International Journal of Solids and Structures 94–95 (2016) 1–20

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Non-linear simulation of coiling accounting for roughness of contacts and multiplicative elastic-plastic behavior

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ARTICLE INFO

Article history:
Received 1 October 2015
Revised 9 May 2016
Available online 20 May 2016

Keywords:
Coiling
Roughness
Contact
Multiplicative elasto-plasticity
Finite strains
Optimization

ABSTRACT

In this paper numerical simulations of coiling (winding of a steel strip on itself) and uncoiling are developed. Initial residual stress field is taken into account as well as roughness of contacts and elastic-plastic behavior at finite strains, considering the Tresca yield function and isotropic hardening. The main output is the residual stress field due to plastic deformations during the process. This enables to quantify additional flatness defects. The presented coiling simulation relies on a modeling strategy that consists in dividing each time step into two sub-steps. Each sub-step can be solved semi-analytically and numerical optimizations enable to obtain a general solution. Thus, reasonable computation times are reached and parametric studies can be performed in order to develop coiling strategies considering the process parameters. Comparisons with previous models from the literature are presented. Moreover, the comparison with a Finite Element simulation presents the same order of magnitude, however, it shows that direct computations using classical FE codes are difficult to perform in terms of computation times and stability if an explicit integration scheme is chosen. Numerical results are also given in order to determine the effect of some parameters such as roughness, yield stress, applied force, strip crown or mandrel's radius.

1. Introduction

The coiling process consists in winding under tension a steel strip on a cylindrical mandrel. This process is very commonly used for storage in the steel-making industry and takes place after two main processes namely the rolling process on the one hand where the strip thickness is reduced between two rotating rolls and the run out table on the other hand where a cooling path is imposed in order to reach a targeted micro-structure. A schematic view of these is presented in Fig. 1. Large heterogeneous plastic deformations and phase changes occur during these latter processes leading to significant residual stress issues. Residual stress profiles are called flatness defects because they are responsible for out of plane deformations when tension is released and the strip is cut. Flatness prediction is one of the major issue of the steel-making industry, thus many papers proposed numerical simulations of rolling process in order to improve knowledge of residual stresses as a function of rolling parameters. One can mention a review of numerical simulations of rolling process published by Montmitonnet (2006). 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). Nakhoul et al. (2014) used a coupled Finite Element Modeling in order to predict manifested flatness defects. The impact on flatness of heterogeneous temperature field on the one hand and friction on the other hand is investigated. Kpogan and Potier-Ferry (2014) developed a simplified numerical method in order to predict the response of long thin strips considering residual stresses. Nakhoul et al. (2015) developed a two-scaled buckling model to predict the occurrence and geometric characteristics of manifested flatness defects. Recently Cuong et al. (2015) published an experimental and numerical modeling of flatness defects. Furthermore inverse methods dedicated to experimental evaluation of contact conditions during the rolling process have been developed in order to offer an experimental counter-part to predictive models. For instance, Weisz-Patrault (2015) reviewed some flatness control procedures and proposed an inverse Cauchy method using conformal mapping techniques that evaluate the residual stress profile in the strip. In addition, Weisz-Patrault et al. (2011, 2013b) published fast inverse methods (in 2D and 3D) dedicated to contact

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http://dx.doi.org/10.1016/j.ijsolstr.2016.05.012
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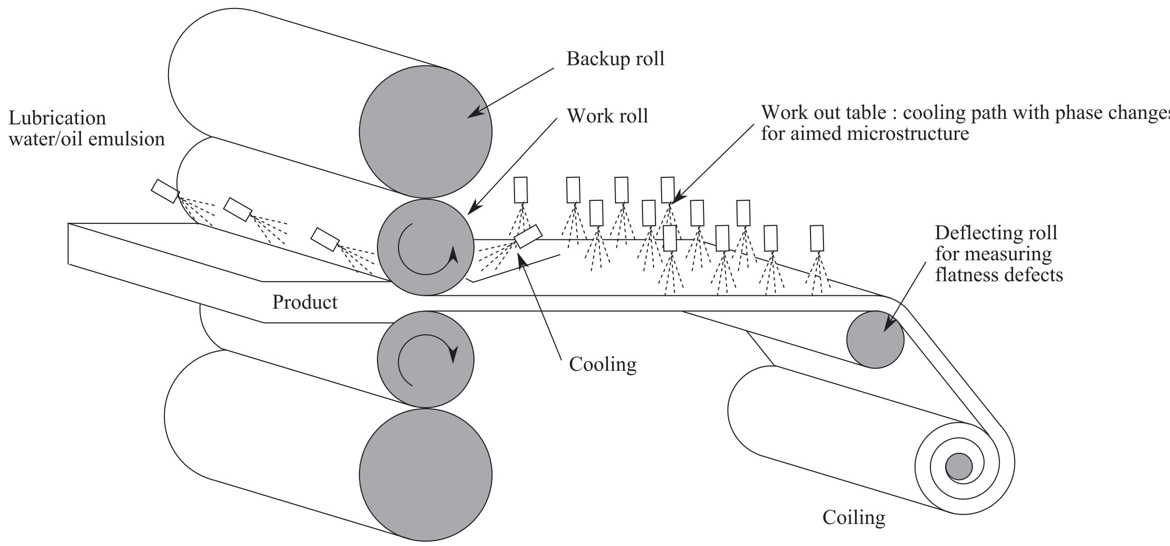

Fig. 1. Schematic view.

stress evaluation in the roll gap in real time during the rolling process. An experimental study based on this inverse method and optical fiber measurements has also been proposed by Weisz-Patrault et al. (2015b). Fast inverse methods have been developed for the thermal characterization of the contact between the strip and the work roll during the rolling process in 2D and 3D by Legrand et al. (2013); Weisz-Patrault et al. (2012a) and a thermo-elastic coupling have been published by Weisz-Patrault et al. (2013a). Experimental studies showing the feasibility of temperature measurements during the rolling process and performances of the associated inverse methods have been led by Legrand et al. (2012); Weisz-Patrault et al. (2014, 2012b).

Specific flatness defects occur during the coiling process as illustrated by Counhaye (2000). Indeed, for rather thick strips or small mandrels radii the curvature can generate significant plastic deformations. Furthermore, the geometrical strip profile of a cross section is not rectangular but more often parabolic, thus the strip center is thicker than the edges. Therefore the contact of the strip on itself is not ensured all along the coil width and a barrel shape is commonly observed. Usually the contact length decreases from the first layer to the last one and concentrates at the strip center (for parabolic geometrical profiles where the strip center is thicker). Consequently the contact pressure increases. This induces over-tension in the strip that is responsible for plastic deformations especially for the last layers where long center defects (or wavy center) are often observed because plastic elongations are localized at the center. Moreover, when large coils are obtained the first layers near the mandrel are submitted to large compressions that can also induce plastic deformations and short center defects (or wavy edges) are observed because plastic shrinkage is localized at the center. These defects are presented in Fig. 2. In addition, when the coil cools down phase changes occur modifying the residual stress distribution. Thus, modeling the coiling process is part of the general effort to predict flatness defects. There are several attempts to simulate effectively the winding of a strip on a mandrel.

Edwards and Boulton (2001) presented major issues related to the coiling process as well as an interesting review of the early models. For instance, soft or tight center collapses of coils are described on the basis of industrial experiences, however, the present contribution does not deal with such issues and focuses on numerical coil winding simulation. Most of coil winding models use thin or thick-walled elastic theory for hollow cylinders. Within this frame work (Sims and Place, 1953) proposed an approach based on the theory of wire-winding of gun barrels. Based on experimental results, (Wilkening, 1965) emphasized that the model proposed by Sims and Place (1953) fails after 55 wound wraps, because stresses are widely overestimated. Altmann (1968) introduced an analytical solution considering constant radial Young's modulus, but tangential stress could not evolve. Wadsley and Edwards (1977) fixed the radial Young's modulus of the coil to a very low value compared with the standard value of the constituting material. This anisotropy is an attempt to model roughness of contacts. Thus, the coil is modeled as a hollow cylinder but the radial Young's modulus is decreased in order to take into account surfaces interpenetration due to roughness. However, the strip thickness variations are not taken into account. The model proposed by Edwards and Boulton (2001) also uses a radial Young's modulus that varies with the number of wound wraps. However, it seems that contact is imposed all along the coil width, no open gaps are formed between the wraps at any point. As detailed above, the contact length actually decreases because of the geometrical profile of the strip. It

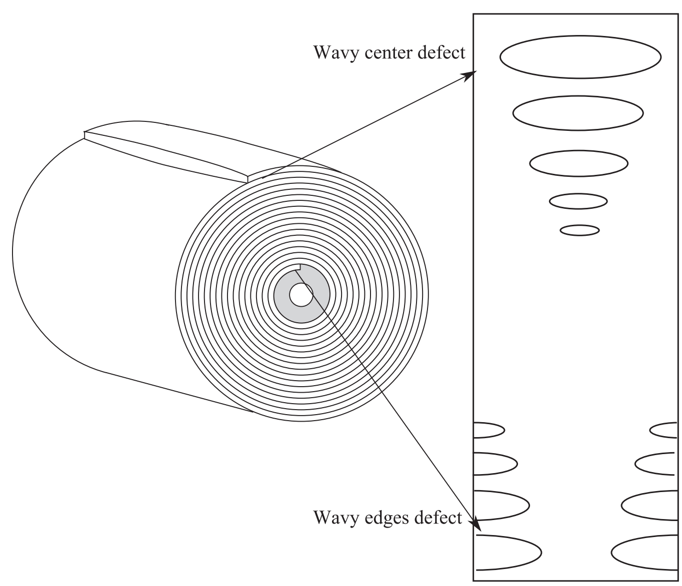

Fig. 2. Specific flatness defect.