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Analysis of the thermal-mechanical problem in the process of flexible roll profile electromagnetic control

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ABSTRACT

Roll profile electromagnetic control technology (RPECT) is a new technology for obtaining flexible roll profile curves. Based on induction heating technology and using the thermally driven and internal constraint mechanism of an electromagnetic stick, the technology cleverly converts the energy of induction heating into a thermal-mechanical hybrid power source, thus greatly improving the degree of roll profile control. However, in the process of roll profile control, during roll heating, the phenomenon of roll uniform temperature may appear, which may affect the roll profile curves. The stability of the roll profile after changing is the core problem addressed by the described technology. Therefore, based on a $\varnothing$270 mm $\times$ 300 mm roll profile electromagnetic control experimental platform, an electromagnetic-thermal-mechanical coupled axisymmetric model is established by using the finite element software MSC.MARC. The effect of different cooling intensities on the roll temperature and the effect of the roll temperature on the roll profile are analysed through experiments and simulations in the process of cooling after continuous heating and during periodic heating after continuous heating. The results show that roll uniform temperature appears in the roll during roll profile control, which seriously affects the roll profile curves. The phenomenon of roll uniform temperature can be effectively inhibited by controlling the temperature of the electromagnetic stick and establishing a reasonable roll surface cooling intensity, and its effect on the roll profile can be eliminated.

1. Introduction

Flatness control technology is a core technology of cold-rolled strip steel production. With the rapid development of the processing and manufacturing industry, customers are making stricter demands regarding the geometry and size of the rolled strip, which highlights the importance of flatness control. A variety of shape control methods have been proposed to obtain good strip shape, including roll tilting, hydraulic roll bending, the original crown roll, spray water cooling and roll bulging. However, in a wide thin strip, a high-order strip shape can easily appear during the rolling process, which seriously affects strip quality. At present, the CVC(Continuously Variable Crown) series technology [1], spray water cooling, the VC(Variable Crown) roll [2] and the DSR(Dynamic Shape Roll) roll [3] are used to control the high-order strip shape. After years of development, the CVC series technology is now widely applied in high-order strip shape control. However, many problems remain. First, once roll processing and moulding are complete, the roll profile is relatively fixed and cannot adapt to different strip specifications. Second, the original roll crown produces wear. Thus, the roll profile cannot be measured, and the roll must constantly be replaced. The VC roll and the DSR roll are examples of hydraulic bulging technology, which can achieve flexible roll profile control and substantially reduce the influence of the original roll crown wear on strip shape control. The VC roll and the DSR roll have achieved significant economic benefits in the production of cold-rolling wide thin strip. However, Because of the roll structure and hydraulic seal problems, opportunities to use the VC roll and the DSR roll are severely limited [4]. To promote the development of the strip-processing industry, the development of a roll profile control technology with flexible roll profile control ability that can be applied on a large scale is urgently required.

In addition to hydraulic bulging, Kamii [5], Hoesch Werke [6] and Sumitomo Metal Industries [7] have proposed thermal bulging technology. This technology is based the principle of the thermal expansion of the metal and achieves flexible roll profile control through local heating of the roll. Because of slow heating and large thermal inertia, thermal bulging technology remains in patent status. In view of the problems of the technology, the roll profile electromagnetic control technology (RPECT) [8] based on induction heating technology is proposed to achieve micro-scale flexible roll

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profile control. The underlying principle is shown in Fig. 1. RPECT is based on the electromagnetic control roll (ECR), which consists of a roll with hole, induction coil, electromagnetic stick and electric conduction link. Induction heating is used to rapidly heat the electromagnetic stick and the local area of the roll hole. The temperature increase of electromagnetic stick causes its diameter to increase, and the local temperature increase of the roll through hole causes the diameter of the roll through hole to decrease. Therefore, larger contact pressure is produced in the contact surface. The roll profile is changed under the contact pressure and thermal expansion of roll. Thus, the technology converts the energy of induction heating into a thermal-mechanical hybrid power source by using the thermally driven and internal constraint mechanism of the electromagnetic stick. This approach substantially improves the response rate of the roll crown and does not impair roll stiffness. When the technology is used for roll profile control, the roll profile curve consists of two parts. One part is the roll profile curve caused by the contact pressure between the electromagnetic stick and the roll's through hole. The other part is the roll profile curve caused by the roll's thermal expansion. When the contact pressure distribution is constant and the temperature field of the roll and the electromagnetic stick are stable, the roll profile curve obtained by RPECT is fixed and does not change with time. However, according to the principle of RPECT, the phenomenon of uniform temperature necessarily occurs in the roll during roll profile control. This phenomenon affects the temperature field of the roll and the contact pressure, causing roll profile curve fluctuations. In the shape control process, the roll profile curve fluctuations seriously affect strip shape control over time [9], and strip quality cannot be guaranteed. Therefore, it is necessary to investigate the problems of heat transfer in the process of roll profile control, to develop a method to control the roll temperature field, and to provide guidance for the application of RPECT.

The heat transfer problem in RPECT is multidisciplinary and involves electromagnetics, heat transfer and mechanics. In recent years, scholars have performed substantial research in this area. Jiin-Yuh Jang et al. [10] numerically and experimentally investigated a metallic hollow cylinder subjected to step-wise electromagnetic induction heating. Min Churl Song et al. [11] analysed the forging of marine crankshafts by coupled electromagnetic and thermal methods. Wang B et al. [12] studied induction heating of the workpiece before the gear rolling process with different coil structures through experiment and finite element calculation. Yi Han et al. [13,14] studied the induction heating process of heavy-duty sprockets and gears through experiment and finite element calculation. Yi Han et al. [15] analysed the heat treatment process by induction heating for longitudinally welded pipe using ANSYS software. Yang et al. [16] established the electromagnetic-ther mal-mechanical coupled mathematical model, analysed the thermal- mechanical characteristics of the cable joint under different internal defects, and verified the accuracy of the coupled model by experiment. The research on electromagnetic-thermal coupling and electromagnetic-thermal-mechanical coupling provide theoretical support for the establishment of the electromagnetic-thermal-mechanical coupled model of RPECT. The methods used in the literature also provide guidance for this research.

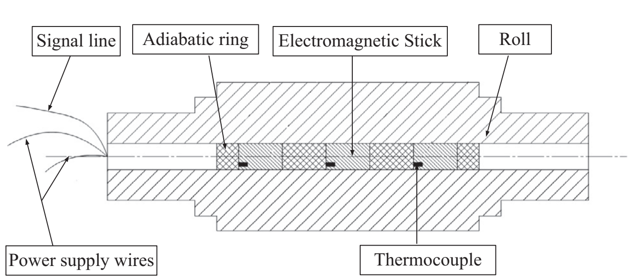

Fig. 1. Diagram of RPECT underlying principle.

In this paper, based on the roll profile electromagnetic control experimental platform, an electromagnetic-thermal-mechanical coupled axisymmetric model is established by using the finite element software MSC.MARC. In the process of roll profile control, the temperature field of the roll and its effect on the roll profile are analysed through experiment and calculation. Additionally, a strategy for controlling the temperature field of the roll and the roll profile are provided.

2. Mathematical model

2.1. Electromagnetic field

According to electromagnetic theory, the Maxwell equation is used to describe the magnetic field in the electromagnetic field calculation process. Its characteristics are as follows:

$$\begin{cases} \nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \\ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\ \nabla \cdot \vec{B} = 0 \\ \nabla \cdot \vec{D} = \rho \end{cases} \tag{1}$$

where $\vec{H}$ is magnetic field intensity, $\vec{J}$ is current density, $\vec{D}$ is the electric displacement vector, $\vec{E}$ is electric field intensity, $\vec{B}$ is magnetic flux density and t is time.

$\vec{H}$ 、$\vec{J}$ 、$\vec{D}$ 、$\vec{E}$ 、$\vec{B}$ obey the following relations:

$$\begin{cases} \vec{D} = \varepsilon \vec{E} \\ \vec{B} = \mu \vec{H} \\ \vec{J} = \gamma \vec{E} \end{cases} \tag{2}$$

where ε is the dielectric constant, μ is the magnetic permeability and γ is the conductivity. The induction heating process, $\frac{\partial \vec{D}}{\partial t} \ll \vec{J}$, can be ignored. Additionally, the magnetic vector potential $\vec{A}$ is introduced. The relationship between $\vec{A}$ and $\vec{B}$ is as follows:

$$\vec{B} = \nabla \times \vec{A} \tag{3}$$

Therefore, $\vec{A}$ obeys the following relation on the workpiece:

$$\begin{cases} \nabla \left(\frac{\nabla \times \vec{A}}{\mu} \right) - j\omega\gamma\vec{A} + \vec{J_s} = 0 \\ \vec{J}_e \Big| = j\omega\gamma\vec{A} \end{cases} \tag{4}$$

where ω is the angular frequency, $\vec{J}_s$ is the current density of the source and $\vec{J}_e$ is the induced current density in the workpiece.

2.2. Temperature field

In the induction heating process, the temperature field obeys not only the first law of thermodynamics but also Fourier's law during heat conduction. The Fourier formulation can be expressed as follows:

$$\mathrm{div}(k \cdot \mathrm{grad}T) + Q = \rho C_p \left(\frac{\partial T}{\partial t} \right) \tag{5}$$

In the calculation process, the ECR is an axisymmetric model, and the load is also axisymmetric. Therefore, we have the following: