Journal of Materials Processing Technology 233 (2016) 53–67

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

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

Novel approach to computational simulation of cross roll straightening of bars

Jindřich Petruška, Tomáš Návrat, František Šebek*

Faculty of Mechanical Engineering, Brno University of Technology, Technická 2896/2, 616 69 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 3 September 2015
Received in revised form 29 January 2016
Accepted 5 February 2016
Available online 9 February 2016

Keywords:
Cross roll straightening
Finite element analysis
Eulerian material flow
Elastoplastic bending

ABSTRACT

A new finite element formulation, aimed at the modeling of cross roll straightening of circular bars is presented. It is based on Eulerian description of elastoplastic material flow through a stationary finite element mesh, which is fixed in space and coupled with the multi-roller straightening machine. This approach leads to extremely effective computational algorithm which provides the relation between input parameters like curvature, diameter and material of the bar, straightening rollers geometry and intermeshing on one hand and output bar curvature and residual stress distribution on the other. Using this strategy, multiple repetition of the straightening process analysis for variable intermeshing scheme is a feasible task, aimed to optimization of roller intermeshing. Basic features of the algorithm are described, some verification results presented and compared with real experiments realized in industrial conditions. The industry was also a motivation for the optimization study, presented in the last part of paper. The results prove that the suggested solution strategy is a mighty tool for effective analysis of cross roll straightening and show a great potential for other types of straightening processes as well.

1. Introduction

Cross roll straightening of circular bars is based on repeated elastoplastic bending of the bar, moving through the straightening machine with simultaneous rotation around its longitudinal axis. The bending is caused by vertical intermeshing w_A, w_C, w_E and w_G with angular deviation β of subsequent straightening rollers of a typical straightening machine in Fig. 1. Optimal setting of these parameters to reach the best performance of the machine for different bar diameters, material or input curvature is a complicated problem. It was solved by a number of approaches, starting from empirical experience combined with a basic theoretical knowledge and analytical solutions of elastoplastic bending of beams. This classical approach starts from known curvatures, applied as a forced kinematical loading to rotating bar or tube with constant initial curvature and ideally plastic material. Cyclic changes of curvature result in redistribution of strain, stress and bending moment over the bar cross section, as in Tokunaga (1960). Using material model with linear hardening, residual stress and curvature can be obtained from relatively simple formulas, too, as in Wu et al. (2000). Here, the imposed kinematical loading with constant amplitude of curvature at rotation is ensured by the assumption of full length line contact between the bar and two-roller straightener. Moving from full contact to air-bend in two-rollers, or to more bending sectors in multi-rollers straighteners, similar formulas can be elaborated, as in Das Talukder and Johnson (1981). In Das Talukder et al. (1990), special attention is given to the relation between separating forces and Das Talukder and Singh (1991) presents the summary of the influence of different types of roller arrangements to the throughout speed and degree of final straightness of the product. Relation between curvature and bending moment is still the central idea of the analysis but necessary rollers intermeshing to reach desired curvature and moment is not so easy to evaluate. In plate or section straightening, this problem is solved by curvature integration as described in Liu et al. (2012). In Nastran and Kuzman (2002), the curvature integration method is applied to evaluate optimal roller intermeshing in the wire straightening machine. Nevertheless, the fact of rotation of the bar around its longitudinal axis in multi-bay cross roll straighteners complicates the situation, as the bar curvature in the global coordinate system connected with the machine is changing periodically during each revolution.

Abbreviations: CPU, central processing unit; CV, coefficient of variation; DOF, degrees of freedom; FEM, finite element method; FE, finite element; SD, standard deviation; PC, personal computer.

* Corresponding author.
E-mail address: sebek@fme.vutbr.cz (F. Šebek).

http://dx.doi.org/10.1016/j.jmatprotec.2016.02.004

Nomenclature

Roman letters
A, B, C, D, E, F, G Rollers label
c Contact length
d Bar diameter
E Modulus of elasticity
E_T Tangential modulus of hardening
E_m Modified elastoplastic modulus of material
F_{tol} Force tolerance factor
$F_A, F_B, F_C, F_D, F_E, F_F, F_G$ Rollers loading
H Strain hardening parameter
i Iteration number
j Angular position
I, J Nodes label
J_y, J_z Area moment of inertia
$k_{in}, k_{out}, k_y, k_z$ Engineering curvature
L Length of finite elements
M_y, M_z Bending moments
n Number of discrete angular positions
${}^jO$ Material point in angular position j
R_e Yield stress
R_m Tensile strength
R_0 Initial radius of curvature
r Reduction parameter of elastic increment
U_{tol} Displacement tolerance factor
w_A, w_C, w_E, w_G Vertical intermeshing of adjustable rollers
w, w_y, w_z Bar deflection and its components
w'' Curvature of the bar
$\Delta w''$ Curvature increment
x_L, y_L, z_L Local coordinate system
Z Reduction of the cross-sectional area

Greek letters
β Roller deviation
ε Strain
$\Delta\varepsilon$ Strain increment
ξ Axial coordinate of the beam element
σ Stress
σ_{max} Maximal residual stress
σ_{init} Initial stress
φ_y, φ_z Nodal rotation of the beam element

Matrices
$\boldsymbol{B}$ Matrix of second derivative of shape functions
$\boldsymbol{D}_m$ Flexural stiffness matrix
$\boldsymbol{\delta}$ Matrix of nodal DOF
$\boldsymbol{f}_{eqv}$ Element matrix of equivalent nodal loads
$\boldsymbol{F}$ Global loading matrix
$\boldsymbol{F}_{eqv}$ Global matrix of equivalent nodal loads
$\boldsymbol{k}$ Element stiffness matrix
$\boldsymbol{K}$ Global stiffness matrix
$\boldsymbol{K}_T$ Tangential stiffness matrix
$\boldsymbol{M}$ Matrix of bending moments
$\boldsymbol{N}$ Matrix of beam shape functions
$\boldsymbol{O}$ Global coordinates matrix of the material point
$\boldsymbol{U}$ Global deflections/slopes matrix
$\Delta\boldsymbol{U}$ Deflections/slopes matrix increment
$\boldsymbol{w}$ Matrix of deflection components

The solution which couples intermeshing, curvature, bending moments and stress distribution can be found using the FEM with high speed computing. One of the successful attempts to simulate the process of cross roll straightening as a fully three-dimensional FE analysis was presented in Mutrux et al. (2008). Only two-rollers straightening is analyzed here, but the numerical model is able to incorporate many aspects which are not feasible in classical analytical approach. It can be the influence of local contact stress to hardening of bar surface, stamping of the bar between the opposite rollers, or sophisticated models of material behavior. Nevertheless, accuracy of the detailed solution is even in the case of high-speed computation strongly limited by CPU time. One possible remedy is based on the idea to simulate only a thin slice of the bar with additional assumptions concerning the behavior of the cross section faces. This approach has already been used in Macura and Petruška (1996) for simulation of pass rolling of circular bars and in Mutrux et al. (2011) to cross roll straightening simulation in two-roller machines. Similar approach was also used by Biempica et al. (2009) for multi-rollers straightening of rails, using a sophisticated iteration between 1D model of full length span and 3D model of a short section of the rail. Full multi-rollers cross roll straightening of heavy caliber steel tubes is presented in Huang et al. (2011). Nevertheless, only radial stamping between opposite roller pairs to eliminate cross-sectional ovality of the tube is simulated in this reference and the authors do not comment CPU time needed for the analysis.

The experience with FEM computations in straightening simulation presented above shows large potential to solve many specific problems of industrial sector. Nevertheless, due to inherent nonlinearity of the process, the FE simulation is still a time consuming procedure which puts limits to practical application of this approach to optimize straightening parameters of real processes. The optimization studies in Huh et al. (2003) are based on repeated analysis of a huge amount of computational work which is feasible in academic, but hardly in the industrial sector. In Song et al. (2010), simpler theoretical models are often adequate as the amount of input data necessary for advanced modeling is limited, but substantial speed-up of data processing is inevitable. With this idea in mind, Návrat and Petruška (2014) applied the Eulerian approach presented in Demarco and Dvorkin (2005) to section straightening of rails, where only small strain elastoplastic deformation was supposed. In the following study, the same approach is applied to cross roll straightening of bars in multi-rollers machines.

In the following paragraphs, basic idea and equations of the fast algorithm for cross roll leveling process simulation is presented, based on Eulerian flow of material in the longitudinal direction of the bar, while its transversal shape is determined by Lagrangian approach. Its verification was performed by experiment, as described in Chapter 3. Performance of the algorithm is illustrated on the example of optimization of the leveling machine intermeshing adjustment for variable input parameters, like the yield stress of material or bar diameter.

2. Description of the fast straightening algorithm

2.1. Basic assumptions

Fig. 1 shows a schematic view of a cross roll leveling machine. Material of the bar is moving through the machine from the left side, rotating along its longitudinal axis on skewed rollers. Three bottom supporting rollers B, D and F are the driving vertically fixed rollers, whereas the top rollers A, C, E and G are adjustable to obtain optimal bending to straighten the product. With the aim to formulate an effective, fast computational algorithm, following assumptions were accepted:

- The bar deflection, slope and curvature can be described by bending theory of beams with uniaxial state of stress.