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# Evolution of microstructure, temperature and stress in a high speed steel work roll during hot rolling: Experiment and modelling

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ABSTRACT

The present study aimed to investigate the microstructure, temperature and thermal stress evolution in a high speed steel (HSS) work roll under service conditions during the early stage of hot rolling. Microstructural observations revealed the formation of micro-voids at the work roll surface due to spalling of carbides at grain boundaries, which can act as initiation sites of cracks during further cyclic heating and cooling. A transient thermo-mechanical model predicted a maximum surface temperature of 580 °C during the first rolling revolution and a stable maximum temperature of about 630 °C with further rolling revolutions, and the results will be used as reference temperatures in future study on high temperature oxidation and wear mechanisms of HSS work roll materials under practical service conditions. No tensile thermal stress at the surface was observed during the early stage of the hot rolling process, which is significantly influenced by the work roll body temperature. The residual stress at work roll surface was compressive with magnitude of about 200 MPa as measured by X-ray diffraction technique.


## 1. Introduction

Hot rolling is one of the most important industrial processes to manufacture finished or semi-finished bulk products. The finishing stands of a hot strip mill are generally operated by five to seven pairs of work rolls. The surface layer of these work rolls are subject to rapid changes of mechanical and thermal loads due to the cyclic contact with the hot strip and the cooling water with every revolution. Consequently, cyclic mechanical and thermal stresses are imposed on the work roll surface, which leads to the development of cracks when the magnitude of the stress exceeds the hot strength of the material (Garza-Montes-de-Oca et al., 2011).

It has been reported that the work rolls are responsible for up to 15% of overall production costs during hot rolling (Boccalini and Sinatora, 2002). Therefore, efforts have been made to understand the work roll thermal, oxidation and tribological behaviour during hot rolling. The thermal behaviour includes both the temperature and thermal stress distributions within a work roll. The first study on this issue was conducted by Stevens et al. (1971), where several thermocouples were embedded in a work roll to record the temperature variation during industrial in-service hot rolling of steel slabs. Then, several similar experiments were conducted. For example, Tseng et al. (1990) studied the thermal behaviour of metal and work roll during hot rolling of aluminium alloys. Sonboli and Serajzadeh (2010) have conducted hot rolling experiment using commercial pure aluminium plate, and temperatures were recorded by embedding thermocouples within the metal being deformed. However, a relatively large difference was observed when the initial temperature was different (Sonboli and Serajzadeh, 2012). In addition to the previous experiments, modelling has also played an important role in understanding the thermal behaviour of work rolls. For example, Lai et al. (1991) has calculated the transient thermal stresses in a work roll using coupled thermo-elasticity method. Colas (1998) developed a two-dimensional mathematical model by considering the steel strip, while Guo (1998) only focused on the transient thermal behaviour of work rolls during hot rolling. Chang (1999) developed a quasi-static solution presented in integral form for an arbitrary temperature distribution in the work roll. Benasciutti et al. (2010) proposed a simplified two-dimensional numerical approach to compute thermal stresses. Lee et al. (2000) studied the surface thermal behaviour of work rolls by assuming a three-dimensional inverse problem. Li et al. (2002) conducted a

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three-dimensional finite element method (FEM) analysis of high chromium work roll temperature field at a finishing stand during hot rolling. It has been found that predictions from those two-dimensional models with appropriate assumptions are consistent with the three-dimensional simulation results.

The oxidation behaviour of a work roll during hot rolling is very complicated, and it is significantly influenced by temperature, time, environmental conditions, chemical composition and distribution of carbides in the work roll materials (Garza-Montes-de-Oca and Rainforth, 2009). It has been reported by Joos et al. (2007) that a compact oxide scale at the roll surface can act as a protective layer reducing further oxidation and in addition acts as an effective solid lubrication for better product surface quality. According to Vergne et al. (2006), the oxide scale is thin and adherent and provides a good resistance against wear and a low friction coefficient with chromium content larger than 2%. Those reports were consistent with a recent three-dimensional microstructure study of oxide scaleby Zhu et al. (2011).

In addition to the thermal and oxidation behaviours, the tribological behaviour of the work rolls has attracted a lot of interest due to its influence on the surface quality of products and the work roll life. Studies on the work roll tribological behaviour were mainly conducted using disc-on-disc or pin-on-disc test configurations. For example, using disc-on-disc method, Kang et al. (2001) has studied the effect of carbon and chromium additions on the wear resistance and surface roughness of cast high–speed steel rolls, and Pellizzari et al. (2009) has studied hot friction and wear behaviour of high speed steel and high chromium iron for rolls. On the other hand, Tieu et al. (2011) and Zhu et al. (2013) have successfully conducted investigations into the tribological behaviour of a work roll by means of high temperature pin-on-disc tests. However, both disc-on-disc and pin-on-disc test configurations were under isothermal conditions, which is not able to simulate the practical thermal cycles in the hot rolling process.

It should be noted that the majority of the available reports on the work roll behaviour were conducted under laboratory conditions, and investigations on industrial in-service conditions are still essential. Therefore, the present study was designed to understand the correlation between microstructure, temperature/thermal stress distribution, and residual stress during the early stage of hot rolling by studying an in-service high speed steel (HSS) work roll. The microstructure and residual stress at the work roll surface were characterised by scanning electron microscope (SEM) and X-ray diffraction (XRD). A finite element (FE) model was applied to investigate the temperature and thermal stress distributions in the investigated HSS work roll. It should be noted that, combined experimental and modelling investigation on microstructure, temperature and thermal stress, residual stress in a practical high speed steel work has not been reported yet.

## 2. Experimental procedures

An industrial HSS work roll used for hot strip rolling has been investigated in this study. Samples with dimension of 12 × 12 mm$^2$ in cross-section and 6 mm in thickness were cut from a HSS work roll, provided by a steel company, after its removal from service. Care was taken to ensure that the sample surface was not affected and contaminated. All samples were ultrasonically cleaned with acetone to remove rolling debris and lubricant prior to testing. The chemical composition of the investigated HSS work roll is listed in Table 1.

Hardness measurements were conducted using a load of 1.5 N with dwelling time of 15 s. The microstructures of the HSS work roll surface before and after use in-service were studied using a JEOL JSM-6490 scanning electron microscope (SEM). It should be noted, due to the unavailability of samples from the surface of unused work rolls in this work, the microstructure about 20 mm beneath the roll surface after rolling was examined and assumed to represent the original microstructure before use in-service. This is based on the uniform microstructure and properties of the work roll within a depth of 50 mm below its surface as suggested by the work roll makers. Residual stress measurements via X-ray diffraction (XRD) was performed on a PANalytical X'Pert-PRO MRD goniometer with a Cu tube operating at 40 kV and 45 mA. Conventional $sin^2\psi$ method was used to analyse the results and the residual stress was averaged from three measurements.

## 3. Finite element model description

The temperature and thermal stress evolution in the HSS work roll during hot rolling is a transient state thermal problem, which can be mathematically described by the following heat transfer constitutive law in cylindrical coordinates (Sonboli and Serajzadeh, 2010):

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

where $T$ is temperature; $t$ is time; $r$, $\theta$ and $z$ are the radial, circumferential and axial directions, respectively; $K_w$, $\rho_w$ and $c_w$ indicate the thermal conductivity, density and specific heat of work roll, respectively.

Due to the geometric symmetry of the work roll, Eq. (1) can be simplified as Eq. (2) by neglecting the heat conduction along the circumferential direction ($\theta$-direction). In addition, Eq. (1) can also be simplified as Eq. (3) by neglecting the heat conduction along the roll longitudinal axis ($z$-direction).

$$\frac{1}{r}\frac{\partial}{\partial r}\left(K_w r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(K_w\frac{\partial T}{\partial z}\right)-\rho_w c_w\frac{\partial T}{\partial t}=0 \quad (2)$$

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

In this study, a fully coupled thermal-stress analysis was conducted using a commercial FE code Abaqus/Standard to solve simultaneously for the stress, displacement and temperature fields in the HSS work roll during hot strip rolling. The transient heat transfer equations were integrated using a backward difference scheme, and the nonlinear coupled system is solved using Newton's method as illustrated in Eq. (4) (Abaqus, 2011):

$$\begin{bmatrix} K_{UU} & K_{UT} \\ K_{TU} & K_{TT} \end{bmatrix}\begin{Bmatrix} \Delta U \\ \Delta T \end{Bmatrix}=\begin{Bmatrix} R_U \\ R_T \end{Bmatrix} \quad (4)$$

where $\Delta U$ and $\Delta T$ are the respective corrections to the incremental displacement and temperature, $K_{ij}$ are submatrices of the fully coupled Jacobian matrix, and $R_U$ and $R_T$ indicate the mechanical and thermal residual vectors, respectively.

In order to minimise computational time, two two-dimensional simulations were conducted in the cross-section and axial plane of the HSS work roll. Eight boundary zones along the work roll circumferential direction have been divided and two boundary zones along the work roll axial direction have been divided. In the present study, simulations were conducted based on the first stand of a hot strip finishing rolling mill (F1) at a steel company. The required rolling parameters, physical and mechanical properties of the HSS work roll are given in Tables 2, 3 and 4, respectively. Room temperature of 25 °C was assumed.

As shown in Fig. 4, eight regions have been divided along the $\theta$-direction (circumferential direction) of the work roll during one rolling revolution in the $r$-$\theta$ model. Region AB indicates the contact between work roll and hot strip; regions BC and HA indicate the