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A precision on-line model for the prediction of thermal crown in hot rolling processes

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ABSTRACT

The tendency towards an increase in rolling speeds, which is characteristic of the development of modern sheet rolling, causes an increase requirement of accurate prediction on-line control models for the thermal crown of work rolls. In this paper, a precision on-line model is proposed for the prediction of thermal crown in hot-strip rolling processes. The heat conduction of the roll temperature can be described by a nonlinear partial differential equation (PDE) in the cylindrical coordinate. After selecting a set of proper basis functions, the spectral methods can be applied to time/space separation and model reduction, and the dynamics of the heat conduction can be described by a model of high-order nonlinear ordinary differential equations (ODE) with a few unknown nonlinearities. Using a technique for further reducing the dimensions of the ODE system, neural networks (NNs) can be trained to identify the unknown nonlinearities. The low-order predicted model of the thermal crown is given in state-space formulation and efficient in computation. The comparisons of prediction values for the thermal crown with the production data in an aluminum alloy hot rolling process show that the proposed method is effective and has high performance.

1. Introduction

The tendency towards an increase in rolling speeds, which is characteristic of the development of modern sheet rolling, causes an increase in the instability of a number of production factors which influence the shape of the strip [1]. The flatness and profile of the strip are mainly dependent on the configuration of the roll gap across the width of the strip. The shape of the work rolls is one of the main factors affecting the shape of the roll gap, which has a significant effect on the roll gap contour. However, the shape of the work rolls changes dynamically due to the thermal deformation and wear of the rolls in continuous rolling of strip. With the exception of the work roll thermal crown expansion, the factors can be satisfactory compensated by a proper setup computation just before the rolling of each strip [2,3]. Therefore, real-time control of the uniformity of the thermal expansion of work rolls becomes the key factor in obtaining a good roll gap contour.

Normally, an adequate design of the cooling system of work rolls can contribute to minimize the magnitude and shape irregularity of the thermal crown generated during the rolling process. It can keep the roll temperature and the thermal expansion within a proper range. In order to study the influence of cooling system for hot rolling processes, a good understanding of the thermal crown of rolls during hot rolling processes is critical. Due to the rapidity of the rolling process and the impossibility of measuring the thermal crown of work rolls online, an on-line model with precise computational efficiency is very important for the prediction of thermal crown.

The problem of obtaining the thermal crown of work rolls is stated as a transient heat transfer problem. Heat transfer inside the work rolls is considered to occur by conduction and around the work rolls periphery by radiation and conduction (with the strip) and convection (with the water and air). And the fact that the influence of the rotation of work rolls in the heat transport phenomenon is negligible, when different methods of solution, such as analytical, experimental and numerical, have been used to predict the temperature and thermal crown profile of work rolls.

An analytical solution was developed by Pawelski [4] for the heat transfer equation between work rolls and strip (roll bite region) to find the heat transfer coefficient in this region. This coefficient is a function of roll speed, scale thickness, physical properties of rolls and strip, and roll bite contact time. Tseng [5] also developed an analytical understanding of thermal expansion of work rolls to provide thermal displacements and expansion of the rolls. Guo [6] developed a semi-analytic solution of wok rolls

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thermal crown to establish a correlation between the thermal profile of the rolls and the strip shape. Because of the limitations of the analytical solution in which all the boundary conditions are not considered comprehensively, it cannot give the accurate predicted thermal crown of the work rolls.

Most of the investigators preferred to use numerical and experimental solutions. A great many investigators have studied the thermal crown using the finite difference method (FDM) which is a common numerical method to solve the multidimensional heat transfer problems. Wilmotte and Mignon [7] used an axisymmetric finite difference method model to study the circumferential mean values of the roll thermal expansion. Zhang et al. [8] proposed a 2-dimensional axisymmetric model developed by the finite-difference method to predict the transient temperature field and the thermal profile of the work rolls in hot strip rolling process. The calculation results were compared with the production data of a 1700 mm hot strip rolling mill, and good agreement was found. Nakagawa [9] studied the transient build-up of the thermal crown based on a three-dimensional Lagrangian finite difference model and concluded that the reduction, strip temperature, and cooling condition are three major influential parameters. Bennon [10] developed as Eulerian finite-difference scheme to predict the thermal expansion at different spray cooling patterns in cold rolling of aluminum. Zhang et al. [1] developed a finite difference model to simulate the thermal deformation of the continuously variable crown (CVC) work rolls in hot strip rolling. Generally speaking, the results of the calculation of the roll temperature using the finite difference method are in good agreement with the measured values. However, finite difference method for the calculation of the thermal crown in rolling processes will produce high-order models that are unsuitable for synthesizing implements and real-time control.

There are also other published researches concerning mathematical modeling of the hot rolling processes, while numerical techniques particularly the finite element analysis have been utilized for determining the deformation behavior of work roll. Guo et al. [11] developed a simplified finite element method (FEM) to analyze the temperature field and thermal crown of the roll according to the practical boundary conditions. Park et al. [12] carried out the coupled analyses of heat transfer and deformation for casting rolling by using the finite element software MARC to examine the thermal crown. Benasciutti et al. [13] proposed a simplified numerical approach based on finite-elements to computer thermal stresses occurring in work roll of hot rolling mills, which are caused by a non-uniform temperature distribution over the work roll surface. The FEM can be used to analyze the temperature field and thermal deformation conveniently, and the results of the simulation have high precision. However, the FEM method is not efficient in computation and also produces high-order models that are unsuitable for synthesizing controller design and real-time prediction control.

The present study derives an on-line model with high performance for the prediction of the thermal crown in hot rolling processes. The heat conduction of the roll temperature can be described by a nonlinear partial differential equation (PDE) in the cylindrical coordinate. After selecting a set of proper basis functions, the spectral methods can be applied to time/space separation and model reduction, and the dynamics of the heat conduction can be described by a model of high-order nonlinear ordinary differential equations (ODE) with a few unknown nonlinearities. Using a technique for further reducing the dimensions of the ODE system, neural networks (NNs) can be trained to identify the unknown nonlinearities using the production data of the rolling mill, and a lower-dimensional hybrid intelligent model of the thermal crown is given in state-space formulation, which is efficient in computation and suitable for the further application of the traditional control techniques. The comparisons of prediction for the thermal crown with the production data in an aluminum alloy hot rolling process show that the proposed method is effective and has high performance.

2. Fundamental dynamics of the heat transfer of work rolls

The thermal expansion is one of the important factors affecting the roll gap profile. The work roll periodically contacts with hot strips and cooling liquid and as a result the surface temperature changes drastically. Heat transfer in the work roll is considered to occur by conduction and around the work roll periphery by radiation and conduction with the strip and convection with the water and air [14]. The work roll, rotated at high speed, is considered as a cylinder and the partial differential equation governing the heat conduction in a cylindrical coordinate can be expressed as:

$$\rho c \frac{\partial T}{\partial t} = \lambda_t \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \psi^2} + \frac{\partial^2 T}{\partial x^2} \right) + q + \mu(T) + g(T) + h(T) \tag{1}$$

where r and ψ are the radial and circumferential direction, respectively. Because the influence of the work roll is second-order magnitude, the variation of temperature along the circumferential direction of the work roll can be ignored, i.e. $\partial^2 T/\partial\psi^2 = 0$. Eq. (1) can then be transferred into

$$\rho c \frac{\partial T}{\partial t} = \lambda_t \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial x^2} \right) + q + \mu(T) + g(T) + h(T) \tag{2}$$

where $T = T(x, r, t)$ denotes the temperature of the work roll, t is the time variable. $r \in [0, R]$ and $x \in [0, l]$ are cylindrical coordinates in radial and axial direction. λ_t is the thermal conductivity coefficient, ρ, c are the density and specific heat, respectively. The rest of variables are introduced as follows:

(1) q is the heat generation rate.
(2) $\mu(T)$ denotes the quantity of heat conduction between work rolls and the strip in unit time, which is a function of the surface temperature of the work rolls.
(3) $g(T)$ is the quantity of heat convection between work rolls and the coolant in unit time, which is also a function of the surface temperature of the work rolls.
(4) $h(T)$ is the quantity of heat convection between work rolls and the air in unit time.

The surface around the work roll periphery by radiation and conduction with the strip and convection with the water and air, and the boundary conditions are not completely known. As it is difficult to obtain reasonable boundary conditions using only physical insights, for simplicity one can set the boundary conditions to be unknown nonlinear functions of the boundary temperature, the space coordinates (x, r) of the work roll and the ambient temperature T_E as follows:

$$\lambda_t \frac{\partial T}{\partial x}\bigg|_{x=0} = f_{b1}, \quad -\lambda_t \frac{\partial T}{\partial x}\bigg|_{x=l} = f_{b2} \tag{3.a}$$

$$\lambda_t \frac{\partial T}{\partial r}\bigg|_{r=0} = f_{b3}, \quad -\lambda_t \frac{\partial T}{\partial r}\bigg|_{r=R} = f_{b4} \tag{3.b}$$

where

$$f_{b1} = f_1(x, r, T, T_E)|_{x=0}, \quad f_{b2} = f_2(x, r, T, T_E)|_{x=l}$$
$$f_{b3} = f_3(x, r, T, T_E)|_{r=0}, \quad f_{b4} = f_4(x, r, T, T_E)|_{r=R}$$

With $f_{b1} - f_{b4}$ being unknown nonlinear functions.