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Inverse three-dimensional method for fast evaluation of temperature and heat flux fields 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 justify 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 0.07 s/cycle. The 3D unsteady heat equation is solved analytically in the roll, managing only one assumption so that restrictions of the measurement system (i.e., successive times) are taken into account. The solution is validated by comparing the outputs (surface temperature) and a prescribed temperature field (corresponding to hot rolling conditions). A satisfying 1.1% error is obtained. The accuracy is therefore promising. Furthermore noise sensitivity is evaluated by adding random values to the inputs (temperature computed at a depth of 0.5 mm under the surface) and the accuracy has not bee compromised (1.8%). Therefore good noise robustness is demonstrated.

Introduction

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.

The on-line monitoring of temperature fields could improve significantly the use of cooling systems and flatness control devices, by adapting them in real time with a close-loop control. Therefore this paper aims at developing the basis of an on-line industrial tool for evaluating industrial temperature fields in real time during the rolling process by interpreting some temperature measurements done with several thermocouples aligned along the axial direction and fully embedded inside the roll body (see Fig.1). A three dimensional inverse method is therefore needed.

Therefore highly heterogeneous temperature fields and heat fluxes can be evaluating accurately by the inverse method presented here, this allows a precise experimental validation of predictive models and a precise computation of the thermal expansion of the work roll (essential for flatness control) by solving the Navier's equation which involves all the components of the heat flux (and not only radial heat flux).

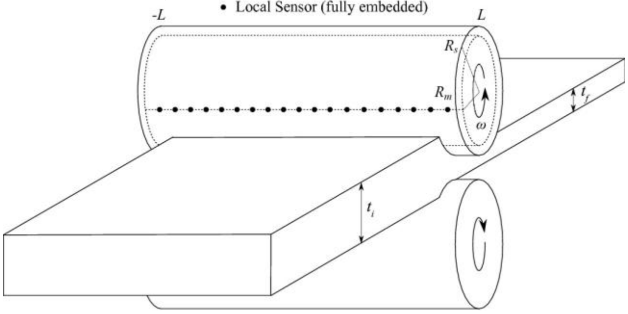

Figure 1. Measurement system

Developments and Results

In the roll the temperature verifies the unsteady heat equation:

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}=\frac{1}{D}\left(\frac{\partial T}{\partial t}+\omega\frac{\partial T}{\partial \theta}\right)$$

where ω is the rotation speed and D is the thermal diffusivity of the roll assumed to be independent on temperature. Asymptotic developments enable to take into account variations of thermal properties depending on temperature, although this has not been tempted here.

The main idea of the resolution is to split the total time interval into several sub-intervals of the duration of one cycle. Thus, by using the family of solutions:

$$\gamma J_n\left(r\sqrt{\frac{1}{D\tau}-\frac{i\omega n}{D}+\delta^2}\right)\exp\left(in\theta\right)\exp\left(\delta z\right)\exp\left(-\frac{t}{\tau}\right)$$

it is possible to verify the initial condition and to match measurements done at 0.5 mm under the surface of the roll. This solution involves expansions into a Fourier series for the measurements, and into a Fourier-Bessel and a Dini series for the solution.

An analytical temperature field is prescribed (exact solution of the unsteady heat equation) in order to validate the method. This field corresponds to a roll heated on its surface (corresponding to typical contact occurring during rolling process) with heterogeneous evolutions of temperature along the axial direction. The heat flux entering the roll is computed with a Heat Transfer Coefficient (HTC=70 000 $W.m^{-2}.K^{-1}$), which corresponds well to the contact strip/roll, but remains strongly incorrect outside the roll-gap, therefore the cooling by air is overestimated. However, as an example to quantify the accuracy of the method, this is widely sufficient for this first attempt.

This prescribed temperature field is used to compute the inputs (temperature at a depth of 0.5 mm) (cf Fig.2). Artificial noise is added or not to this field. Then, the inverse calculation is run and the surface temperature is obtained. Thus, the inverse method results can be compared with the prescribed temperature field previously evaluated at the surface of the roll (cf., Fig. 3 et 4). The error between the outputs and the prescribed temperature at the surface (cf Table I) defines the accuracy of the method. The latter presents not only a very satisfying precision but also very good noise robustness.

Table I. Error

	Without noise	With noise +/-0.5 K
First cycle	1.1 %	1.8 %

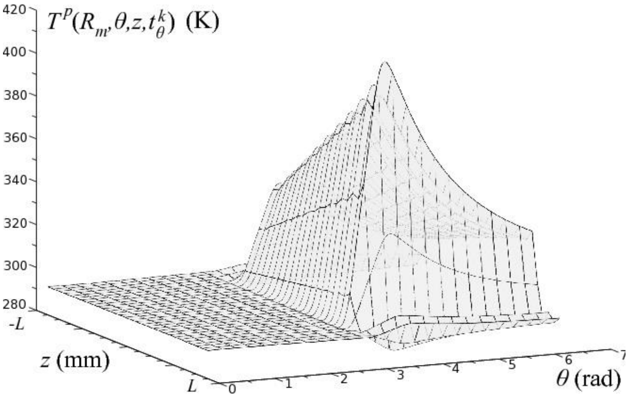

Figure 2 Inputs : measurements at a depth of 0.5 mm

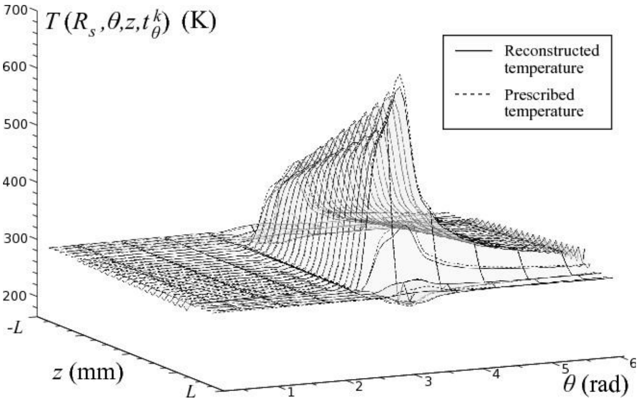

Figure 3. Reconstruction without noise

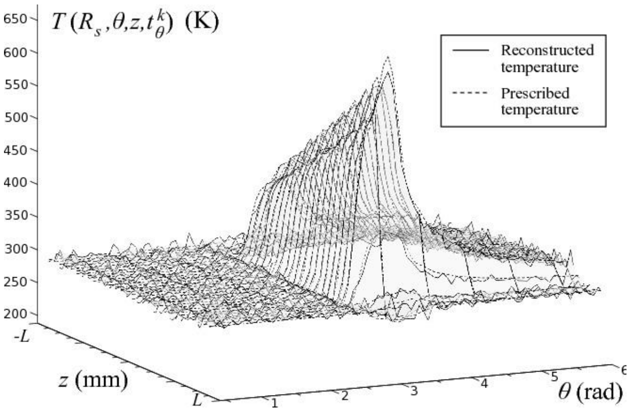

Figure 4. Reconstruction with noise (+/-0.5 K)

Industrial interest

Weisz-Patrault *et al* (2011, 2012a, 2012b) have already published several 2D inverse methods: for the evaluation of contact stress, of temperature and heat flux fields and on the other hand for coupling both solutions in order to obtain thermal stress (fatigue) and thermal expansion. The thermal inverse method has been tested experimentally by Weisz-Patrault *et al* (2012c) et Legrand *et al* (2012). Thus, taking into account these works in 2D, the industrial motivation of extending results in 3D is that the strip is less wide than the work roll and therefore at the edge of the slab (main heat source for the roll) axial heat fluxes are not negligible because the temperature decreases sharply along the axial direction in this area (cf Fig.3 et 4).

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