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Research on Roller Circumferential Contour Model of Deformation Zone for Warm Rolling Strip

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Abstract
Study the circumferential contour of the deformation zone in the strip warm rolling, according the flow stress characteristic of warm deformation, the contact arc of deformation area is divided into three different curvature arc, the roller elastic flattening model of deformation zone is established using the method of quadratic curve fitting. The roller circumferential contour was calculated that iterative solver the roller elastic flattening deformation area and the distribution of rolling force along the rolling direction. Deformation process of warm-rolling was simulated using ANSYS/LS-DYNA finite element, the trend with simulation and calculated in the forward and backward slip zone is accordance, the model is more consistent with deformation process of the strip warm rolling.

Key words: WARM ROLLING, UNIT ROLLING PRESSURE, QUADRATIC CURVE FITTING, CIRCUMFERENTIAL CONTOUR

1. Introduction

In the strip warm rolling process, the roller produces the elastic flattening due to large rolling pressure, it has very important influence to rolling force prediction and strip forming precision after rolling[1-2]. The roller circumferential contour model of deformation area is one of the most important parameters to rolling force calculation and analyze roller elastic flattening, and controlling strip thickness in the process of strip warm rolling.

The common calculation methods of roller elastic flattening are analytical and numerical method [3]. The common analytical method is the formula for Hitchcock [4-5], in the case that the contact arc is circular arc between workpiece and roller, the calculating accuracy is low due to simplify non-circular shape. The common numerical method is influence function method[6-8], roller divided into several units, to roll on the load and its elastic deformation are discretized by the same unit, firstly, determining the each unit caused deformation when putting unit force, then getting the deformation value of each unit with the deformation superposition[9-10], this method is great amount of calculation and ignores the elastic deformation of entrance and exit, the unit deformation and accumulative deformation result some errors.

Early research shown that the characteristics of the flow stress is severe changes, in this article, it puts forward using non-circular arc contact roller of deformation area, based on unit rolling pressure with piecewise quadratic curve fitting, the roller circular contour model of deformation area is established with strip warm rolling process, through the finite element simulating with ANSYS/LS-DYNA, it shows that the model is accurate to describing the actual warm rolling deformation.

2. The model of roller circular contour established

2.1. Roller contour equation

With strip warm rolling process, the contact arc of deformation zone is all sliding zone, the workpiece remains vertical plane in the process of rolling. Units of rolling pressure is divided into three sections along the rolling direction, the two cut-off points are respectively the peak stress corresponding points of metal flow stress and the junction point between and backward slip zone and former slip zone(neutral point). When the strip rolling, roller circumferential contour is shown in figure 1, the upper and down roller for line of centers as y axis, and the symmetry center workpiece thickness as x axis, dotted lines arc AB is no-load roller circumferential outline, when rolling plate, point B changes to point B' due to the roller producing elastic flattening, actual circumferential outline of roller is solid-line curve in deformation area.

By the geometric relations, the basic equation for roller circumferential outline of deformation area is:

$$\begin{aligned} h_x &= h_0 - 2(\sqrt{R^2 - x^2} - \sqrt{R^2 - x_l^2}) + 2\delta_x \\ &= h_0 - 2\sqrt{R^2 - x^2} + 2\sqrt{R^2 - x_l^2} + 2\delta_x \end{aligned} \tag{1}$$

There,

h_x --workpiece thickness of coordinating x for deformation area(mm);

h_0 --workpiece thickness of entrance side for deformation area(mm);

R--roller radius(mm);

x_l --point A coordinates of entrance side for deformation area;

δ_x --roller elastic flattening of x coordinate for deformation area(mm);

l --contact arc length of arc roller contact(mm);

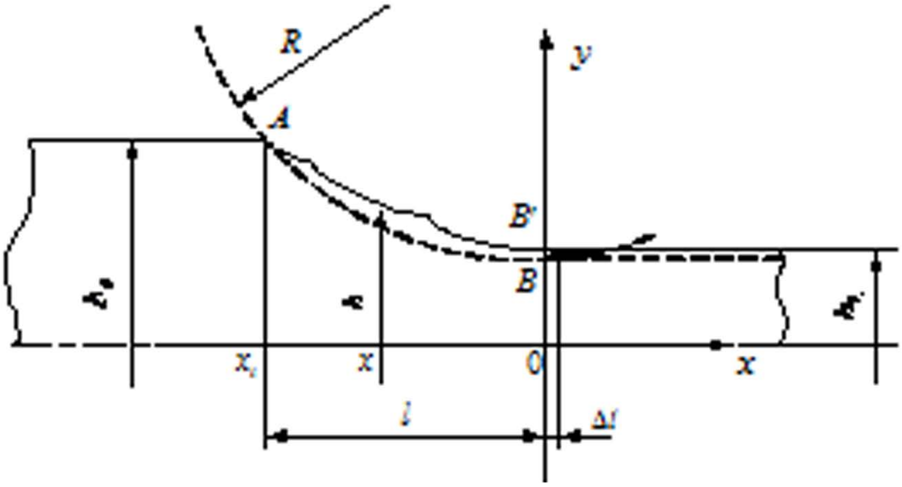

Figure 1. The schematic diagram for roller circumferential outline of deformation area

Δl --augmenter of contact arc length after roller producing elastic flattening(mm), ignores the influence of contact arc.

2.2. Unit rolling pressure piecewise fitting

When strip with warm rolling, the unit of rolling pressure along the deformation area is divided into three parts to carry on the fitting, according to the flow stress characteristics of the strip warm rolling, the unit of rolling pressure along the rolling direction adopts piecewise quadratic function curve form, the total number of segments is $n = 3$, the i segment curve can be expressed as,

$$p_i(x) = a_i x^2 + b_i x + c_i (x_{i1} \le x \le x_{i2}) \tag{2}$$

There,

a_i, b_i, c_i --quadratic curve constant;

x_{i1}, x_{i2} --boundary points of the i segment curve.

On the surface of an elastic half space, as shown in figure 2, there is effect normal distribution force in the x coordinate interval (m, n). According to the elastic theory [11-13], in the action of distribution force for $p(x)$, any point x of the surface elastomer produced by vertical displacement can be expressed as,

$$u_z = -\frac{2(1-v^2)}{\pi E}\int_m^n p(s)\ln|x-s|\,ds + C \tag{3}$$

There,

v--poisson's ratio of elastomer;

E--elastic modulus of elastomer (MPa);

C--constant reference with displacement point.

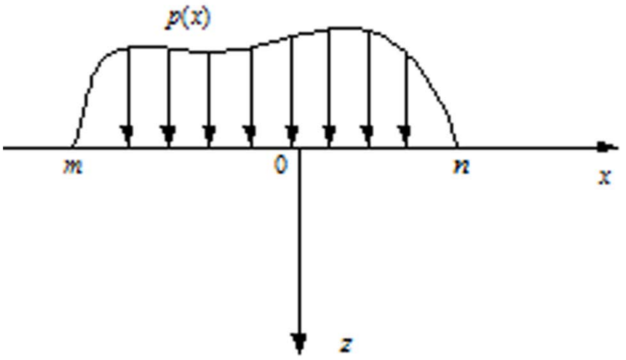

Figure 2. The schematic diagram for normal distribution force

On both ends of formula (3) is derivate getting the displacement gradient as,

$$\frac{du_z}{dx} = -\frac{2(1-v^2)}{\pi E}\int_m^n \frac{p(s)}{x-s}ds \tag{4}$$

When the unit rolling pressure is evenly distributed with $p(x) = 1$, put $p(x) = 1$ into formula(4), so getting as,

$$\frac{du}{dx} = -\frac{2(1\qquad)}{E}\int\ \frac{1}{x\quad s}ds \tag{5}$$

The integrand of right formula (5) occurs bizarre and change symbols in place $x = s$, so when desired point locating in the loading area of $m \le x \le n$, the integral needs to respectively the two parts [14]: namely, from $s = m$ to $s = x - \delta$ and from $s = x + \delta$ to $s = n$. This ξ is close to zero positive, that is,

$$\begin{aligned}\int_m^n \frac{1}{x-s}d_s &= \int_m^{x-\xi}\frac{1}{x-s}d_s + \int_{x+\xi}^n \frac{1}{x-s}d_s \\ &= \ln(x-m) - \ln(n-x)\end{aligned} \tag{6}$$

When desired point locating in the no-loading area of ($x > n$ or $x < m$), that is,

$$\int_m^n \frac{1}{x-s}d_s = \begin{cases}\ln(x-m) - \ln(x-n) & x > n \\ \ln(m-x) - \ln(n-x) & x < m\end{cases} \tag{7}$$

By the formula (5), (6), (7), receiving that,

$$\begin{aligned}u_z &= -\frac{2\left(1-v^2\right)}{\pi E}\iint_m^n \frac{1}{x-s}d_s d_x \\ &= -\frac{2\left(1-v^2\right)}{\pi E}\left\{\begin{matrix}\frac{1}{2}\begin{bmatrix}(x-m)\ln(x-m)^2 \\ -(x-n)\ln(x-n)^2\end{bmatrix} \\ +m-n\end{matrix}\right\} + C_1\end{aligned} \tag{8}$$

Similarly, when the unit rolling pressure is linear distribution with $p(x) = x$, that is,

$$\begin{aligned}u_z &= -\frac{2\left(1-v^2\right)}{\pi E}\iint_m^n \frac{s}{x-s}d_s d_x \\ &= -\frac{2\left(1-v^2\right)}{\pi E}\left\{\begin{matrix}\frac{1}{4}\begin{bmatrix}\left(x^2-m^2\right)\ln(x-m)^2 \\ -\left(x^2-n^2\right)\ln(x-n)^2\end{bmatrix} \\ +\frac{1}{2}(m-n)x + \frac{3}{4}\left(m^2-n^2\right)\end{matrix}\right\} + C_2\end{aligned} \tag{9}$$

When the unit rolling pressure is parabolic distribution with $p(x) = x^2$, that is,

$$\begin{aligned}u_z &= -\frac{2\left(1-v^2\right)}{\pi E}\iint_m^n \frac{s^2}{x-s}d_s d_x \\ &= -\frac{2\left(1-v^2\right)}{\pi E}\left\{\begin{matrix}\frac{1}{6}\begin{bmatrix}\left(x^3-m^3\right)\ln(x-m)^2 \\ -\left(x^3-n^3\right)\ln(x-n)^2\end{bmatrix} + \\ \frac{1}{3}(m-n)x^2 + \frac{1}{6}\left(m^2-n^2\right)x \\ +\frac{11}{18}\left(m^3-n^3\right)\end{matrix}\right\} + C_3\end{aligned} \tag{10}$$

2.3. The model of roller elastic flattening

The unit rolling pressure with strip warm rolling, each segment distributed of unit rolling pressure can be presented as the superposition that above three kinds of simple distribution, it can be expressed by the quadratic curve of formula (2). In the process of rolling, ignoring the shear stress, the roller assumes as an elastic half space, by the formula (2), (8), (9) and formula (10), at any location, the unit rolling pressure causes the surface elastic displacement of roller as,

$$u_i(x)=\frac{1-v^2}{6\pi E}\left\{\begin{array}{l}4a_i\left(x_{i2}-x_{i1}\right)x^2+\\ 2\left(x_{i2}-x_{i1}\right)\left[\begin{array}{l}a_i\left(x_{i2}+x_{i1}\right)\\+3b_i\end{array}\right]x\\ -\left[\begin{array}{l}2a_1\left(x^3-x_{i1}^3\right)+\\3b_i\left(x^2-x_{i1}^2\right)\\+6c_i\left(x-x_{i1}\right)\end{array}\right]\ln\left(x-x_{i1}\right)^2\\ +\left[\begin{array}{l}2a_1\left(x^3-x_{i2}^3\right)+\\3b_i\left(x^2-x_{i2}^2\right)\\+6c_i\left(x-x_{i2}\right)\end{array}\right]\ln\left(x-x_{i2}\right)^2\end{array}\right\}+C \quad (11)$$

Analyzing the roller circumferential contour of deformation area based on figure 1, put the roller contour $x=x_l$ as benchmark, according to formula (11) to calculating the elastic displacement of roller surface, it can be obtained the roller surface elastic flattening at any location as follow,

$$\delta(x)=\sum_{i=1}^{n}u_i(x)-\sum_{i=1}^{n}u_i(x_l) \quad (12)$$

There, n--the number of segments segmented conic.

3. Simulation and analysis for roller circumferential contour

3.1. simulation for roller circumferential contour

According to the formula (12) of roller surface elastic flattening and the formula (1) of roller circumferential contour, it can be calculated the roller circumferential contour of deformation zone in the strip warm rolling process. It can be seen from the formula (11), calculating the roller surface elastic flattening need known distribution of the unit rolling pressure, while, calculating distribution of the unit rolling pressure need known the roller circumferential contour for the deformation area. Therefore, the computation of roller circumferential contour with deformation area, it is the basic idea that iterative solution the roller elastic flattening and unit rolling pressure, until convergence, the calculation is finished.

When the strip with warm rolling, workpiece is bitten into the roll gap through the friction caused by between the rotating work roller and workpiece. It is all surface-to-surface contact both the contact between workpiece and work roller, and between work roller and support roller. The finite element model is shown in figure 3 after imposing restriction and setting initial load conditions.

Figure 3. Finite element model of strip rolling after imposing restriction

3.2. Results

Using the distribution of unit rolling pressure with a conventional strip rolling technology, it is respectively calculated by finite element simulation and numerical calculation, both calculation results as shown in figure 4. It can be seen from the diagram that the unit rolling pressure trends of deformation zone are basically the same with finite element simulation and numerical calculation, the unit rolling pressure has increased dramatically when workpiece into the deformation zone, it begins slowly increasing from the entrance about 10%, and reaches the largest about 67% of deformation area, then entre into the forward slip zone. The unit rolling pressure rapidly down in the forward slip zone until exports. Contrast analyzing, the results are in good agreement between element simulation and numerical calculation, the model is more suitable for the strip warm rolling.

When strip with warm rolling, roller elastic flattening and distribution of unit rolling pressure as shown in figure 5, it can be seen from the diagram, the elastic flattening distribution is a parabola in the whole deformation zone, and a symmetrical distribution along the rolling direction. Because the rigidity of roller outside, elastic press flatting is small near the entrance and exit. In the backward slip zone, rolling

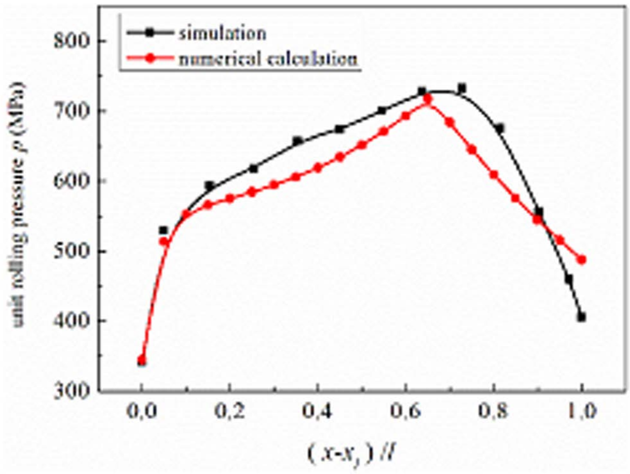

Figure 4. Contrast the distribution of unit rolling pressure with element simulation and numerical

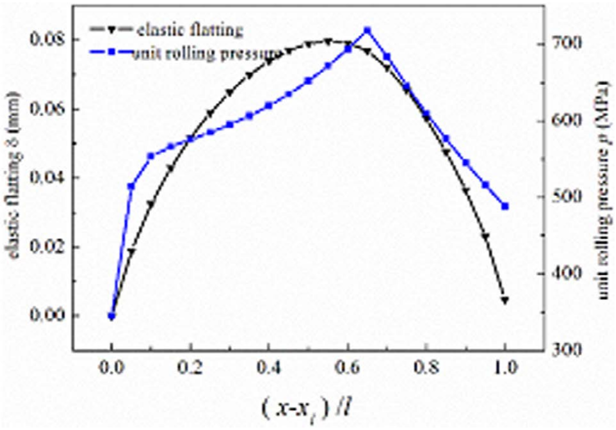

Figure 5. Changes of roller elastic flattening and unit rolling pressure in deformation zone

pressure is increase with the thickness of rolled strip after bite into, and the roller.

4. Conclusions

(1) The two cut-off points of deformation area are respectively the peak stress corresponding points of metal flow stress and the junction point between the forward and backward slip zone (neutral point). The unit rolling pressure is divided into three sections along the rolling direction, normal displacement equation of roller elastic deformation is established based on the quadratic curve fitting with unit rolling pressure, and determined the model of roller elastic flattening at any place in the strip warm rolling deformation zone.

(2) Calculating the roller surface elastic flattening namely roller circumferential contour needs to know the distribution of unit rolling pressure, while, calculating the distribution of unit rolling pressure needs to know roller circumferential contour. So, solving the roller circumferential contour is that iteration solving the unit rolling pressure and roller elastic until convergence.

(3) The strip with warm rolling deformation process is simulated by ANSYS/LS-DYNA finite element, the results of simulation and the numerical calculation to show that the trend of unit rolling pressure is basically consistent in the deformation area, the results of simulation and numerical calculation are in good agreement and the model is more suitable for describing deformation process of strip warm rolling.

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