Microsc. Microanal. Microstruct. **7** (1996) 541–547 OCTOBER/DECEMBER **1996**, PAGE 541

Classification
Physics Abstracts
42.30 — 07.05.Pj — 07.05.Rm — 68.35.Bs — 83.50.Yt

Morphological Simulation of the Roughness Transfer on Steel Sheets

Dominique Jeulin and Pascal Laurenge

Centre de Morphologie Mathématique, ENSMP, 35 rue Saint Honoré, 77305 Fontainebleau, France

Résumé. — Le transfert de rugosité a lieu lors de la dernière étape de laminage des tôles en acier. L'un des buts de l'opération consiste à modifier la surface de la tôle afin de lui donner une morphologie de surface qui conditionne certaines propriétés de mise en œuvre de la tôle. Un modèle de simulation morphologique, basé sur des essais expérimentaux, est proposé pour prévoir la topographie de surface de la tôle connaissant celle du cylindre. Des résultats de prévision sont montrés et comparés à des essais réels de transfert de rugosité.

Abstract. — The roughness transfer is made during the last stage of the cold rolling of the steel sheets. One of the aims of the operation is to modify the surface of the strip by imposing a particular surface morphology controlling, some use properties of the sheet. A model of morphological simulation, based on experimental data, is proposed to predict the surface topography of the plate from the topography of the cylinder. Results of prediction are shown and compared to experiments of roughness transfer.

1. Introduction

Steel sheets used in car industry are skin-passed at the end of the cold rolling process, one of the aims being to obtain a well defined surface morphology. The roll cylinders have a specific roughness which is partly transferred on the plate surface during the process. We propose in this paper to model this roughness transfer.

Mechanical approaches of the indentation of a smooth surface by an indenter with a simple geometry are available in the literature [1, 2]. It is difficult to extend them to the case of indenters with a more complex morphology, and to multiple interactions between indenters. In this paper, a model based on a morphological approach [3, 4] is proposed.

To build a model of transfer, it is necessary to explain how the plate surface is deformed under the contact with a rough cylinder. For this, 3D maps of the surface of the cylinder and of the printed plate (the heights of the rough surface are of the order of some microns) can be used. In addition, these data are available for different pressures, or equivalently for different levels of contact. Finally, the maps of the cylinder and of the plate correspond to the same location. They enable us to observe how the plate surface is deformed, and to validate the model.

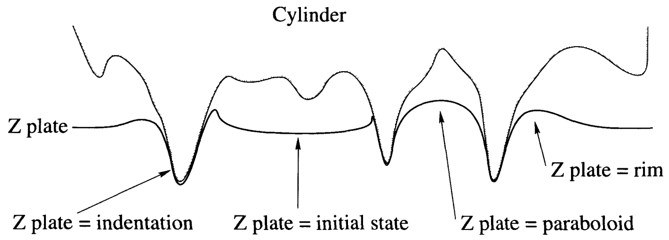

Fig. 1. — The plate deformation can be decomposed into 4 different types of deformation.

The first and trivial model of transfer is obtained from a threshold of the surface of the cylinder to simulate its penetration into the plate [5]. Observations of plates show that this simple model can be used correctly in very few situations. In a first step, the proposed model is presented, and in a second step the results of simulations are compared to data.

2. Introduction to the Model of Simulation

2.1 DESCRIPTION. — The aim of the model of simulation is to predict the plate morphology from the knowledge of the surface of the cylinder. One notes $Z_{\text{cylinder}}(x)$ the height of the cylinder at point x, and one considers a given separation between the cylinder and the plate (or equivalently a given applied pressure). We want to predict in every x the height of the plate $Z_{\text{plate}}(x)$. From experimental observations, it can be shown that every point x of the plate surface can belong to one of the following four states (Fig. 1).

1. In point x the cylinder and the plate are in contact: there is an indentation, and
$$Z_{\text{plate}}(x) = Z_{\text{cylinder}}(x).$$
2. Point x is out of any influence of indentations: its height remains the height of the initial plate:
$$Z_{\text{plate}}(x) = Z_{\text{plate}}^{\text{initial}}(x).$$
3. Point x is close to an indentation: the plastic deformation appears as a rim, the metal climbing around the indenter. One has:
$$Z_{\text{plate}}(x) = B(x).$$
Experimental observations of individual indentations allow us to propose the following function as a model of rim:
$$B(r) = k\, r e^{-\beta r^2} \tag{1}$$
where r is the distance of point x to the first indentation. This information is obtained by means of a distance function calculated on the complementary set of the contact zones between the cylinder and the plate. It is obtained from a mathematical morphology software, and it accounts for the shape of planar sections of the indenter.
4. Point x is located between two neighboring indenters: the deformation appears like a paraboloidal climb. In our model we add the functions $B(r)$ of overlapping rims. As shown in Figure 2a this assumption reproduces fairly well the observed shape.

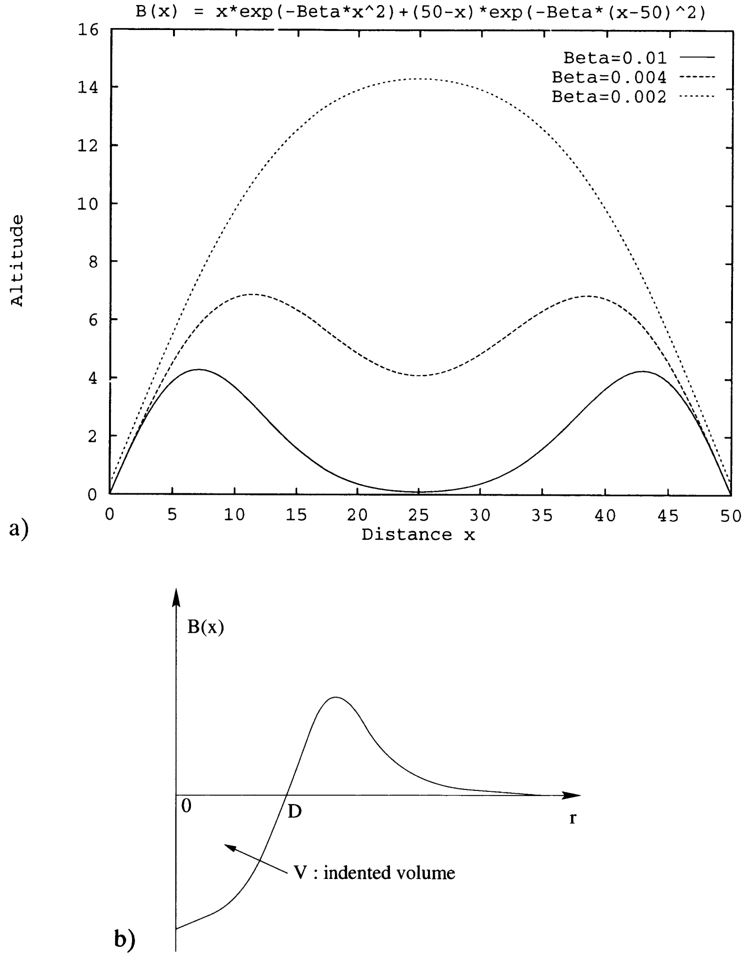

Fig. 2. — a) Examples of rims for two different values of β: they overlap by addition, giving a paraboloidal shape for a short distance, as observed in experiments. b) Conservation of the indented volume (with a revolution symmetry).

2.2 IDENTIFICATION OF THE PARAMETERS.

2.2.1 *Coefficient k.* — From experimental observations, the indented volume is equal to the volume of the rim, as a result of the volume conservation. (Fig. 3a). This fact is used to calculate the parameter k of the model of rim. The calculation is made for a cylinder symmetry of the indentation and of the rim (Fig. 2b). The obtained coefficient k depends on the second parameter β and on the volume and on the surface area of the section of the indentation:

$$k = \frac{2\,\sqrt{\beta}\;V_{\text{indentation}}}{\pi\,\left(\sqrt{\pi} + 2\,\sqrt{\frac{S_{\text{indentation}}}{\pi}}\;\beta\,\sqrt{\beta}\right)}. \tag{2}$$

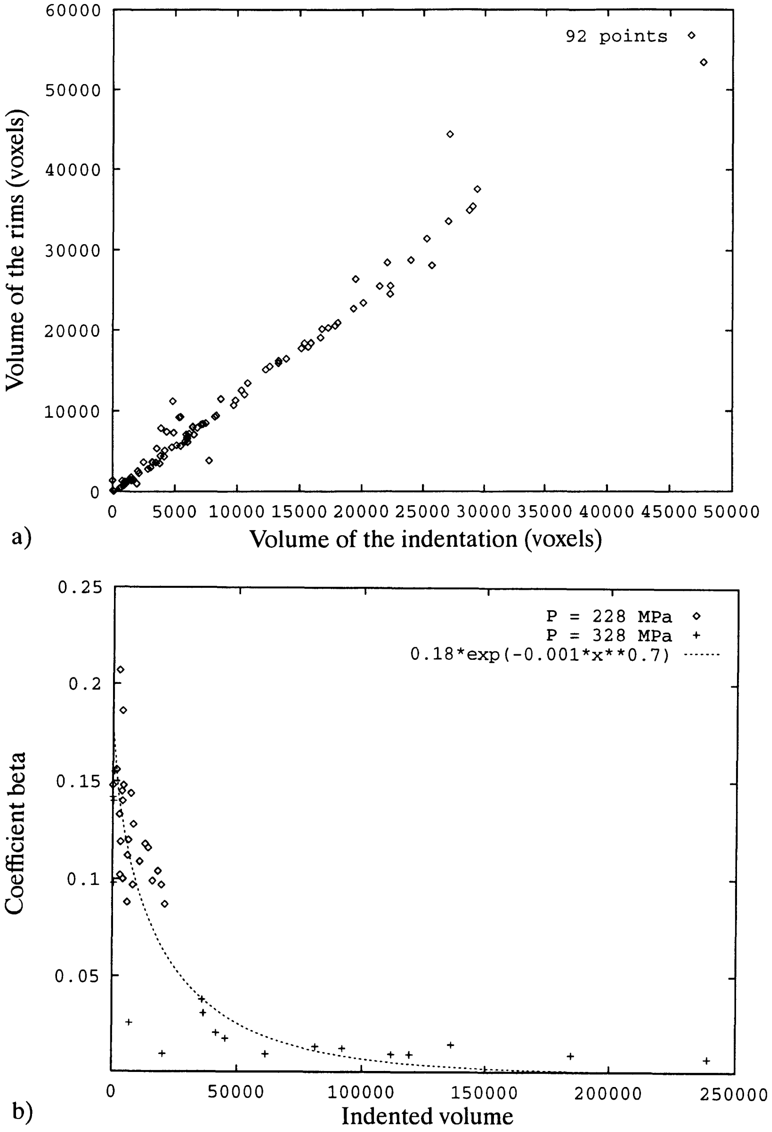

Fig. 3. — a) Volume of the rims as a function of the volume of the indentation. Every measurement is made on separate indentations (see the map in Fig. 4a). b) Estimation of $\beta = f(V_{\text{indentation}})$.

2.2.2 *Coefficient* β. — The coefficient β is fit from individual indentations extracted on two maps obtained for two pressures. The results are given in Figure 3b showing the variation of β with the indented volume. The following law $\beta(V)$ was fit from the data, and is used in the model of rim $B(x)$ (Eq. (1)):

$$\beta(V_{\text{indentation}}) = 0.18\ \mathrm{e}^{-0.001\ V_{\text{indentation}}^{0.7}}. \qquad (3)$$

2.3 INCREMENTAL MODEL. — The previous version of the model, introduced in [3, 5], predicts in one step the deformation of the plate surface for a given level of transfer. The simulation depends

Table I. — *Correlation coefficients between the heights of the plate and the heights of the simulation (Fig. 4).*

Pressure	Full map	rims
228 MPa	0.95	0.62
328 MPa	0.93	0.44
959 MPa	0.99	0.68

on the projected surface of contact and the volume of indenters, but not on their tridimensional morphology. In addition, during the process, the deformation of the surface of the plate is continuous after the first indentation. To reach a given distance h between the cylinder and the plate, it is necessary to follow a continuous path that controls the final result. This can be simulated by an incremental version of the model, with the following algorithm: let $B(x,h)$ be the deformed surface corresponding to the distance h. One has

$$B(x,h) = \int_0^h \frac{\partial B(x,u)}{\partial u}\,\mathrm{d}u. \tag{4}$$

This integral is approximated by a discrete sum:

$$B(x,h) = \sum_{i=0}^{n} B(x,(i+1)\,\delta h) - B(x,i\delta h) \tag{5}$$

where δh is an increment of distance ($h = n\delta h$). The rims calculated by relation (1) are added step by step to the result of the indentation, while is also accounted for the penetration of the indenters of the cylinder into the plate. No deformation of the cylinder is introduced in the simulation.

3. Simulations and Validation

The validation of the model of transfer is made with three compression tests on a mild steel sheet (with the hardness 430 MPa). The plate was polished before the test, to start with a very smooth surface. The roughness of the tool is irregular and anisotropic with parallel valleys. The incremental model is applied with the punch, and stopped at three levels of the distance corresponding to experimental data (this is checked by the projected area of contact). Experimental maps were obtained with a mechanical stylus instrument. They can be compared to simulated maps, as shown by grey level images in Figure 4.

The linear coefficients of correlation (Tab. I), estimated on the part of the surface made of rims (for comparison, the model based on a threshold of the surface gives a coefficient of correlation close to zero in these zones), shows that the model gives satisfactory results for low pressures, when there is no interaction between indentations (the model was fit with data corresponding to this situation). For shorter separations (corresponding to higher pressures), similar coefficients of correlation are obtained, while it is lower for intermediary cases. This shows that the model gives good predictions for a large or a low separation of indenters; the prediction is slightly less accurate at the beginning of the interaction between rims. In [3, 4] is proposed to use as additional

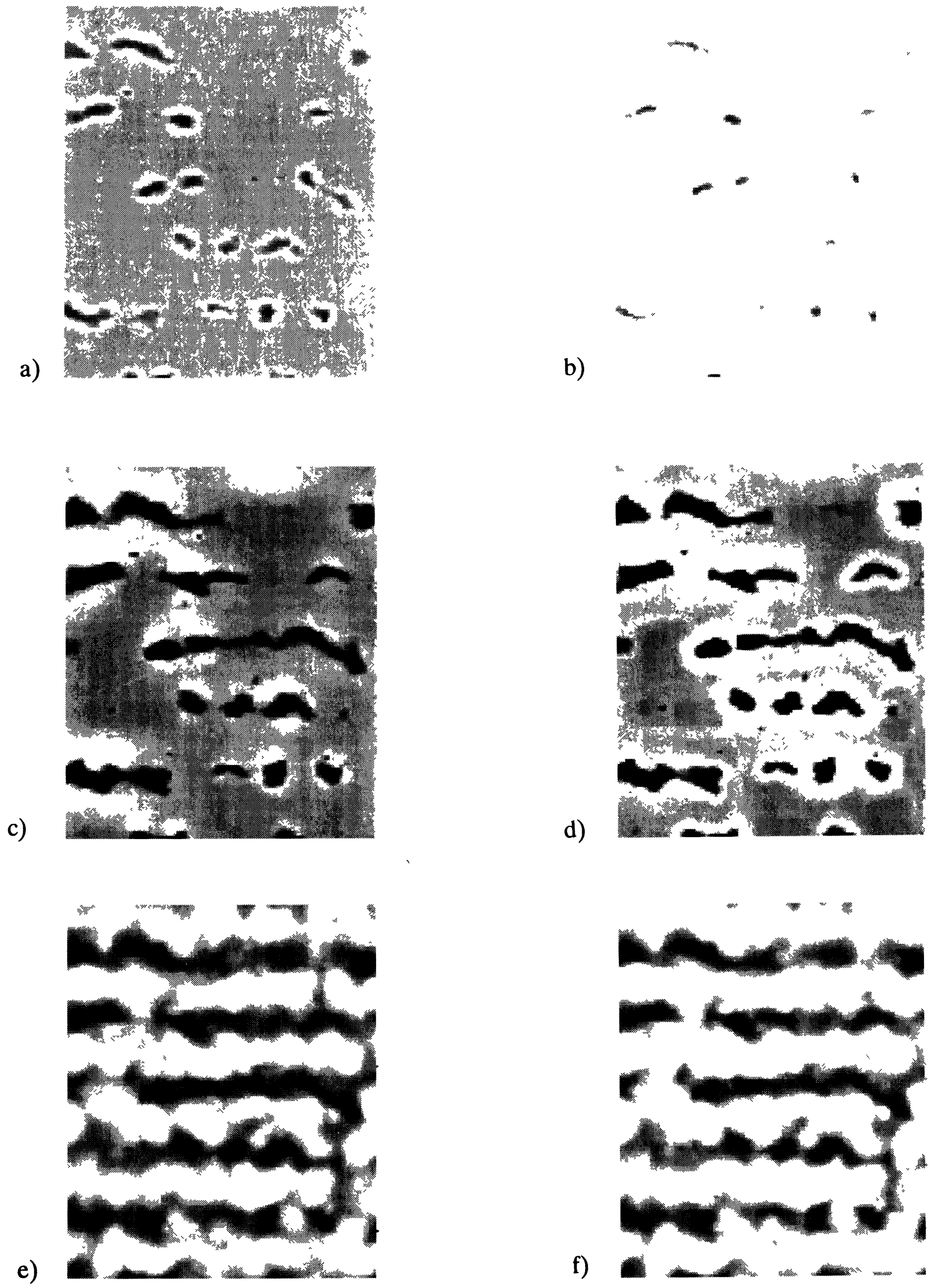

Fig. 4. — Comparison between simulated maps (incremental model) and maps obtained by punching experiments (940 × 1180 m^2; range of heights $\simeq$ 40 μm). a) 228 MPa: real surface. b) 228 MPa: simulation. c) 328 MPa: real surface. d) 328 MPa: simulation. e) 959 MPa: real surface. f) 959 MPa: simulation.

information the distance between a point x of the surface and the second neighboring indenter, in addition to the first one. Applying this model of transfer of the roughness to simulated textures of the cylinder [6], it will become possible to control the final roughness of steel sheets.

Acknowledgements

The authors are grateful to B. Fournel (IRSID) for his contribution to the experimental part of this study, which was supported by IRSID and by MRE (contract n° 92.A.0518).

References

[1] Johnson K.L., Contact Mechanics (Cambridge University Press, 1985).

[2] Storåkers B. and Larsson P., *J. Mech. Phys. Solids* **42** (1994) 307.

[3] Laurenge P. and Jeulin D., Modélisation de l'interaction métal-cylindre en skin-pass, N-35/95/G, Internal Report, School of Mines, Paris (1995).

[4] Laurenge P., Analyse et modélisation du transfert de rugosité, Thèse de Doctorat de l'École Nationale Supérieure des Mines de Paris (April 1996).

[5] Laurenge P., Jeulin D. and Fournel B., Morphological description of the textured roll surfaces and simulation of the roughness transfer during rolling, in Proc. Int. Congress Rolls 2000, Birmingham, UK (1996).

[6] Jeulin D. and Laurenge P., in "Mathematical Morphology and its Applications to Image and Signal Processing" Proc. ISMM'96 Conference, Atlanta, P. Maragos, R.W. Schafer and M.A. Butt, Eds. (Kluwer Academic Publishers, Dordrecht, 1996) pp. 289-296.