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Experimental evaluation of contact stress during cold rolling process with optical fiber Bragg gratings sensors measurements and fast inverse method

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ABSTRACT

There is a strategic importance for the steel rolling industry to get a better understanding of the strip–roll interaction to improve roll-gap models, increase strip quality and decrease roll degradation. This requires roll-gap sensors able to measure this interaction under industrial rolling conditions and in real time in order to propose a feed-back control of process parameters. To reach these goals, this paper proposes a new roll-gap friction sensor based on an inverse method that interprets optical fiber Bragg gratings (FBG) strain measurements under the roll surface (fully embedded), which enables to evaluate contact stresses with very short computation times, compatible with real time interpretation. This elastic inverse method is analytical and relies on plane-strain and isothermal assumptions. The experimental apparatus is detailed, technical issues are clearly exposed as well as calibration procedures. Several pilot cold rolling tests have been performed at various rolling speeds and different strip thicknesses in order to demonstrate the industrial feasibility. Resulting evaluations of contact stresses are then compared with numerical simulations. Reasonable agreement is obtained for normal stress (i.e., pressure) but not for shear stress (only an order of magnitude is obtained).

1. Introduction

Future customer requirements for higher quality of flat rolled products (i.e. strip thickness, strip flatness and strip surface free from defects) need a better understanding of the interaction between strip deformation in the roll bite and work roll surface (Fig. 1). This need is also due to the current trend of rolling mills to combine higher rolling speeds, larger reduction, harder steel grades and thinner rolled strips, that all affect the three strip qualities (thickness, flatness and surface). The final goal is to decrease product yield associated to these rolled strip quality defects and to improve mill productivity by minimizing roll degradation. Typically, three main rolling conditions are used to produce flat steel products: hot, cold and temper rolling. Thick strips (thickness from 30 cm to 1 cm) are rolled at around 1500 K under hot rolling conditions. The contact between the strip and the roll is a few centimeters long. Thinner strips (thickness from 5 mm to 1 mm) are rolled at around 400 K under cold rolling conditions. Shorter contact lengths are obtained (around 10 mm). Finishing steps, for packing for instance, are done under temper rolling conditions for very thin strips (a few hundreds of micrometers) with very short contact lengths (a few millimeters). Product quality is quantified by terms of flatness, defect free surface and thickness homogeneity. The different rolled materials (low or high alloy steels, low or high carbon steels, stainless or special steels) behave differently with respect to defects. Rotation speed of work rolls, rolling force (pressure applied by backup rolls), incoming strip speed, strip temperature, cooling and lubrication systems orientation are significant parameters regarding quality issues. Modern rolling mills combine higher rolling speeds, larger reduction ratios, harder steel grades and thinner rolled strips. Empirical settings do not apply anymore, thus to ensure a better product quality, knowledge of friction and lubrication in the roll gap becomes a very significant issue. Indeed, unknown shear stress and normal pressure as well as lubrication conditions take place in the strip/roll contact, where plastic deformations are generated, determining product quality.

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Nomenclature

R_m	inner radius (radius of the measurements by optical fiber)
d	depth of optical fiber Bragg grating sensors
L	roll width
l	strip width
r, θ	polar coordinates
$z = r\exp(i\theta)$	complex coordinate
Φ, Ψ	holomorphic potential
$\varepsilon_{rr}^m, \varepsilon_{45}^m, \varepsilon_{\theta\theta}^m$	measured strains at the inner radius R_m
$\varepsilon_{rr}, \varepsilon_{r\theta}, \varepsilon_{\theta\theta}$	strain tensor in the roll
$\sigma_{rr}, \sigma_{r\theta}, \sigma_{\theta\theta}$	stress tensor in the roll
λ, μ	Lamé coefficients
E, ν	Young and Poisson moduli
ω	rotation speed
f	data acquisition frequency
t_0	strip entry thickness
t_1	strip exit thickness
$T = (t_0 - t_1)/t_1$	thickness reduction ratio
l_C	contact length
F_R	rolling force
σ_0^T	strip entry tension
σ_1^T	strip exit tension

Many numerical simulations have been developed in order to characterize contact conditions as a function of rolling parameters. An interesting review of numerical simulations dedicated to the rolling process has been published by Montmitonnet (2006). For example, Jiang and Tieu (2001) proposed a rigid plastic/visco-plastic FEM and Hacquin (1996) published a 3D thermo-mechanical strip/roll stack coupled model called LAM3/TEC3 developed by Cemef, Transvalor, ArcelorMittal Research and Alcan. Abdelkhalek et al. (2011) computed the post-bite buckling of the strip, which is added to the older simulation of Hacquin (1996), in order to predict accurately flatness defects. Shahani et al. (2009) simulated a hot rolling process of aluminum by FEM and used an artificial neural network in order to predict the behavior of the strip during the rolling process (the artificial neural network being trained by the simulation). Numerical simulations adapted for particular hot rolling of large rings have been proposed by Wang et al. (2009).

Such predictive models are necessary to understand phenomena (material flow in the roll gap, strain, stress and temperature rate fields) in order to establish rolling strategies for better productivity and quality. However, contact conditions (friction) of these numerical simulations do not have experimental validation in industrial or semi-industrial conditions. Moreover, the roll-strip contact is usually described by Coulomb or Tresca friction laws which are over-simplified to describe the complexity of the interface. Furthermore, a closed-loop control of rolling parameters depending on real-time measurements of contact conditions would be a substantial improvement of the process. Thus, the development of one-line roll gap sensors adapted for measuring in real-time contact stresses (pressure and shear stresses) is motivated by this double issue: model validation on the one hand and monitoring and controlling rolling parameters through feed back control on the other hand. To reach these goals, a European project RFS-PR-08051 (2014) has been launched with the aim to develop three complementary roll gap sensors for measuring simultaneously the mechanical, thermal and lubrication conditions at the roll–strip interface. The present work, which is part of this European project, presents the development of the mechanical sensor for measuring contact stress during pilot rolling tests. Pin sensors already provide measurements of contact stresses, although the presence of the pin disturbs the local lubricant flow at the interface, and the contact strongly marks the strip; industrial use is therefore impossible. Nevertheless, many investigators have designed direct friction pin sensors such as Jeswiet and Rice (1982) for normal stress or Lu et al. (2002) for shear stress or Andersen et al. (2001) who developed a commercial transducer. An indirect measurement that does not degrade contact conditions has been preferred in this study. More precisely an inverse method, that interprets strain measurements under the roll surface performed by optical fiber sensors fully embedded inside the roll body, has been developed. Consequently, marks on the strip are limited and contact conditions are preserved. Technical issues related to optical fiber sensors insertion under the roll surface, as well as equipment and design are detailed. A calibration procedure is proposed and clearly exposed. Then, pilot rolling tests are presented and the evaluation of contact stresses obtained by inverse method is compared with numerical simulations done with LAM3/TEC3 proposed by Hacquin (1996). In previous works, Weisz-Patrault et al. (2011) developed an analytical inverse method adapted for rolling processes that interprets stresses at only one position under the roll surface, in order to obtain contact stresses. Weisz-Patrault et al. (2012a) also proposed an inverse method that interprets temperature data under the roll surface in order to infer heat fluxes in the roll gap, and a thermoelastic coupling have been proposed by Weisz-Patrault et al. (2013a). An extension in three dimensions (with several points aligned along the roll axis) has been also developed by Weisz-Patrault et al. (2013b) for stresses and Weisz-Patrault et al. (2014b) for temperature. Pilot tests have been performed for thermal inverse problems dedicated to heat flux determination in the roll gap by Weisz-Patrault et al. (2012) and Legrand et al. (2012) with detailed experimental apparatus (insertion of the thermocouple under the roll surface, etc.) and calibration procedures, and by Legrand et al. (2013) with a specific study on thermal fatigue of rolls. More recently, Weisz-Patrault (2015) proposed a semi-analytical inverse method based on conformal mapping techniques applied for latent flatness defect detection during rolling process. In this paper, contact stresses are evaluated through strain measurements obtained by several optical fiber sensors inserted into the roll, at only one location under the roll surface (around 2 mm under the surface). An isothermal assumption is made since cold rolling tests are studied here: temperature increase in the roll bite is sufficiently moderate not to propagate at sub-surface so that these sensors measure only the mechanical roll strain. The inverse method used for inputs interpretation is based on the isothermal inverse method proposed by Weisz-Patrault et al. (2011), however a substantial adaptation

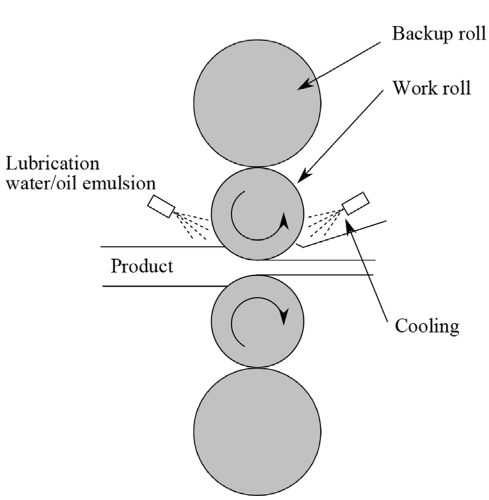

Fig. 1. Rolling process.