Plastic coefficient on-line calculation method for hot rolling

Chunyu He*, Zhijie Jiao, Di Wu

[1]*The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110004, China*

Received 2 August 2014, www.cmnt.lv

Abstract

Aiming at the requirement of the high precision rolled piece plastic coefficient in the hot rolling process, this paper puts forward an on-line calculation method for the plastic coefficient. Based on the rolling mechanism model and fitting the plastic curve by the quadratic curve, the paper is to solve the tangency at the rolling pressure point, which is the plastic coefficient. The plastic coefficient calculation method exploited in the paper could be embedded in the basic automation directly before the calculation of the automatic gauge control (AGC) regulation quantity. According to the changes of the rolling force and the roll gap, the method can make the correction computation on the plastic coefficient, so as to improve the thickness compensation accuracy of the AGC system.

Keywords: hot rolling, plastic coefficient, quadratic curve, AGC

1 Introduction

At present, the hot rolling mills generally adopt the automatic AGC. The common AGC control models are the gauge meter AGC control model and the dynamic setting AGC model [1-4], the forms of these models are shown as Equations (1) and (2):

$$\Delta S_k = -\frac{M+Q}{M} \cdot \Delta h_k \,, \tag{1}$$

$$\Delta S_k = -\left(\frac{Q}{M} \cdot \Delta S_{k-1} + \frac{M+Q}{M^2} \cdot \Delta P_k \right), \tag{2}$$

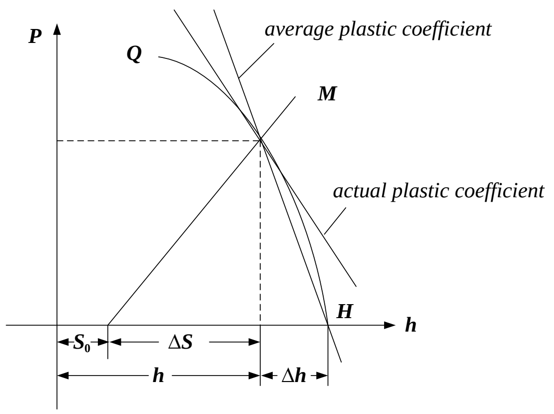
where, M is the mill stiffness, Q is the rolled piece plastic coefficient, ΔS_{k-1} is the roll gap control quantity at the last time.

In the AGC control model, the mill stiffness M and the rolled piece plastic coefficient Q are the key parameters and they directly affect the rolled piece thickness compensation accuracy. Through the spring curve obtained during the stiffness test, the mill stiffness based on strip width compensation gets the accurate calculation. The plastic coefficient Q is defined as the needed rolling force when the rolled pieces come up with the unit transformation [5-7], that is:

$$Q = -\frac{\partial P}{\partial h} \,, \tag{3}$$

where, Q is the parameter to reflect the rolled pieces' mechanical properties in rolling process. In the present AGC system, the plastic coefficient calculation is mainly accomplished by the process computers. According to the rolling schedule, it needs to calculate out an approximate plastic coefficient by the equation $P/(H-h)$ as the each pass, and send to basic automation as AGC control parameter before biting rolled piece [8-11].

In mill spring and plastic curve diagram, the average plastic coefficient is compared with actual plastic coefficient, as shown in Figure 1. The intersection point of the plastic curve and the coordinate axis h corresponds to the entry thickness of rolled pieces. The intersection point of plastic curve and elastic curve corresponds to the exit thickness of rolled pieces. The tangent slope of the point on the plastic curve is actual plastic coefficient. During the rolling process, the shape of plastic curve will change because of the plate width fluctuation, the uneven temperature of longitudinal direction, and other conditions. So the exit thickness and plastic coefficient is constantly changing. This is the reason for on-line calculation of plastic coefficient. Average plastic coefficient is directly calculated using the average entry thickness, exit thickness and average rolling force. There are following drawbacks in adopting the method of average calculation.



H – entry thickness, *h* – exit thickness, S_0 – roll gap, ΔS – mill spring

FIGURE 1 The comparison of average plastic coefficient and real value

***Corresponding author** e-mail: hecy@ral.neu.edu.cn

The error of the approximate calculation is large, namely the difference between the tangency of actual rolling pressure point and the average slope is large.

During the rolling process, because the rolled piece is affected by the temperature difference between the head and the tail, the watermark and other factors, the plate thickness fluctuation directly affects the actual value of the plastic coefficient. So it will cause the system thickness control to be inaccurate in using a fixed average plastic coefficient to conduct AGC model calculation.

The calculation of average plastic coefficient is often done by process computer, so the control functions of automation system depend on the process computer. When the process computer is down, the accuracy of thickness control will be lower.

2 Model building

According to the calculation and application of plasticity coefficient, this article proposes a calculation method using a quadratic curve fitting plastic curve, so that the tangent slope at the pressure position can be easily solved. The method for solving the plastic coefficient does not depend on the process computer, it can be directly embedded in the basic automation and calculated in each PLC cycle time. With the rolling processing, according to the change of the rolling force and roll gap, the plasticity coefficient continues to be modified. Thereby, the compensation precision of thickness control system is improved.

The force calculation equation in hot rolling process adopts the SIMS equation [12, 13]:

$$P = 1.15 \cdot \sigma \cdot Q_P \cdot l_C \cdot B\,, \tag{4}$$

where, σ is the resistance to deformation, Q_P is the shape influence function in the deformation zone, l_C is the contacted arc length considering of the elastic flattening, B is the rolled piece's width.

The resistance to deformation model is defined in the following equation:

$$\sigma = a_0 \cdot \exp(a_1 + a_2 T) \cdot \varepsilon^{a_3} \cdot \dot{\varepsilon}^{a_4}\,, \tag{5}$$

where, T=(t°+273)/1000, ε is the strain, $\dot{\varepsilon}$ is the strain rate, and a_0~a_4 are the regression coefficients corresponding to different steel grade.

The hot rolling process is generally multi-passes rolling. For the first pass, the entry thickness is the slab thickness and for other passes, it adopts the Equation (6) to calculate the entry thickness:

$$H = gap_{avg} + (P_{avg} - P_{zero}) / M + W\,, \tag{6}$$

where, gap_{avg} is the average gap of the last pass, P_{avg} is the average rolling force of the last pass, P_{zero} is the zero point of rolling force, M is the mill stiffness considering the compensation of the roll size and the rolled pieces' width, W is other thickness influence items.

The actual exit thickness of rolled pieces can be calculated according to date from the production site, as shown in Equation (7).

$$h_{act} = gap_{act} + (P_{act} - P_{zero}) / M + W\,, \tag{7}$$

where, h_{act} is the rolled pieces' actual thickness in the rolling process, gap_{act} is the actual gap; P_{act} is the actual rolling force.

The plastic curve reflects the relationships between rolled pieces' thickness and rolling force. In order to use conic to fit plastic curve, we need to solve out the key points in the plastic curve. There are two known key points: (H, 0), and (h_{act}, P_{act}).

Suppose that in the rolling process, the strain is ε, according to Equation (4), we can get the rolling force $P(\alpha\varepsilon)$ when strain is $\alpha\varepsilon$ (0< α <1). The ratio of $P(\varepsilon)$ to $P(\alpha\varepsilon)$ is shown as following formula:

$$\frac{P(\varepsilon)}{P(\alpha\varepsilon)} = \frac{\sigma(\varepsilon) Q_P(\varepsilon) l_c(\varepsilon) B(\varepsilon)}{\sigma(\alpha\varepsilon) Q_P(\alpha\varepsilon) l_c(\alpha\varepsilon) B(\alpha\varepsilon)}\,. \tag{8}$$

In the rolling process, the changes of deformation zone shape influence function Q_p and rolled piece width B is small, they can be ignored. The Equation (8) can be simplified as followed:

$$\frac{P(\varepsilon)}{P(\alpha\varepsilon)} = \frac{\sigma(\varepsilon) l_c(\varepsilon)}{\sigma(\alpha\varepsilon) l_c(\alpha\varepsilon)}\,. \tag{9}$$

Strain ε is represented by entry and exit thickness.

$$\varepsilon = \ln\left(\frac{H}{h}\right), \tag{10}$$

Under the strain ε and $\alpha\varepsilon$, the ratio of rolling reduction, resistance to deformation and contact arc length can be expressed as:

$$\frac{\Delta h(\varepsilon)}{\Delta h(\alpha\varepsilon)} = e^{\alpha\varepsilon - \varepsilon} \frac{He^{\varepsilon} - H}{He^{\alpha\varepsilon} - H} = e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon} - 1}{e^{\alpha\varepsilon} - 1}\,, \tag{11}$$

$$\frac{\sigma(\varepsilon)}{\sigma(\alpha\varepsilon)} = \frac{1}{\alpha^{a_3 + a_4}} \left(e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon} - 1}{e^{\alpha\varepsilon} - 1} \right)^{-\frac{a_4}{2}}\,, \tag{12}$$

$$\frac{L_C(\varepsilon)}{L_C(\alpha\varepsilon)} = \sqrt{\frac{H - \dfrac{H}{e^{\varepsilon}}}{H - \dfrac{H}{e^{\alpha\varepsilon}}}} = \left(e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon} - 1}{e^{n\varepsilon} - 1} \right)^{1/2}. \tag{13}$$

Substituting the Equations (12) and (13) into Equation (9) and we get:

$$\frac{P(\varepsilon)}{P(\alpha\varepsilon)} = \frac{1}{\alpha^{a_3 + a_4}} \left(e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon} - 1}{e^{\alpha\varepsilon} - 1} \right)^{\frac{1-a_4}{2}}. \tag{14}$$

In the place of strain $\alpha\varepsilon$, the rolling pressure is:

$$P(\alpha\varepsilon) = P(\varepsilon)\alpha^{a3+a4} / \left(e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon}-1}{e^{\alpha\varepsilon}-1} \right)^{\frac{1-a_4}{2}} . \quad (15)$$

It follows from Equation (15) that when α takes different values, we can get $P(\alpha\varepsilon)$ by $P(\varepsilon)$ which means that we have got other key points ($h(\alpha\varepsilon), P(\alpha\varepsilon)$) needed by fitting curve, that is:

$$H / e^{\alpha\varepsilon}, P(\varepsilon)\alpha^{a3+a4} / \left(e^{(\alpha-1)\varepsilon} \frac{e^{\varepsilon}-1}{e^{\alpha\varepsilon}-1} \right)^{\frac{1-a_4}{2}} .$$

In order to get the third key point needed by conic fitting, this paper adopts $\alpha = 0.5$, then gets ($h(0.5\varepsilon)$, $P(0.5\varepsilon)$). Fitting the plastic curve of three points as follows: $(H, 0)$, ($h(0.5\varepsilon), P(0.5\varepsilon)$), (h_{act}, P_{act}).

Suppose the conic shape is shown as follow:

$$y = b_0 + b_1 x + b_2 x^2 . \quad (16)$$

Substitute $(H, 0)$, (h_{act}, P_{act}) and ($h(0.5\varepsilon), P(0.5\varepsilon)$) to the above formula, then we can get b_0, b_1 and b_2, as shown below:

$$\begin{aligned} b_2 &= \frac{P_{act}(h(0.5\varepsilon)-H) - P(0.5\varepsilon)(h_{act}-H)}{(h(0.5\varepsilon)-H)(h_{act}-H)(h_{act}-h(0.5\varepsilon))} \\ b_1 &= \frac{P_{act}}{h_{act}-H} - b_2(h_{act}+H) \\ b_0 &= -b_1 H - b_2 H^2 \end{aligned} . \quad (17)$$

The plastic coefficient is the tangency of the conic in actual rolling pressure point (h_{act}, P_{act}), that is:

$$Q = y'(h_{act}) = b_1 + 2b_2 h_{act} . \quad (18)$$

In Equation (17), the coefficients b_0, b_1 and b_2 of plasticity coefficient calculation need only to be related to plate thickness, rolling force, strain, and the deformation resistance coefficient a_3, a_4. The equations are simple in structure, but also the derived model based on the rolling mechanism is consistent with the definition of plasticity coefficient, without loss of computational accuracy.

The given above equation of plastic coefficient is simple and stable, it is easy to embed in the basic automatic system, and can achieve the fast and high-precision plastic coefficient calculation. Automation system for thickness control diagram is shown in Figure 2. Plastic coefficient on-line calculation module embedded before thickness control algorithm. When plate exiting thickness is obtained based on the roll gap and the rolling force, compared with set thickness to obtain thickness deviation. Then the plastic coefficient and mill stiffness are sent to the AGC control model to obtain the compensation value of the hydraulic system, and achieve high-precision thickness control.

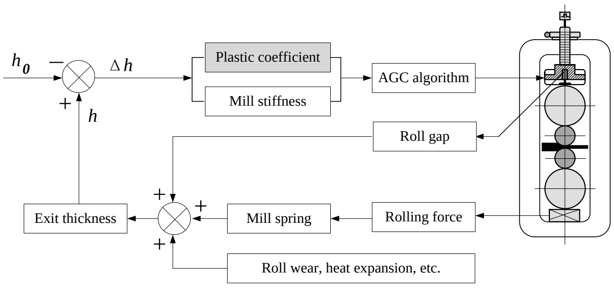


FIGURE 2 Schematic diagram of system for thickness control

3 Calculation process

The rolling force is constantly changing because of the fluctuations of the plate width, the rolling temperature and other factors during the rolling process. So the mill spring is constantly changing meanwhile. For this reason, the exit thickness of rolled pieces deviates from the set value. After the rolling mill gauge control model is put, the thickness correction is calculated based on the real-time measurement of the thickness changes, and then the compensation of the thickness fluctuation is implemented by adjusting the roll gap. The typical tendency of rolling force and roll gap is shown in Figure 3 in the rolling process.

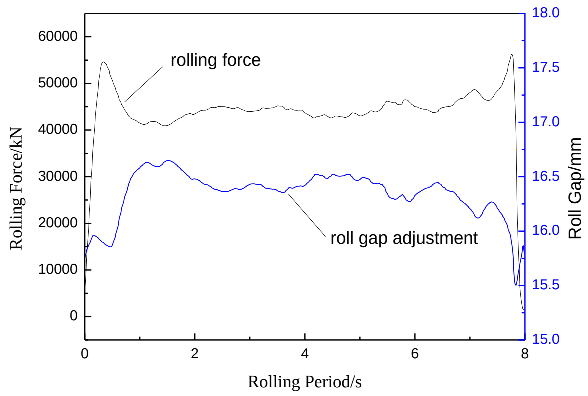


FIGURE 3 The rolling force and roll gap change tendency

To achieve accurate compensation for thickness fluctuations of rolled pieces, actual plastic coefficient must be calculated on the basis of actual rolling force and actual exit thickness. That is, the plastic coefficient of on-line calculation can maximally meet the requirements to eliminate thickness deviation.

Based on the above deduction of plastic coefficient calculation formula, we can get the following plastic coefficient's computational processes.

Step 1. Select deformation resistance model and force calculation equation. The calculation method of plastic coefficient is derived based on the deformation resistance Equation (5) in the paper.

Step 2. Confirm the regression coefficients of deformation resistance corresponding to different steel grades by primary data input.

Step 3. Get the current pass rolled pieces' entry thickness. If the current rolling pass is the first pass, the entry thickness is slab thickness; otherwise the entry thickness is the exiting thickness of preceding pass.

Step 4. Making use of displacement and pressure sensor installed on the mill, measure the gap changes and rolling pressure in the rolling process and calculate rolled pieces' actual exit thickness.

Step 5. Make sure two known key points (H, 0) and (h_{act}, P_{act}) in the plastic curve, and deduce the third key point based on the rolling force formula.

Step 6. Bring the three known point coordinates to the quadratic curve equation, and use the conic to fit plastic curve and solve the equation's coefficients b_0, b_1 and b_2.

Step 7. In the fitting curve we have calculated the actual rolling pressure point (the actual exist thickness and actual rolling force), that is the tangency at (h_{act} , P_{act}) and then we can get the plastic coefficient.

Step 8. Put the actual plastic coefficient into thickness control model, calculate the compensation value of the roll gap, and execute this value by the control system to achieve the thickness compensation.

The calculation process diagram of plastic coefficient is shown in Figure 4.

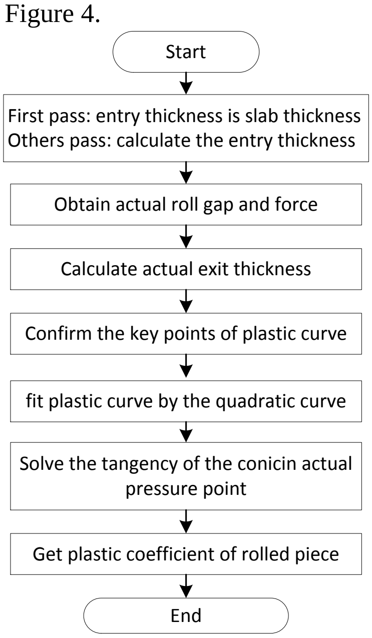


FIGURE 4 Calculation diagram of plastic coefficient

4 Result analysis

Use the above formula to calculate the plastic coefficient with Q345 and 25 mm thickness plate during the last rolling pass, and verify the accuracy of the plastic coefficient calculation formula. The details of rolling parameters are shown in Table 1.

TABLE 1 Rolling process parameters

Category	Value
Roller length	3000 mm
Work roll diameter	950 mm
Steel grade	Q345
Slab thickness	230 mm
Slab width	1550 mm
Slab length	2750 mm
Entry thickness	27.1 mm
Exit thickness	25.0 mm
Rolled piece width	2200 mm
Average temperature	915 ℃
Average speed	60 rpm
Average rolling force	11856 kN
Zero point force	20000 kN
Mill stiffness	7200 kN/mm

The on-line calculation result is shown as Figure 5 during the last rolling pass. From the figure we can see plastic coefficient changes constantly in the rolling process. The calculated plastic coefficient is less than the average value, so the thickness accuracy will be reduced by using average plastic coefficient in control system. Since the average plastic coefficient is calculated by process computer, the plate prediction thickness is poor, and the difference between real plastic coefficient and average plastic coefficient is bigger.

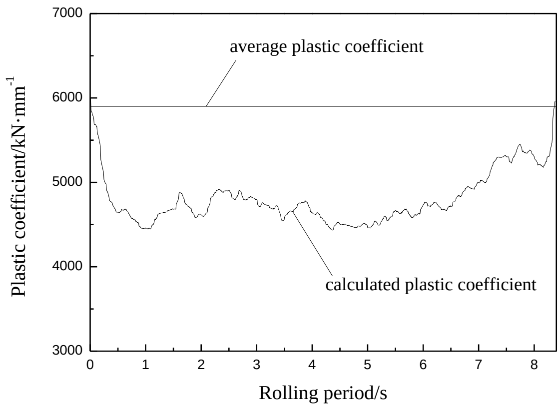


FIGURE 5 Schematic diagram of plastic coefficient change

The variation of calculated plastic coefficient shows the fluctuation of plate thickness, width, and temperature in the rolling process, the fluctuation results illustrate the change in plate plasticity, and reflected by plastic coefficient. The plate's head and tail temperature is lower than middle temperature, therefore the head and tail's plastic coefficient is bigger than middle position. The calculation result also reflects this changing process.

5 Conclusions

1) The plastic coefficient on-line calculation model is derived based on the rolling mechanism model, and the calculation formula is not influenced by the production site's complex factors. The result is stable and is easy to embed in the automatic system of hot rolling. The calculation results of plastic coefficient can be directly transferred to the thickness control algorithm and applied to high-precision AGC control system.

2) Based on determining the key points of plastic curve, the method that using quadratic curve instead of plastic curve is developed in the paper, and then the plastic coefficient is solved. The calculation formula of plastic coefficient is simple and fast in calculation speed. If more precision plastic coefficient is needed, the above formula can be adopted to determine the more critical point on the plastic curve, and use high-order curve fitting plastic curve.

3) The plastic coefficient got by the paper's calculation is the tangency of the actual rolling pressure point in the plastic curve. It exactly matches the plastic coefficient's definition, and the computational accuracy is higher than traditional method. Compared to the traditional method to solve plastic coefficient mean, its solving accuracy is increased by more than 6%, and the coefficient is more suitable for high-precision thickness control system.

References

[1] Gao Y J, Wang Y Q, Kong X D 1998 The study on dynamic model of hydraulic AGC system in a strip mill *Journal of Yanshan University* **22** 259-62 *(in Chinese)*

[2] Wang Z L, Tong C N, Sun Y K 2005 Real-time simulator of AGC systems for hot-rolling mill, *Journal of University of Science and Technology Beijing* **27** 600-603 *(in Chinese)*

[3] Zhong Y F, Tan S B, Xu X H 2009 Research and application of the feedforward-AGC system in hot strip rolling mills *Journal of Northeastern University (Natural Science)* **30** 169-71 *(in Chinese)*

[4] Wang J, Li J P, Wang G D 2002 Mill modulus control on pressure closed loop *Control Decisions* **17** 126-8 *(in Chinese)*

[5] Zhang J Z 1989 New method for measuring plastic coefficient of rolling stock and its application, *Iron & Steel* **24** 33-7 *(in Chinese)*

[6] Jiang L Y, Zhao C J, Zhang J Z 2011 Methods for calculating plastic coefficient of rolling stock and their errors *Mechanical Engineering & Automation* **5** 102-4 *(in Chinese)*

[7] Zhang D H, Zhang W X, Yan D 2010 Study and application of q prediction feedforward agc in hot tandem rolling *Iron & Steel* **45** 51-4 *(in Chinese)*

[8] Linghu K Z, He A R, Yang Q 2007 Feedback-decoupling for a combined shape and gauge control system in hot strip rolling, *Journal of University of Science and Technology Beijing* **29** 338-41 *(in Chinese)*

[9] Takashi O, Naoki S, Toshiki Y 1995 Adaptive technology for thickness control of finisher set-up on hot strip mill *ISIJ International* **35**(1) 42-9

[10] Prodip B 1996 Modeling and simulation of hydraulic gap control system in a hot strip mill *ISIJ International* **36**(5) 553-562

[11] Zhang D H, Li X, Zhang H, Han J Z 2008 Algorithmic design and application of pure lag compensation controller for monitor AGC via gap *Iron & Steel* **43**(6) 52-5 *(in Chinese)*

[12] Hu X L, Zhao Z, Liu X H, et al 2007 Analysis of oversize in thickness of plate at head and tail ends, *Iron & Steel* **42** 50-2 *(in Chinese)*

[13] Li H J, Xu J Z, Wang G D 2009 High-precision rolling force prediction model for hot strip continuous rolling process *Journal of Northeastern University (Natural Science)* **30** 669-72 *(in Chinese)*

Authors

Chunyu He, born in March, 1973, Shenyang, Liaoning, China

Current position, grades: Northeastern University, associate professor.
University studies: PhD degree in materials processing engineering, Northeastern University, Shenyang, China, 2009.
Scientific interests: rolling theory, optimization of rolling technology, adaptive control.
Publications: 15.

Zhijie Jiao, born in July, 1976, Shenyang, Liaoning, China

Current position, grades: Northeastern University, associate professor.
University studiess: PhD degree in materials processing engineering, Northeastern University, Shenyang, China, 2006.
Scientific interests: rolling theory, development of rolling model.
Publications: 20.

Di Wu, born in June, 1952, Shenyang, Liaoning, China

Current position, grades: Northeastern University, professor.
University studies: PhD degree in materials processing engineering, Northeastern University, Shenyang, China, 1987.
Scientific interests: rolling theory and technology of section steel, fast cooling technology.
Publications: 60.