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# Temperature and heat flux fast estimation during rolling process

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ABSTRACT

Monitoring and controlling flatness during the rolling process becomes critical for ensuring the product quality. Flatness defects are due to highly three-dimensional phenomena. Indeed, strips with different widths are rolled during the same campaign and cooling systems are heterogeneous along the axial direction to modify the thermal expansion of the roll. Therefore this paper presents a fully three-dimensional inverse analytical method to determine the temperature field and heat fluxes (especially at the surface of the roll) by interpreting measurements of temperature done with several thermocouples fully embedded in the roll body and aligned along the axial direction. Since the method is dedicated to on-line interpretation and designed as a tool for adapting the rolling parameters during the rolling process, iterative methods are not studied to avoid long computation times, which justifies the development of an analytical solution of the problem. The computation time displayed by Scilab 5.3 with a quadcore 2.8 GHz is around 0.5 s by cycle for accurate computation and 0.07 s by cycle for rough computation. This paper improves a previous work (2D and relying on four assumptions designed for the prediction of wear). In the present contribution the 3D unsteady heat equation of the rotating roll is solved analytically with only one assumption in order to deal with the restriction of the measurement system (i.e., measurement according to successive times). Therefore not only radial and tangential heat fluxes are taken into account but also axial heat flux. The solution is validated by comparing the outputs of the method and some prescribed analytical temperature fields. Good agreement is obtained. Noise sensitivity is estimated by adding artificial random numbers to the inputs, and good accuracy is observed. Moreover sensitivity to sensor depth is estimated and demonstrated to be not compromising.


## 1. Introduction

### 1.1. Context

In steel rolling processes, two rolls are used as tools to reduce the thickness of a workpiece. Flatness control improvement is essential for productivity, automation and quality, since the requirements for strip crown and flatness are more and more severe. Flatness defects origin is the difference between the incoming strip profile and the work roll deformed profile. The cooling system as well as crown control devices for shape correction are voluntary heterogeneous along the axial direction in order to compensate the heterogeneous temperature fields. Moreover a rolling campaign involves often many different strip widths. Therefore the mechanisms involved in flatness problems are highly three-dimensional.

Predictive models are very useful for the design of flatness control devices and cooling system. Thus many studies focus on more and more comprehensive approaches of flatness during rolling process. A complete flatness model combines thermo-mechanic models for the strip and thermo-elastic models for the roll. For example Jiang and Tieu [1] developed a predictive 3D finite element method (FEM) which gives the contact stress between the strip and the roll, the deformation of the roll and especially the shape of the roll generatrix and by taking into account the shape of the incoming strip gives the longitudinal stress profile of the outcoming strip. More recently Abdelkhalek et al. [2] proposed a comprehensive FEM which moreover takes into account the buckling of the outcoming strip and the coupling between plastic deformation of the strip in the roll gap and the buckling of the outcoming strip.

All the predictive models of flatness need the computation of the work roll deformation and especially the thermal expansion. Therefore three-dimensional temperature fields should be computed, most of the time by numerical methods. Several authors focus on this latter task. For example Abbaspour and Saboonchi [3]

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**Nomenclature**

| | |
|---|---|
| $R_s$ | outer radius (radius of the surface of the roll) |
| $R_m$ | inner radius (radius of the measurements) |
| $e$ | error of the sensor depth |
| $\omega$ | rotation speed |
| $r$ | radial position |
| $\theta$ | angular position |
| $z$ | axial position |
| $t$ | time |
| $k$ | index of the current cycle |
| $t_k$ | time at the beginning of the $k$th cycle ($=t_{k-1}+2\pi/\omega$) |
| $t_\theta^k$ | time related to the angular position ($=t_k+\theta/\omega$) |
| $f$ | frequency of acquisition of the measurements |
| $\lambda$ | thermal conductivity of the roll |
| $D$ | thermal diffusivity of the roll |
| $\varepsilon$ | percentage of error |
| $T$ | temperature field (solution) |
| $\boldsymbol{H}$ | heat flux field (solution) |
| $T_1$ | first part of the temperature field (solution) |
| $T_2$ | second part of the temperature field (solution) |
| $T^m$ | measured temperatures (inputs) |
| $A_{n,p}^k$ | $n,p$th cosine coefficient of Fourier of $T^m$ ($k$th cycle) |
| $B_{n,p}^k$ | $n,p$th sine coefficient of Fourier of $T^m$ ($k$th cycle) |
| $T^s$ | temperature at the surface of the roll (outputs) |
| $\boldsymbol{H}^s$ | heat flux at the surface of the roll (outputs) |
| $T^p$ | prescribed temperature field (validation of the method) |
| $T_a$ | ambient temperature |
| $T^*$ | surrounding temperature (validation of the method) |
| $a_{n,p}^*$ | $n,p$th cosine coefficient of Fourier of $T^*$ |
| $b_{n,p}^*$ | $n,p$th sine coefficient of Fourier of $T^*$ |
| HTC | heat transfer coefficient (validation of the method) |
| $N_1$ | order of truncation (integer) |
| $N_2$ | order of truncation (integer) |
| $P_1$ | order of truncation (integer) |
| $P_2$ | order of truncation (integer) |
| $Q_1$ | order of truncation (integer) |
| $Q_2$ | order of truncation (integer) |
| $S$ | number of thermocouples (integer) |
| $N_\theta$ | number of reconstruction points along circumferential direction |
| $N_z$ | number of reconstruction points along axial direction |
| $N_\theta^i$ | number of interpolation points along circumferential direction |
| $N_z^i$ | number of interpolation point along axial direction |
| $\zeta_{n,p}$ | coefficients (complex) |
| $\chi_{n,p}$ | coefficients (complex) |
| $J_n$ | Bessel function of the first kind of the order $n$ |
| $\alpha_{n,p,q}^{(k)}$ | coefficients (complex) |
| $\beta_{n,p,q}^{(k)}$ | coefficients (complex) |
| $a_{n,p}$ | coefficients (complex) |
| $b_{n,p}$ | coefficients (complex) |
| $c_{n,p,q}$ | coefficients (complex) |
| $d_{n,p,q}$ | coefficients (complex) |
| $h_n$ | auxiliary function |
| $x_{n,q}$ | successive positive zeros of $J_n$ |
| $y_{n,q}$ | successive zero of $h_n$ |
| $\gamma$ | coefficient (complex) |
| $\tau$ | relaxation time (complex) |
| $\tau_{n,p,q}$ | relaxation time (complex) |
| $\upsilon_{n,p,q}$ | relaxation time (complex) |
| $\tau_{n,p,q}^*$ | relaxation time (complex) |
| $\upsilon_{n,p,q}^*$ | relaxation time (complex) |
| $\Theta$ | angle |
| $\boldsymbol{u}$ | displacement field |
| $(\lambda_0,\mu_0)$ | Lame's coefficients of the roll |

proposed predictive models for the optimization of cooling system. Thermal crown has been investigated by Zhang et al. [4,5] with two dimensional FEM (radial and axial directions) by neglecting circumferential direction. Truly three-dimensional predictive models have also been proposed by Zone-Ching and Chang-Cheng [6] or more recently by Li et al. [7]. Montmitonnet [8] gave also a comprehensive review of predictive three-dimensional models (by FEM and FDM) of the whole rolling process, by coupling the strip and the roll thermal behaviors with iterative methods.

All these simulations consider very complex boundary conditions. Indeed, the contact between the strip (from around 300 K for cold rolling conditions to around 1200 K for hot rolling conditions) and the roll (initially at the room temperature) is responsible for conducting heat, which is often modeled with a heat transfer coefficient. This model parameter is often assumed to be constant in the contact like in the model of Corral et al. [9]. But since pressures are not constant in the contact, this heat transfer coefficient is actually not constant as demonstrated by Legrand et al. [10]. The heat flux entering the roll by conduction from the strip can also be modeled by a heat flux like in the work of Hacquin [11]. Moreover, the cooling and lubrication systems involve a forced convection at the entry and exit of the roll gap and the surrounding air is responsible for a free convection. To a lesser extend, the friction between the strip and the roll, the plastic deformations of the strip and radiations from the strip, are also heat sources for the roll. This complicated thermal problem is summarized in Fig. 1.

The idea of this paper is to avoid such a complicated model by replacing this kind of direct and theoretical computations of three-dimensional temperature and heat flux fields inside the roll, by a real-time evaluation based on temperature measurements done with several thermocouples fully embedded inside the roll body. This evaluation is performed by inverse analysis and does not require external conditions around the roll. Temperatures and heat

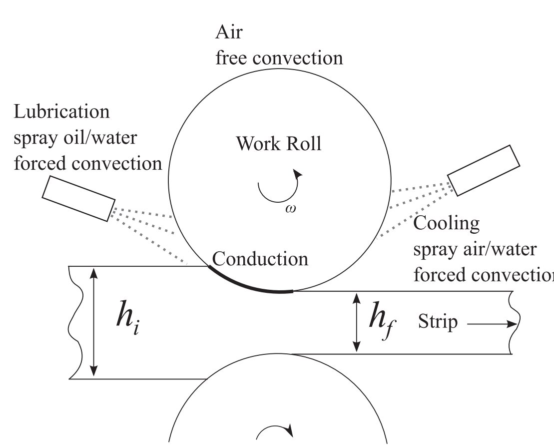


**Fig. 1.** Thermal conditions during rolling process.