle of strip. Without taking into account the effect of the latent heat, the transformed fraction of ferrite in the edge can reach 97.63%, which is roughly equal to the pure ferrite. In such a situation, the transverse microstructure difference is significant. However, when the effect of the latent heat is considered, the latent heat as internal heat source can lead to the temperature rise, which will in turn decrease the undercooling and restrain the transformation process. Thus during the same time, the transformed fraction of ferrite in the edge decrease to 82.99%. It can be found that the latent heat has an inhibitory effect on the phase transformation. The more latent heat released, the more obvious the inhibitory effect is. The inhomogeneity of transverse microstructure distribution is improved.

4.2. Effect of Transformation and Latent Heat on Hot Rolling Deformation

After the phase transformation between finishing mill stands, the temperature field and phase field of strip are redistributed and become inhomogeneous. Subsequently the strip with such an initial state is deformed in the roll gap of next mill stand. The uneven temperature and microstructure may lead to the non-uniform distribution of deformation resistance of material along strip width direction, which will affect the distribution of per unit roll force and eventually change the roll gap profile. By the rolling model established in front, the total roll force, distribution of per unit roll force and roll gap profile are calculated under different conditions to comparatively analyze the effect of transformation and latent heat on the hot rolling deformation, as shown in Fig. 11.

Figure 11(a) shows the effect of transformation and latent heat on the total roll force. When the partial transformation occurs, the average deformation resistance decreases with the increase of ferrite, which result in the decrease of total roll force by about 7%. In addition, the latent heat has little influence on the total roll force.

Figure 11(b) shows the effect of transformation and latent heat on the distribution of per unit roll force. Without taking into account the transformation, the deformation resistance of material in the edge of strip becomes larger due to the lower temperature, and the pressure spikes easily emerge during the plastic deformation of the edge metal. However, when the effect of the transformation is considered, due to the qualitative change for the edge metal, the pressure spikes are eliminated by the softening effect of ferrite. Therefore the per unit roll force becomes uniform throughout the strip width. In addition, the latent heat has little influence on the distribution of per unit roll force. The reason is that although the release of latent heat make the temperature recovered, it also reduce the amount of precipitation of ferrite. The former causes the deformation resistance of material to decrease, and the latter makes the softening effect weaken. Finally the two effects cancel each other out.

Figure 11(c) shows the effect of transformation and latent heat on the roll gap profile. Due to the decrease of roll force, the roll flattening is reduced and the center thickness of rolled strip is reduced by about 0.05 mm. It is generally known that with the roll force decrease, the roll deflection and the crown of roll gap will be reduced. However, for the non-oriented electrical steel including phase transformation, due to the transformed soft phase structure in the edge of strip, the edge metal flows easily and the adjustment of roll force on the crown is enhanced. Eventually, the crown of roll gap is unexpectedly increased by $70\,\mu m$ compared to the traditional analysis. It reveals the reason why the edge drop of hot rolled non-oriented electrical steel is more significant than conventional carbon steels. In addition, due to the improving effect of latent heat on the inhomogeneity of temperature field and phase field, the roll gap profile becomes smoother, but the change of crown is limited by only $3\,\mu m$. 

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Fig. 11. Effect of transformation and latent heat on hot rolling deformation. (a) Effect on total roll force. (b) Effect on per unit roll force. (c) Effect on roll gap profile.
due to the partial transformation, which results in the total roll force reducing by about 7% and the center thickness of rolled strip reducing by about 0.05 mm. Although the roll force decrease, the adjustment of roll force on the crown is enhanced due to the transformed soft phase structure in the edge of strip. The crown of roll gap is unexpectedly increased by 70 μm compared to the traditional analysis. It reveals the reason why the edge drop of hot rolled non-oriented electrical steel is more significant than conventional carbon steels. In addition, the roll gap profile becomes smoother due to the latent heat, but the change of crown is limited.

(3) Compared to the austenitic rolling, the rolling pressure spikes are eliminated due to the appearance of soft ferrite phase in the edge of strip and the roll force becomes uniform throughout the strip width. In addition, the effects of latent heat on the deformation resistance of material cancel each other out. Thus the latent heat has little influence on the total roll force and distribution of per unit roll force.

6. Conclusion

In this study, a full analytical process, which is from the experiments to the mathematical models, and then realized by the finite element secondary development, is established to study the effect of transformation and latent heat on the hot rolling deformation of non-oriented electrical steel. The models and conclusions has laid the foundation for further research on non-oriented electrical steel, which can significantly improve the control accuracy of gage and shape.

5. Model Validation

Roll force, as the most important factor of determining the control accuracy of gage and shape, can be used to validate the presented model. The model prediction errors under different conditions are calculated by comparing the calculated values and measured values of roll force of F4 mill stand. The measured value of roll force is taken from the average value of pressure sensor when threading. It can be seen from Fig. 12 that when rolling in the dual-phase region, the prediction error of roll force is more than 10% if the traditional austenite rolling model (A) is still used. The prediction error can be reduced to 4.2% if the variation of phase structure is considered. The prediction error can be improved to 3.9% if both the variation of phase structure and latent heat are considered. Obviously, the new model considering the effect of transformation and latent heat is more suitable for the high temperature rolling in the dual-phase region of non-oriented electrical steel, which can significantly improve the control accuracy of gage and shape.

Fig. 12. Comparison of prediction accuracy of roll force under different conditions.

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No. 51674028, 51404021 and 51304017). The authors would like to thank Dr. D. F. Guo and W. J. Wang working in the institute of research of iron and steel of Sha-Steel for the assistance.

REFERENCES