2D asperity deformation of stainless steel strip in cold rolling

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ABSTRACT: A sequential fluid-structure weak coupling approach is developed in order to compute the deformation of 2D asperities in mixed lubrication regime. The cold rolling model involves the strip with its asperities, the lubricant and the working roll. Reynolds equations are solved at the asperity level and lead to the evaluation of the fluid pressure acting on the asperity sides. Then solid finite element models, where the top of the asperity are in contact with the working roll and the fluid pressure is applied on asperity sides, are performed. Reynolds solving and finite element computations are performed on an asperity, from the entry to the exit of the roll bite. The methodology is applied to quantify effect of shot blasting on asperity flattening.

Key words: cold rolling; stainless steel; mixed lubrication; fluid-structure weak coupling

1 INTRODUCTION

In order to reduce friction and to better control workpiece final roughness, most metal forming processes require mixed lubrication regime at tool work-piece interface [1]. The main peculiarity of the mixed lubrication regime is that the contact pressure between tools and workpieces is partly managed by the contact between asperities, and partly by the lubricant. The top of work-piece asperities are then upset by the tools, when the asperity sides are deformed by the pressurized lubricant.

The mixed lubrication regime has been widely studied, more particularly in the field of cold rolling [2-4]. Recent studies were based on a coupling between fluid mechanic equations and a flattening asperity model [5,6]. The total pressure at the roll-strip interface P is expressed as a function of the pressure at asperity tips Pa, the fluid pressure in the valley Pb and the real area of contact A:

$$P = A.Pa + (1-A).Pb \qquad (1)$$

The total pressure P is identified from equilibrium equations of the process. Relation between the pressure Pa and the real area of contact comes from flattening asperity models [7]. Fluid pressure Pb is identified by solving Reynolds equations along the contact surface. These analyses are very useful to compute the contact pressure along the roll bite, identify roll separating forces, lubricant film thickness and frictional stress, but can not determine with accuracy the shape of the deformed asperities, which are given by the flattening asperity model.

The present paper deals with a sequential fluid-structure weak coupling approach in order to circumvent the problem. The cold rolling model involves the strip with its asperities, the lubricant and the working roll. The strip asperities are modeled in 2D (trapezoidal shape in the present study). Reynolds equations are solved at the asperity level and lead to the evaluation of the fluid pressure acting on the asperity sides. Then solid finite element models, where the top of the asperity are in contact with the working roll and the fluid pressure is applied on asperity sides, are performed. Reynolds solving and finite element computations are performed on an asperity, from the entry to the exit of the roll bite.

2 THE ROLLING PROCESS

The studied rolling process is used to reduce stainless steel strip from 3 to 0.49 mm. The rolling machine is a Sendzimir mill made up of two work rolls, four first intermediate rolls, six second intermediate rolls and height backup rolls. Work rolls have diameter lower than 100 mm. During the rolling process, a roll separating force (RSF) and a torque (C) are applied on the rolls to maintain pressure on the strip and to reduce its thickness. A rear tension (RT) and a front tension (FT) are applied on the strip in order to guide it correctly at the mill entry (figure 1). The peripheral roll speed ranges from 300 to 650 m/min. The forward slip ranges from 0 to 20%. Mineral oil is used as lubricant.
The final thickness is obtained after 10 rolling passes, with reduction ration decreasing from 25% to 10%.
The strip is shot blasted before cold rolling. The shot blasting is performed to clean the strip and provide a given initial roughness that facilitates the lubricant inflow through the roll gap. The initial arithmetical average roughness Ra is equal to 2.7 µm in the present work.

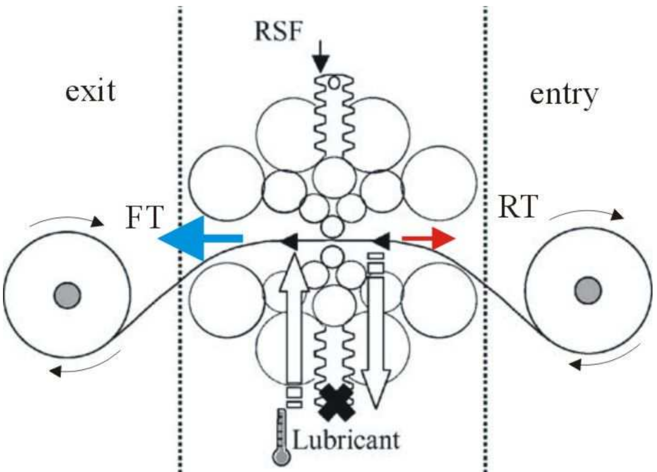

Fig. 1. Overview of a Sendzimir type mill

3 METHODOLOGY

The roll bite is divided in a given number of “steps”. For each step, i.e. for each position of the asperity along the roll bites, a fluid-structure weak coupling is performed. The first solid finite element computation is run to compute the contact pressure at the strip/roll interface. No fluid pressure is applied on asperity sides. The resulting pressure values are used as initial conditions to solve Reynolds equations. Then a second solid computation is performed with pressure on asperity sides. New values of contact pressures are obtained on asperity tops, leading to new initial conditions to solve Reynolds equation. A loop is performed until contact pressures converge.

3.1 Finite element model

ABAQUS/Standard is used to perform the finite element computations. This is an implicit code that has convergence checking at each increment step to ensure the equations are solved accurately. The strip is modelled by 1212 four node plane strain full integration elements. The mesh is refined at the strip surface and in the vicinity of the asperities (figure 2). A total of 5 asperities are meshed. The work roll is supposed to be non deformable and is modelled by a rigid surface.
Strip bulk behaviour is characterized by a Young modulus equal to 210 MPa, a Poisson’s coefficient equal to 0.3 and an initial yield stress equal to 560 MPa.

3.2 Lubricant pressure

The fluid pressure is obtained by solving the average Reynolds equation introduced by Patir and Cheng [8]:

$$\frac{d}{dx}\left(\Phi_x \frac{h_t^3}{12\eta}\frac{dp_b}{dx}\right) = -\left(\frac{u_r + u_w}{2}\frac{dh_t}{dx} + \frac{h_t}{2}\frac{du_w}{dx}\right) \quad (2)$$

where u_w and u_r are respectively the strip and the roll surface velocities, h_t is the average film thickness, η is the oil viscosity, x is the distance from the exit of the roll bite and Φ_x is a flow factor, function of the root mean square roughness. Equation (2) is solved using the finite difference method with a Gauss-Seidel iterative scheme [9]. The fluid pressure is then given by:

$$P_{fi}^{next,k+1} = \frac{X_i^+ P_{fi+1}^k + X_i^- P_{fi-1}^{k+1} - 12\eta X_i \Delta x^2}{X_i^+ + X_i^-} \quad (3)$$

with

$$\begin{cases} X_i^- = (\Phi_{xi-1} + \Phi_{xi})(H_{ti-1}^3 + H_{ti}^3) \\ X_i^+ = (\Phi_{xi+1} + \Phi_{xi})(H_{ti+1}^3 + H_{ti}^3) \\ X_i = \left(\frac{u_r + u_{wi}}{2}\right)\frac{H_{ti+1} + H_{ti-1}}{2\Delta x} + \frac{H_{ti}}{2}\frac{u_{wi+1} - u_{wi-1}}{2\Delta x} \end{cases}$$

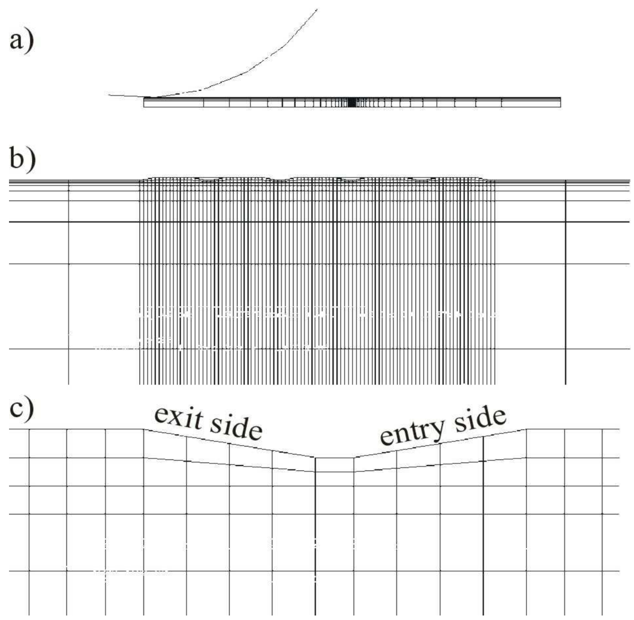

Fig. 2. Finite element mesh. a) finite element mesh b) zoom on the refined area, c) zoom on an asperity

and where k is the iterative index-number, i the node number, P_f the dimensionless fluid pressure ($P_f = p_f/\sigma_0$) and H_t the dimensionless film thickness ($H_t=h_t/R_q$).

3.3 Asperity geometry

The shot blasting of the strip before the first pass lead to an initial surface profile where the asperity tips are flattened. Asperities can not be schematized by triangle are then modelled as trapezoids which geometrical characteristics are the valley length Lv, plateau length Lp, height Rt and angles α and β (figure 3a). For the studied strip, α and β are equal to 10°, Rt ranges from 6 to 10µm, Lv from 5 to 20 µm and Lp from 50 to 200µm. A comparison between true and simplified surface profiles is presented in figure 3b.

4 RESULTS

Two finite element computations are performed to study the influence of the shot blasting. In the first computation only the surface geometry resulting from the shot blasting is considered. The surface profile is the one measured on the real steel strip and presented in figure 3b. The same bulk behaviour law is associated to the 1212 finite elements of the model. In the second computation, the effect of shot blasting on the strip behaviour is also taken into account. An inverse method of identification based

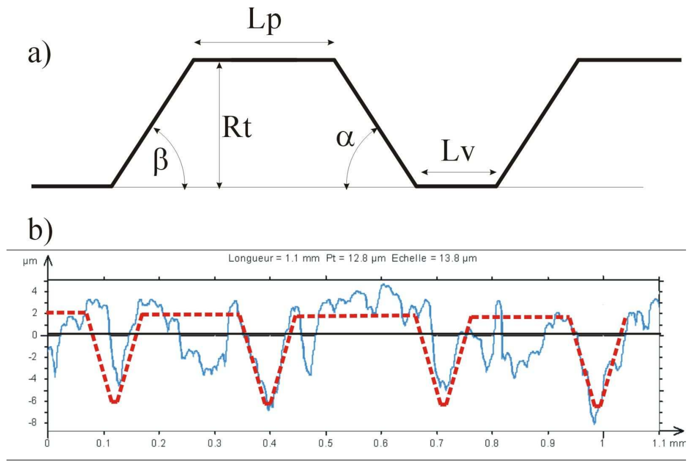

Fig. 3. Asperity profile. a) Geometrical parameter b) true surface profile (blue), simplified profile (red)

on Vickers indentations was used on the real strip to identify the bulk behaviour in the surface vicinity so that the strip thickness affected by the shot blasting operation [10].

The second finite element model involves a first bulk behaviour law for the elements in core of the strip, and a second behaviour law for the element in surface of the strip. The initial yield stress in core equals 565 MPa, the initial plastic stress in surface equals 702 MPa.

Figure 4 presents the asperity valley deformation in the case of single bulk behaviour computation. The fluid pressure acting on valley sides leads to a non symmetrical deformation of the asperities. The “entry” side of valleys tends to folds on the roll surface when the elongation of the strip leads to the stretching of the “exit” side. The slopes of asperity sides are then changed and angles α and β are no more equal.

Taking into account the hardening of the strip surface due to shot blasting does not greatly modified the profile of the deformed asperities. Nonetheless, the reduction in height is greatly modified. When considering only geometrical aspects of shot blasting, the first rolling pass reduces the asperity height by 20%, from 8 to 6.4 µm. When strain hardening is consider, asperity height are only reduced by 8%, from 8 to 7.4 µm.

5 CONCLUSIONS

A fluid-structure weak coupling is proposed to study the flattening of steel strip asperity during a cold rolling sequence. First the fluid pressure is obtained by solving the average Reynolds equation. Then the fluid pressure is applied on asperity sides in a "solid" finite element model. The proposed methodology is applied to quantify the effect a shot blasting on the strip surface profile after rolling. Two computations are run, one taking into account only the geometry generated by the shot blasting operation, another taking into account the geometry and the strain hardening of the strip surface. Results show that, for a given surface profile, strain hardening due to shot blasting reduces asperity flattening. More lubricant can then carried through the roll bite for the next rolling pass.

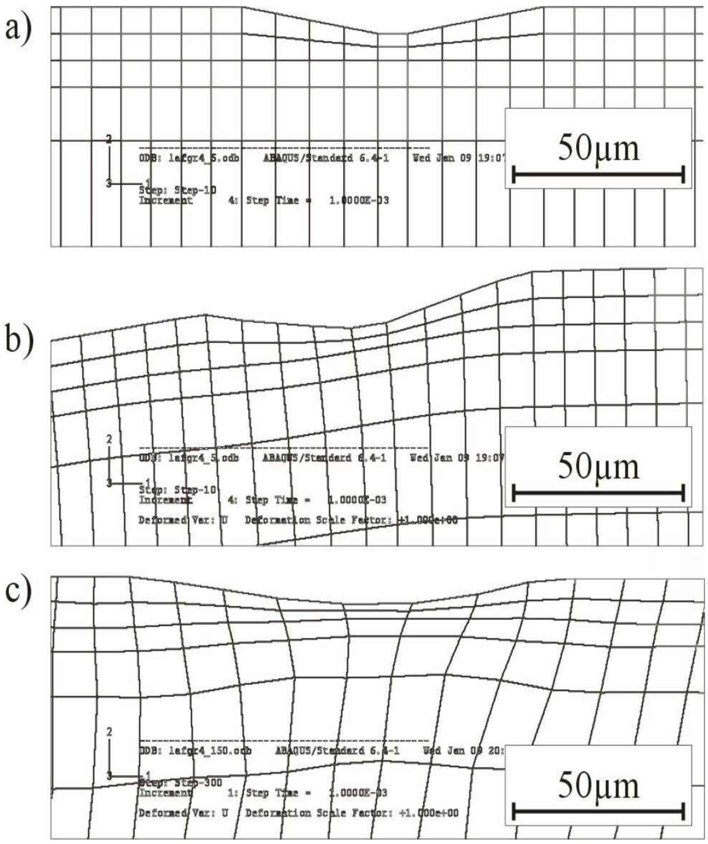

Figure 4. a) initial asperity mesh b) deformed mesh at roll bite entry c) deformed mesh at roll bite exit

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