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Theoretical and experimental investigation of thermal and oxidation behaviours of a high speed steel work roll during hot rolling

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ABSTRACT

In the present study, thermal behaviours of a HSS work roll in actual service condition during hot rolling have been systematically investigated by an experimentally validated model. Influencing factors including finishing stand number, heat transfer coefficients in different circumferential thermal boundaries and initial work roll body temperature have also been carefully examined on the temperature and thermal stress distributions within the work roll. Based on working temperature range at roll surface from the theoretical analysis, oxidation tests of a HSS work roll material have been conducted. It has been observed that the practical HSS oxide scale is obviously different compared to those developed in laboratory not only because of the complicated oxidation atmosphere in industry, but also influenced by the cyclic mechanical load and thermal stress at the work roll surface.

1. Introduction

Hot rolling has been an attractive industrial process for a very long time due to its capacity to manufacture finished or semi-finished bulk materials at temperatures above their recrystallization points. During hot rolling, very complicated interactions between elastic deformations of work rolls and back-up rolls, plastic deformation of strips and heat transfer among the hot strip, work roll and surrounding environment exist. The work rolls are cyclically heated during contact with hot strips (due to conduction of heat from strip, deformation and friction works) and cooled by cooling systems, and the fast temperature variations leads to the development of oxide scale, thermal cracks and fatigue at work roll surface [1–4]. Hence, understanding and improvement of the work roll performances in service have been a very important subject for both engineers and scientists.

Due to very complicated relationship between the working temperature of a work roll during hot rolling and its mechanical, tribological and oxidation properties, it is very critical to understand the detailed temperature evolution in a work roll during its service. Steven et al. [5] have conducted the first on-site industrial experiment to measure the temperature changes in a S.G. cast iron work roll in a roughing stand of a medium-width strip mill. Their measurement for the first time confirmed that the work roll surface temperature could be as high as 500 °C during hot rolling. Unfortunately no other industrial experiment has been reported up to now except their study because of very complicated experimental operations and extremely high cost in industry. Even though there are several similar measurements on hot rolling of aluminium alloy were conducted in laboratory [6–8], however, those results were not comparable with the industrial cases because a lot of practical influencing factors were not been able to be considered in laboratory.

Except the experimental tools, computational model is fortunately nowadays a powerful and reliable tool for simulating different thermo-mechanical-metallurgical processes from macro-, micro- to nano-scale size, with quick development of computer skills [9–11]. To date, a large number of investigations have already been successfully conducted on modelling thermal behaviours of work rolls during hot rolling. For example, a very early model was proposed by Patula [12] to study the steady state temperature distribution in a rotating roll subject to surface heat fluxes and convective cooling. Then Troeder and co-authors [13] have studied stress distribution based on assumptions of uniform heat flux and convective cooling in a three-dimensional work roll model. Lai et al. [14] calculated the transient thermal stress of a work roll using

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coupled thermo-elasticity analytical method. The transient thermal behaviours of work rolls have also been studied by Guo [15] and Hwang et al. [16] using two-dimensional finite element models, and by Lee et al. [17] and Li et al. [18,19] using three-dimensional finite element models, respectively. In Ref. [20], Guerrero and co-authors have developed four different mathematical models to study the work roll temperature field during hot rolling, and Sun et al. [21] have proposed an integrated finite element based model for the prediction of steady-state thermo-mechanical behaviour of the roll-strip system and of roll life. Chang [22] developed an analytical model for the thermal stress of a work roll within the roll bite region with a semi-infinite-solid approximation. Perez et al. [23] predicted the thermal response of a work roll using a mathematical model considering three different levels: independent cycle of the roll, rolling of a strip-rest, and a whole campaign. Strain-life of a work roll during hot rolling was calculated by Corral et al. [24] by means of a hybrid, analytic-numerical model, and temperatures and thermal stress/strains in the roll under various cooling conditions was predicted by Saha et al. [25] applying a mathematical model. In addition, thermal stress and temperature variations within work rolls in hot strip rolling have also been modelled by Fisher et al. [26], Serajzadehet al. [27,28], Benasciutti et al. [29] and Na et al. [30], respectively. In addition to modelling the temperature and thermal stress variations of work rolls as mentioned in the above literatures, analysis on the geometry of water spray and work roll thermal crown profile has also been done as reported in Refs. [31,32] using finite different method.

Since the end of last century, application of high speed steels (HSS) work rolls during hot rolling in industry has been increased quickly and made a breakthrough due to their excellent wear resistance, hardness, and high temperature service performances [33–35]. It has been reported that the HSS work rolls have about three times longer service life than the high chromium cast iron rolls [36]. As revealed by many experimental and theoretical reports, working temperature at work roll surface during hot rolling could be very high and oxidation of work rolls cannot be avoided. Therefore, accurate understanding the oxidation behaviour of hot rolling work rolls is very crucial and a number of efforts have been contributed on investigating oxidation behaviours of HSS roll materials already. For example, Kim et al. [37] have reported a significant influence of alloy elements vanadium (V) and chromium (Cr) by oxidizing three different HSS materials at 600 °C. More details can be found in [38–40], where Cr-rich M_7C_3 carbide had the best oxidation resistance than carbides MC and M_2C because it dissolved high amount of chromium. Those observations were confirmed by the recent studies [41,42] by analyzing the morphology and microstructure evolutions of oxidized HSS samples. Zhou et al. [43,44] have compared the oxidation rate of a HSS material at different temperatures and they have concluded that the matrix was easier than the carbides to be oxidized at low temperatures. However, their conclusions obviously contradict with the results shown in [37–40,45]. In addition, Yin et al. [46] have recently reported that the HSS oxide scale thickness was as large as 5 μm after 2 h oxidations below 600 °C. Actually, the oxide scale in their study was much thicker compared to the previous reports. Except the above mentioned contradictions, majority of the available reports were conducted in laboratory and the oxidation time was much longer than the practical work roll contact time (generally less than one hour) during industrial hot rolling. Therefore, systematical investigation on the oxide scale formation mechanism at HSS work roll surface within reasonable short time is still necessary, and particularly comparison with a practical oxide scale has never been reported yet.

For a better understanding of oxidation behaviour of a HSS work roll in actual service condition during hot rolling, accurate understanding of temperature evolution in the HSS work roll in actual service condition is extremely important and should come first. However, it has been found that very limited reports on temperature analysis of HSS work rolls were available after a careful literatures review. Only two reports [4,30] have been conducted based on practical industrial steel hot rolling process.

The present study is an extension from our previous work [4], and there are three main objectives. Firstly, systematical theoretical analysis on the temperature and thermal stress evolution in a HSS work roll of an industrial hot strip mill is conducted based on finite element models. Influences of thermal boundary conditions and initial work roll body temperature are discussed in details. Then, oxidation experiment of the HSS work roll material is conducted in working temperature range at a work roll surface during industrial hot rolling provided by the theoretical analysis. Surface morphology of the oxidized HSS samples and cross-sections of those oxide scales are carefully examined with a help of scanning electron microscope (SEM), focused ion beam (FIB) and transmission electron microscope (TEM). Influences of the oxidation atmosphere and temperature have been discussed. Finally, comparisons between an industrial practical oxide scale on a HSS work roll and the laboratory developed oxide scales are made in terms of surface morphology and scale thickness. It should be noted that, the present study is the first report on systematically evaluating the temperature, thermal stress and oxide scale evolutions of a HSS work roll in practical steel hot rolling conditions, and it is an important guidance for the steel makers.

2. Description of theory

2.1. Basic mathematic model

As reported in many literatures [1,4,7,18,19,31,32], heat flows from the hot strip to the work rolls when they contact during hot rolling process because there is a large temperature difference between the strip and work roll surface. The general heat transfer mathematical constitutive law in cylindrical coordinates (r- θ- z) can be written as

$$\left[\frac{1}{r}\frac{\partial}{\partial r}\left(K_w r\frac{\partial T(t)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K_w\frac{\partial T(t)}{\partial \theta}\right)+\frac{\partial}{\partial z}\left(K_w\frac{\partial T(t)}{\partial z}\right)\right] + \dot{Q}(t)-\left[\rho_w C_w \upsilon_r\frac{\partial T(t)}{\partial r}+\rho_w C_w\frac{\upsilon_\theta}{r}\frac{\partial T(t)}{\partial \theta}+\rho_w C_w \upsilon_z\frac{\partial T(t)}{\partial z}\right] - \rho_w C_w\frac{\partial T(t)}{\partial t}=0 \tag{1}$$

where r, θ, and z are the radial, circumferential and longitudinal directions of the work roll; $T(t)$ is transient temperature; t means time; $\dot{Q}(t)$ means source of energy inside the work roll; K_w, ρ_w and C_w are the thermal conductivity, density, and specific heat of work roll, respectively.

Assuming no source of energy inside the work roll ($\dot{Q}(t)=0$), no movement along the radial direction ($\upsilon_r\frac{\partial T(t)}{\partial r}=0$) and longitudinal direction ($\upsilon_z\frac{\partial T(t)}{\partial z}=0$), and energy transport along the circumferential direction dominated by convection but not conduction ($\frac{\upsilon_\theta}{r}\frac{\partial T(t)}{\partial \theta}=0$), then Eq. (1) can be simplified as Eq. (2) for a transient state thermal condition ($\frac{\partial T(t)}{\partial t}\neq 0$).

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K_w r\frac{\partial T(t)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K_w\frac{\partial T(t)}{\partial \theta}\right) + \frac{\partial}{\partial z}\left(K_w\frac{\partial T(t)}{\partial z}\right)-\rho_w C_w\frac{\partial T(t)}{\partial t}=0 \tag{2}$$

Considering the geometric symmetry of the work roll, Eq. (2) can be further simplified to a two-dimensional problem as Eq. (3) by neglecting the heat conduction along the longitudinal direction of work roll.

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K_w r\frac{\partial T(t)}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \theta}\left(K_w\frac{\partial T(t)}{\partial \theta}\right)-\rho_w C_w\frac{\partial T(t)}{\partial t}=0 \tag{3}$$

2.2. Thermal boundary conditions

Initial thermal conditions of the work roll during hot rolling can be expressed as [7,30]

$$T(r,\theta,z,t)|_{t,z=0}=T_0 \tag{4}$$

where T_0 means the initial work roll temperature before hot rolling process.