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New concept of friction sensor for strip rolling: Theoretical analysis

N. Legrand*, T. Lavalard, A. Martins

ArcelorMittal Global R & D, Maizières-les-Metz, France

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ABSTRACT

A new concept of sensor is proposed to measure friction at roll–strip interface during strip rolling. By measuring elastic strains inside the roll, it is possible to evaluate contact stresses at roll–strip interface using an inverse analysis, with the great advantage not to mark the strip with the sensor. Using simulations, this new sensor is designed and its ability to evaluate contact stresses is discussed as a function of rolling conditions: influences of roll thermal stresses, roll deflection, roll–strip contact length, distance of measurement points to roll surface on contact stress reconstruction by inverse analysis are characterised. Results show that this sensor could be used in various pilot hot and cold rolling conditions for friction evaluation. Next step of this work is a pilot rolling test of the sensor.

1. Introduction

To achieve higher product quality and productivity on rolling mills, it becomes necessary to get a profound knowledge of friction and lubrication in the roll gap. This need is particularly due to the current trend of rolling mills to combine higher rolling speeds, larger reductions, harder steel grades and thinner rolled strips, all of which influence friction and strip quality (i.e. strip thickness, strip flatness and strip surface defects). The present work is focused on how to measure interfacial friction in the roll gap: after a brief review of the state of the art on friction sensors, a new concept of sensor is studied by simulation and its ability to evaluate friction is discussed as a function of rolling conditions.

2. Friction sensors for strip rolling: state of the art

Extensive work has been made in the past decades to develop friction sensors for metal strip rolling [1–6]. These sensors remained however at a 'pilot stage' and have never been used under industrial rolling conditions. These different sensors are described below, with their limitations, and it is explained why it is necessary to develop a new one.

2.1. Direct pin friction sensor

This sensor consists in implementing inside the roll a pin connected to a transducer (usually using strain gages) to measure directly and locally roll–strip contact stresses: [1–4] are a few references in the very abundant literature on that technique. However, strip marks or perturbation of local lubricant flow at the interface due to the direct pin-strip contact is the main limitation of such sensors. Moreover, the low sensor stiffness, required to measure strains with good accuracy, generates a local deformation higher than in the surrounding roll which is much stiffer, resulting in a certain perturbation of friction conditions in the contact. In spite of this drawback, these techniques have provided very interesting results on the tribology of rolling.

2.2. Integrating friction sensor = rollsurf sensor

More recently, a new transducer design has been proposed [5]. It consists in increasing the contact surface of the transducer, making it larger than the strip-roll arc of contact. The sensor integrates the signal over the contact length; therefore, deriving the signal is needed to recover friction and normal stress profiles. This sensor overcomes the difficulties of local over-deformation of the pin, but the problem of strip marks still exists.

2.3. Indirect friction sensor = roll sensor

The principle of the *indirect friction sensor* is to consider the roll itself as a sensor: by measuring roll elastic strains at different positions inside the work roll during rolling, and by applying

* Corresponding author.
E-mail address: nicolas.legrand@arcelormittal.com (N. Legrand).

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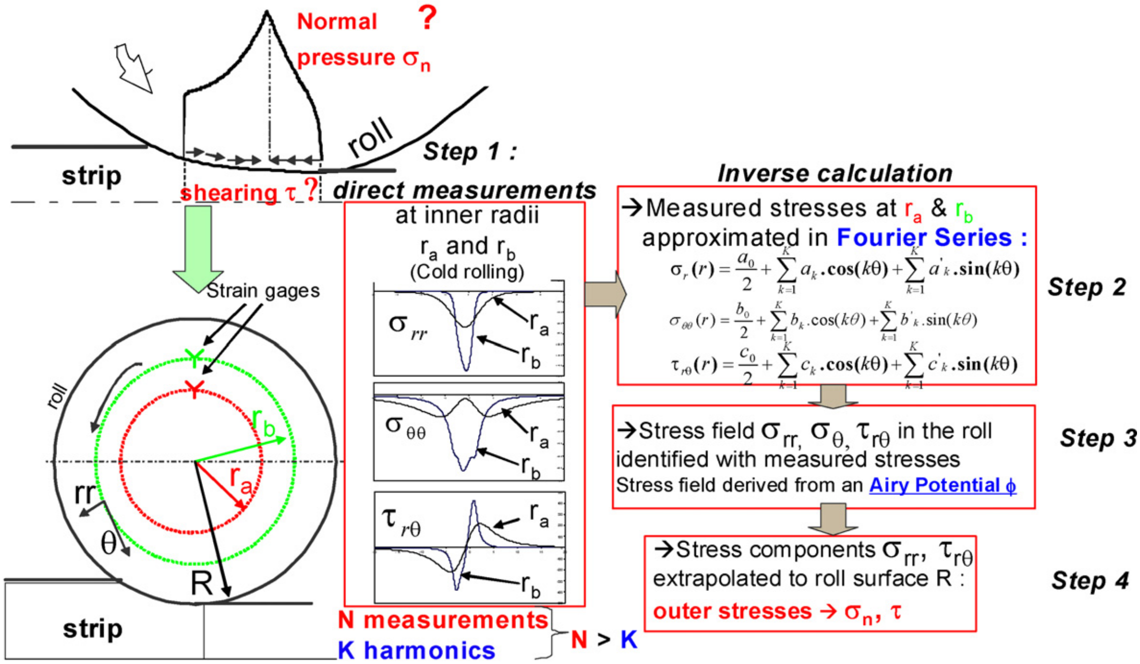

Fig. 1. Principle of the inverse analysis used by the indirect friction sensor ($r_a < r_b < R$).

a mechanical inverse analysis, normal and shear stresses (i.e. friction) at the roll–strip interface can be re-calculated. One advantage of this indirect friction sensor over the previous ones is that there is no direct contact with the strip, avoiding risks of strip marks or lubricant flow perturbation by the sensor in the roll bite. Meierhofer and Stelson [6] have developed such a friction sensor and evaluated it with laboratory trials on lead material. This is far from industrial steel rolling conditions, where the strong thermal gradients and associated thermal stresses near the roll surface can perturb the mechanical stress field generated by contact friction stresses.

2.4. Objectives of the present study

Based on the previous analysis, this paper is focused on the evaluation of the concept of indirect friction sensor for steel strip rolling: under which rolling conditions is this concept of sensor applicable or not? At which distance should strain measurement points be located from roll surface? What is the influence of perturbations such as roll thermal stresses and roll deflection? Note that the present article reports only numerical simulations for sensor design, a preliminary step prior to the real rolling tests on a pilot mill and finally on an industrial mill.

3. New indirect friction sensor: principle and equations

3.1. Principle

The sensor is based on an approach proposed by [6]: interfacial stresses at roll surface are evaluated using the measured roll elastic deformations at two different inner radii (noted r_a and r_b below) combined with inverse analysis. A summary of the approach is shown on Fig. 1.

In the present paper, the approach in [6] has been generalised to three stress components: radial, hoop and shear stress components are used in the inverse analysis to reconstruct interfacial stresses, whereas in [6], only two stress components were considered. Although not shown in this paper, it has been verified that this generalised inverse analysis is more accurate for reconstruction of interfacial stresses.

3.2. Equations

The Airy potential φ for the roll satisfies the mechanical equilibrium equation $\Delta\Delta\varphi = 0$. Expressed in cylindrical coordinates for a 2-dimensional elastic case without body forces, it has the following analytical expression [10]:

$$\begin{aligned}\phi =\ & A_0 \cdot r^2 + B_0 \cdot \ln(r) + C_0 \cdot \theta + A_1 \cdot r^3 \cdot \cos(\theta) + \frac{B_1}{r} \cdot \cos(\theta) \\ & + C_1 \left[\frac{1-\nu}{2} \cdot r \cdot \ln(r) \cdot \cos(\theta) - r \cdot \theta \cdot \sin(\theta)\right] + A'_1 \cdot r^3 \cdot \sin(\theta) \\ & + \frac{B'_1}{r} \cdot \sin(\theta) + C'_1 \left[\frac{1-\nu}{2} \cdot r \cdot \ln(r) \cdot \sin(\theta) - r \cdot \theta \cdot \cos(\theta)\right] \\ & + \sum_{n=2}^{K} (A_n \cdot r^{n+2} + B_n \cdot r^{-n} + C_n \cdot r^n + D_n \cdot r^{-n+2}) \cdot \cos(n\theta) \\ & + \sum_{n=2}^{K} (A'_n \cdot r^{n+2} + B'_n \cdot r^{-n} + C'_n \cdot r^n + D'_n \cdot r^{-n+2}) \cdot \sin(n\theta) \end{aligned} \quad (1)$$

A_i, B_i, C_i, D_i are the unknowns. The different stress components in the roll (radial, hoop, shear stresses), derived from the Airy potential, can be expressed in cylindrical coordinates with the equations:

$$\sigma_{rr} = \frac{1}{r} \cdot \frac{\partial \phi}{\partial r} + \frac{1}{r^2} \cdot \frac{\partial^2 \phi}{\partial \theta^2}, \quad \sigma_{\theta\theta} = \frac{\partial^2 \phi}{\partial r^2}, \quad \tau_{r\theta} = -\frac{\partial}{\partial r}\left(\frac{1}{r} \cdot \frac{\partial \phi}{\partial \theta}\right) \quad (2)$$

Four steps are necessary to evaluate interfacial stresses, as detailed below:

Step 1: stresses evaluation at two different radii inside the roll using measured strains:

Radial, hoop and shear strains ε_{rr}, $\varepsilon_{\theta\theta}$, $\gamma_{r\theta}$ inside the roll are measured with strain gages at two different radii r_a and r_b through one roll rotation. Hooke's law applied in plane strain (a condition