Automatic Control System of Hydraulic Tension Pilot Warm Rolling Mill

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Abstract. In order to meet the warm rolling demand and deal with the inefficiency of cold-rolled deformation metals such as high-strength steel, silicon steel and magnesium-nickel alloy, etc., The state key Laboratory of Rolling technology and Automation of Northeastern University(NEU-RAL) designed and manufactured a new pilot warm rolling mill that can achieve heating on line in the rolling process. This paper introduces equipment constitutes, and its main functions and features. The paper also describes its temperature control system, AGC system and ATC system during the warm rolling process in details. Multiple experiments have proven that the pilot warm rolling mill can not only simulate the actual production process to produce the hard-deformed metals, provide innovative technology, but also offer easy to use experimental equipment for steel industry researchers.

1. Introduction
Warm rolling is the rolling process that is carried out below recrystallization temperature but above the recovery temperature of metal or metal alloy. Since the metal hardening receives certain degrees of recovery during warm rolling, compared to cold rolling, warm rolled material has lower yield strength, higher plasticity, and does not have the drawbacks of hot rolled. Because of these advantages, warm rolling has attracted significant attentions worldwide[1,2].

Fig.1 Hydraulic Tension Pilot Warm Rolling Mill
With creativity and innovation in mind, in order to provide suitable online heating experimental conditions for metallic material researchers, NEU-RAL has designed a new type of warm rolling mill that offers hydraulic tension and reversing capability (As shown in Fig. 1). Its design is based on pilot cold rolling mill by adding resistance heating device between both side chucks and rollers. It can better meet the research’s demands on the warm rolling process, at the same time broad the experimental range and experimental capabilities of the cold rolling mill[3,4].

2. Devices Constitute

The main equipment includes: mechanical system, hydraulic system, control system and data acquisition system. The control system includes online heating system control, automatic gauge control system (AGC) and automatic tension control system (ATC).

Mechanical system is the same as the ordinary four-high mill with work roll system of three sets of different roller diameters. The main motor drive mode is designed to support roller drive. Full hydraulic down system is used for roll gap control. This mill is not only meets the needs of the rolling line adjustment when different work roll system changes, but also ensure the function need of APC and AGC during the rolling process. The main structure of mill is shown in Fig. 2.

Hydraulic system includes hydraulic tension system at the front and rear of the mill, hydraulic down system and hydraulic balancing system. Both ends of the rolling sample are fixed through both side hydraulic chucks, and the tension is produced by hydraulic cylinders. The constant tension control is completed through translating the oil pressure measured by the oil pressure sensor into tension value. Displacement sensor MTS can accurately detect the cylinder stroke to control the exact start and stop position of the rolling sample and finish automatic reciprocating rolling. The hydraulic down system helps to realize the precise AGC control.

Parameters of the main equipment of the mill are as followings: Maximum rolling force: 2500kN; Maximum rolling torque: 60kN.m; Main motor power and speed: DC110kW, 750/1600r/min; Rolling speed: 0.1~0.5m/s; Rolling tension range: 2.5~100kN(tension deviation: ± 2%); Maximum stroke of hydraulic tension cylinder: 2000mm; Maximum stroke of AGC hydraulic cylinder: 140mm; Control range of heating temperature: 20~900°C.

3. Control System

The control system consists of the basic control level and the two-level process control; the basic control level uses the Siemens PLC and ET200 controlled through fieldbus and adopt Siemens S7-400 controller as the master unit. Sub-stations are connected by profibus DP to constitute a distributed I/O mode, to implement centralized control for transmission system, pressure system, hydraulic system and heating system. HMI, two-level process control computer and data acquisition server communicate with the PLC via Industrial Ethernet. HMI is used for parameter setting, status monitoring and trends showing of control process. The process control computer is used for setting calculation and correct calculation.
of rolling schedules according to real-time data. The data acquisition system is responsible for the entire experimental process tracking, data acquisition and data report.

3.1. Temperature Control of the Heating System
The heating system consists of transformers, SCR(silicon controlled rectifier), infrared thermometer, current transformer, electrode rod and the heating electrode. The heating electrodes are installed in the vicinity on both side hydraulic chucks and rolls. The heating system is divided into two parts through the contact point of the rolls and the rolling sample as segmentation point. The sample heating temperature is controlled by adjusting SCR conduction angle of the transformer primary side to control the current of transformer secondary side[5,6].

The temperature control technology of feedforward controller combined with feedback controller is used in heating system. Total control amount($U_m(n)$) of power regulating device is output through analog template. The power regulating device is adjusted by the control system to complete the temperature closed-loop control in the process of warm rolling. The calculation formula of $U_m(n)$ is as follows:

$$U_m(n) = U_{fb}^m(n) + U_{ff}^m(n)$$

(1)

In the formula, $U_{fb}^m(n)$ is the output value of feedback controller. Value range is in -0.2~0.2, that represents control amount is from -20% to 20%; $U_{ff}^m(n)$ is the output value of feedforward controller. Value range is in 0~0.8, that represents control amount is from 0 to 80%; The feedback controller adopts PID controller, and the feedforward controller is calculated according to the mathematical model of resistance heating as shown in Formula (2).

$$U_{ff}^m(n) = \frac{P_m(n)}{P_{max} \cdot \eta_{m-1} \cdot \cos \phi}$$

(2)

$P_{max}$ is the rated power of transformer, kW; $\eta_{m-1}$ is the heating efficiency of the (m−1)th pass; $\eta_0$ the Value range is around 0.7; $\cos \phi$ is the transformer power factor, it is the fixed parameter between 0.6 ~ 0.9 to be set when the transformer leaves the factory.

$$\eta_m = \frac{P_m(n)}{U_m \cdot P_{max} \cdot \cos \phi}$$

(3)

$U_m$ is the steady output value of the total control when the temperature of rolled piece reaches the target value and maintains the temperature.

Assuming that the m-th pass is rolled to the left, and the right part of the rolled piece is the entrance part of the warm rolling mill, the formulas for calculating the electric power $P_m(n)$ required for heating at the m-th pass and the n-th time are as follows.

$$P_m(n) = P_m^1(n) + P_m^2(n)$$

(4)

$$P_m^1(n) = \rho_s \cdot L_m^8(n) \cdot \bar{h}_{m-1} \cdot W \cdot c \cdot \frac{dT_{sample}}{dt}$$

(5)

$$P_m^2(n) = 2 \cdot L_m^8(n) \cdot W \cdot \varepsilon \cdot \sigma \cdot T_{sample}^4$$

(6)

$P_m^1(n)$ is the internal energy for heating the rolled piece; $P_m^2(n)$ is used to compensate the heat loss caused by thermal radiation of rolled piece; Losses from convection and heat conduction are negligible; $\rho_s$ is the sample density, kg/m$^3$; $W$ is the sample width, mm; $c$ is average heat capacity, J/kg·K; $T_{sample}$ is the sample temperature, K; $t$ is time, s; $\varepsilon$ is the samples’ radiation coefficient; $\sigma$ is Boltzmann constant, value is 5.67×10$^{-8}$w/m$^2$·K$^4$. 


$$h_m(n) = \begin{cases} \frac{L_m^u(n) - L_m^u(n-i)}{L_m^u(n) - L_m^u(n-i)} \bar{h}_{m-1}, & \text{Roll to right} \\ \frac{L_m^l(n) - L_m^l(n-i)}{L_m^l(n) - L_m^l(n-i)} \bar{h}_{m-1}, & \text{Roll to left} \end{cases} \quad (7)$$

$h_m(n)$ is the exit thickness of the sample at the $m$th pass and $n$th time; $\bar{h}_{m-1}$ is the exit average thickness of the sample at $(m-1)$th pass; $\bar{h}_0 = H$, $i$ is an integer value greater than 1 to ensure that the denominator value of formula (7) is greater than 20 mm, that is $L_m^u(n) - L_m^u(n-i) > 20$ mm or $L_m^l(n) - L_m^l(n-i) > 20$ mm

### 3.2. Hydraulic AGC Thickness Control

According to bounce equation, the relationship of the actual sample exit thickness, the preset gap $S_0$ and the mill bouncing value $\Delta S$ is as follow.

$$h = S_0 + \Delta S = S_0 + \frac{F}{K_m} \quad (8)$$

Where: $K_m$—mill stiffness coefficient; $F$—rolling force.

In the initial state, the rolling force is $F_0$, the gap is $S_0$.

The real exit thickness is:

$$h_0 = S_0 + \frac{F_0}{K_m} \quad (9)$$

In rolling process, the actual sample exit thickness is:

$$h_1 = S_0 + \frac{F_1}{K_m} \quad (10)$$

Thickness deviation is:

$$\Delta h = h_1 - h_0 = \frac{F_1 - F_0}{K_m} = \frac{\Delta F}{K_m} \quad (11)$$

For the purpose of eliminating the thickness deviation, the control system adjusts the flow rate of the hydraulic cylinder to control the roll gap to compensate for the mill bounce caused by the thickness difference of incoming material[7-9]. At this time, the correction amount of the roll position $\Delta x$ generated by the hydraulic cylinder should be in proportion to the amount of bounce and the direction is opposite, as follows:

$$\Delta x = -C \frac{1}{K_m} \Delta F \quad (12)$$

After such compensation, the rolling thickness deviation is as follow:

$$\Delta h' = \Delta h - \Delta x = \frac{\Delta F}{K_m} - C \frac{\Delta F}{K_m} = \frac{\Delta F}{K_m} - \frac{\Delta F}{K_e} = \frac{\Delta F}{K_e} \quad (13)$$

$\Delta h'$—The sample thickness deviation after roll position compensation

$C$—The roll position compensation coefficient

$K_e$—The equivalent mill stiffness coefficient $K_e = K_m / (1-C)$

$\Delta x$—The amount of the roll position correction

The essence of this method is to change the roll compensation coefficient $C$, that is, to change the mill stiffness $K_e$ to achieve automatic gauge control. As shown in Figure 3.
Due to the existence and changing of this deviation in the rolling process, the preset roll gap needs to be continuously adjusted in the entire rolling process, so the emergence of the plate differences can be effectively suppressed and the impact caused by the incoming thickness variation can be reduced.

3.3. ATC System Control

The tension acting on the sample is a key parameter in the rolling process, the tension control directly impacts the smooth progress of the rolling process and the flatness quality. The oil pressure sensors are installed in two cavity of the left and right hydraulic cylinder of pilot warm rolling mill, real-time tension feedback can be calculated by the oil pressure. Tension preset value generally comes from the warm rolling process two-level computer system or is given manually through HMI. The deviation signal between a given tension and feedback tension is output to the proportional servo valve via the PID controller, constant tension control is completed by the proportional servo valve. The tension closed-loop control block diagram of warm rolling mill is shown in Figure 4.

![Fig.4 Closed-loop tension control diagram](image)

| Tab.1 the control accuracy of the sample thickness |
|-----------------------------------------------|
| thickness (mm) | Thickness tolerance (mm) | Effective length (mm) |
| width | width | |
| 150~200 | 200~300 | |
| 0.2~0.4 | ±0.010 | ±0.012 | ≥800 |
| 0.4~0.8 | ±0.012 | ±0.016 | ≥800 |
| 0.8~1.0 | ±0.02 | ±0.03 | ≥800 |
| 1.0~1.5 | ±0.03 | ±0.04 | ≥800 |
| 1.5~2.5 | ±0.04 | ±0.05 | ≥800 |
4. Conclusion

Hydraulic tension warm mill has the advantage of prominent design and excellent experimental effect; APC positioning accuracy: ±0.15mm; the hydraulic reduction speed: 1mm/s; AGC hydraulic cylinder position system response time: 0.1ms; the step rise time is less than 50ms; HGC positioning accuracy: ±0.01mm; the sample size control accuracy is shown in table 1 without considering the 20% of the head and tail of the sample. The temperature control accuracy is ±15°C.

Hydraulic tension warm mill has been utilized in many steel corporations like Bao Steel, Sha Steel, and Japan Metallurgical Industry Corporation, etc. It has proven that hydraulic tension warm mill can simulate production process, and also provide convenient and reliable experimental device for researchers.

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