Simulation of a Steel Wire Straightening Taking into Account Nonlinear Hardening of Material

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Abstract—**Straightening is used to ensure the straightness of a rod workpiece as well as to redistribute or reduce the residual stresses in a finished product. The accuracy of modeling the operation of this kind plays an important role when manufacturing high quality ropes and cables of a small diameter. The physical model of alternating wire bending in a straightener has been considered in the paper. Computer methodology has been developed to calculate deflected mode and internal bending moment in a cross section of a wire at the different stages of deformation, which allowed taking into account nonlinear hardening of the material.**

Keywords- ***elastic-plastic deformation; deflected mode; nonlinear hardening; straightener***

I. INTRODUCTION

Straightness is one of the most vital quality factors when manufacturing metal ropes and cables of a small diameter. It is evaluated by the residual curvature diameter of the loose length of a finished product. The value of the parameter mentioned depends significantly on the initial curvature of a wire used in cable/rope twisting. With the view of curvature reduction and technological stress redistribution different types of machining are applied in the process of production, straightening relates to the operations of this kind.

Despite the fact that straightening seems to be a rather simple process in terms of mechanical implementation, it is difficult enough to find thorough analysis of the process simulation related to steel wire rope production. The earliest works on solving technological problems and designing the forming process of twisted products were focused on calculations in the absence of computers, so they were based on a very rough simplification. For example, Dorodnykh [1] and Tulenkov [2] used a non-hardening model of material when modeling straightening process. Guericke and et al. [3, 4] proposed the use of a linear hardening model to describe the behavior of a wire being deformed by rollers of a straightener, which refined significantly the numerical calculations. Lee et al. [5] applied FEM to simulate the straightening of metal cord using the software package Abacus. The same approach was employed by K. K. Adewole and S. J. Bull [6] when studying alternative bending of a flat wire.

Very often there is no possibility to apply existent program packages for technological problem solving and a research team has to develop their own specialized procedures for finding the optimal deformation parameters when designing technological processes for steel rope manufacturing. However, in such cases, technical articles are usually limited to a brief description of the models used and focus more on explaining the interface features of the developed software [7].

In this paper, the authors tried to describe in more detail the main stages of developed computer methods for calculating the deflected mode of a steel wire while straightening and taking into account its real stress-strain diagram.

II. OPERATION PURPOSE AND PHYSICAL MODEL OF THE PROCESS

Straightening is a multiple alternating elastic-plastic bending of a rod workpiece on the rolls of a straightener, as shown in Figure 1. This kind of machining is used to ensure the straightness of a rod workpiece as well as to redistribute or reduce the residual stresses in a finished product.

Theoretical analysis and calculation of setup modes for a straightener (i.e. center-to-center distances horizontally A_h and vertically A_v) are based on the physical model of the process, its graphical scheme shown in Figure 2 as a multistep diagram $M_x(k)$. While being straightened, the rod is subjected to pure bending deformation. However, alternating deformation behavior leads to a considerable complication of the mathematical model of this process.

Intermediate positions of random cross section of a rod workpiece moving along the straightener are marked with points 1,2,…,7 in Figure 1a. Respective deflected modes of the cross section are shown in Figure 2b as points 1-7. Separate stages of elastic-plastic deformation (lines 0–2, 2–3, 3–4, 4–5) appear to be described by different nonlinear integral functions as $M_{x,i}(k_{i-1},k)$, where i is the number of the stage of bending deformation. At the two final stages (lines 5–6 and 6–7 in Figure 2b) the diagram has linear character $M_{x,5}(k_5,k)$. In this case, the physical model allows to set down an implicit equation for defining unknown values of the workpiece

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curvature at the four intermediate stages of bending k_2, k_3, k_4, k_5. It might be given on condition that there is no residual curvature of a finished product (straightness condition)

$$M_7 = M_5(k_0, k_2, k_3, k_4, k_5) + M_{x,5}(k_5, k) = 0. \qquad (1)$$

Missed relations between parameters k_2, k_3, k_4, k_5 can be ascertained from kinematic and technological problem specification. Due to the implicit form of the equation (1) mathematical modeling of the process comes to step-by-step numerical computation and construction of the curve under Figure 2b for the variable set of required parameters k_2, k_3, k_4, k_5. The algorithm of iterative procedure should ensure the fulfillment of (1) as the final result. Thus the main problem of the straightening process design is to guarantee that there is no internal bending moment and residual curvature in the finished product through several stages of elastic-plastic alternating bending of a rod workpiece.

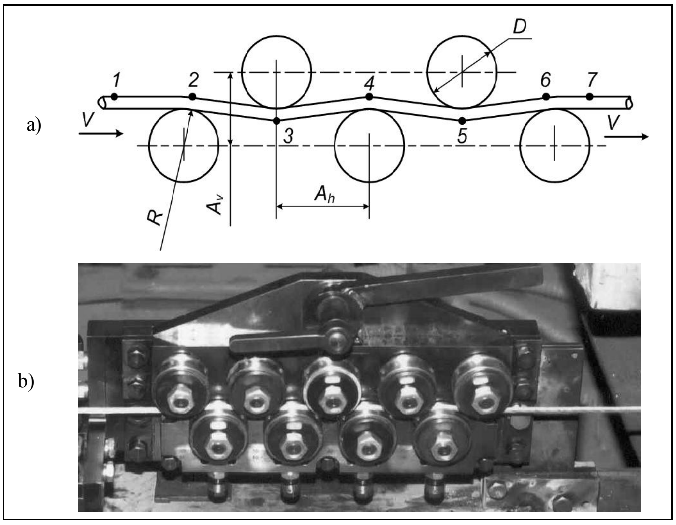

Fig. 1. a) Kinematic scheme of the process and b) appearance of the device for straightening a long-length product

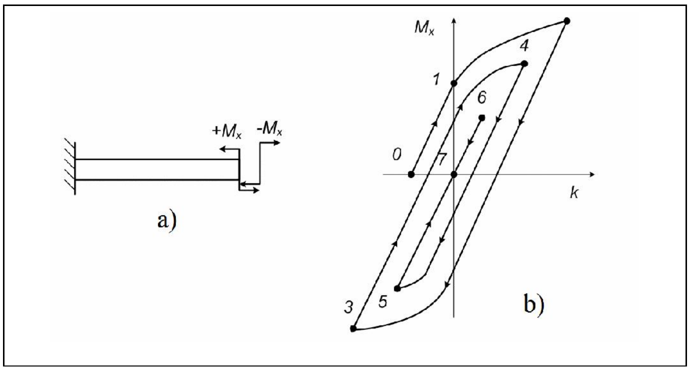

Fig. 2. a) Loading condition and b) deformation diagram of a wire in the course of straightening

III. EXPERIMENTAL STRESS-STRAIN DIAGRAM OF A STEEL WIRE, APPROXIMATION FUNCTION

Stress-strain and shear diagrams have fundamental significance not only for obtaining initial information relating to the material behavior under simple types of loading, they also form the basis for constructing mathematical models for deformable body of any configuration under different types of complex loading.

A real stress-strain diagram of a wire of 1,1 mm in diameter made of steel C60 with ultimate strength of $\sigma_u = 1750$ MPa has been applied for further simulation. It was obtained in the set of tests conducted at the Institute of Metal Forming, TU Bergakademie Freiberg. Mechanical properties for steel wire samples are shown in a table 1.

TABLE I. MECHANICAL PROPERTIES OF WIRE MADE OF STEEL C60

Young's modulus, MPa	Tensile strength, MPa	Elongation, %	Yield strength, MPa
190000	1750	1,5	1020

According to the analysis made in [8], it is reasonable to describe the experimental stress-strain diagram of a steel wire using the following combined analytical function

$$\sigma(\varepsilon) = if\left[\varepsilon < \varepsilon_y, E \cdot \varepsilon, \sigma_y[1 + b(1 - a^{\left(\frac{\varepsilon}{\varepsilon_y} - 1\right)})]\right], \qquad (2)$$

where σ_y, ε_y - yield stress and strain, a, b - invariables determined by three base points of the experimental diagram (for this curve $a = 0{,}312$, $b = 0{,}821$).

In this case approximation function almost completely matches the experimental points of the $\sigma(\varepsilon)$ diagram (Figure 3).

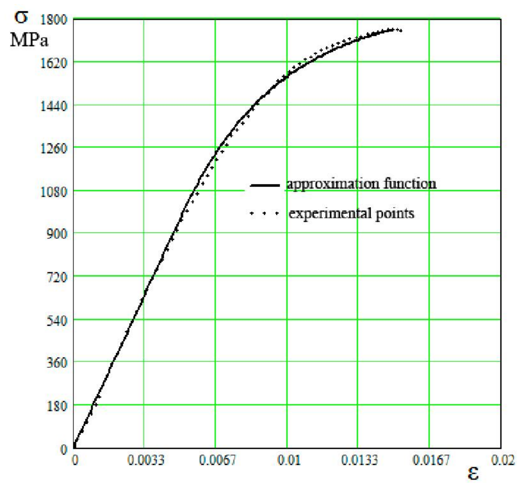

Fig. 3. Experimental stress-strain diagram and approximation function

IV. Methods of Computer Simulation of a Wire Straightening Process

In accordance with the classification provided in [9] modeling of the straightening process comes to solution of the direct problem of technological mechanics of a rod. In this case, having known the equations for the trajectory of deformation of the longitudinal axis of a rod it is necessary to determine the stress state and internal forces under the arbitrary value of a certain process parameter (e.g. curvature of a rod)

The final stress state and rod form i.e. the technical parameters of the finished product are assumed to depend on the history of its deformation in all operations of technological process. In this connection, the method of mathematical simulation should include stepwise calculation of deflected mode changes of the rod material taking into consideration its non-linear properties.

When modeling plane sections hypothesis is applied [10], as well as the following hypotheses and theories are accounted:

- discrete model is used when cross section of a rod is divided into finite number of elementary areas. Stresses at every point of the area are supposed to be constant. Therefore, one part of the cross section might be at the elastic stage while the other is at the plastic one;
- material behavior under pure tension is described by piecewise function (2);
- at the plastic stage, the theory of plastic flow is used for calculating stresses. Due to this theory, the final stresses depend on the trajectory of deformation while equations describing plastic deformation are differential relations that are nonintegrable analytically [11];
- as criterion for plasticity, the condition of tangential stress intensity (von Mises condition) is applied.

Every stage of deformation is divided into a number of steps with curvature increment Δk. The algorithm supports multiple step-by-step calculation of the stresses on the basis of the unified procedure elaborated previously by Khromov [12]. Having calculated the stress value the internal bending moment can be defined according to the integral formula

$$M_x = \int_F \sigma \cdot y \cdot dF . \qquad (3)$$

The main difference of the proposed procedure for stress calculation at the plastic deformation stage is the fact that the nonlinear hardening of the material has been taken into account when solving plastic flow equations. In this case hardening modulus and hardening coefficient depend on accumulated intensity of plastic deformation. Considering (2) at the optional loading stage, they are determined as follows:

$$E'(\varepsilon)=\frac{d\sigma}{d\varepsilon}= if\left[\varepsilon<\varepsilon_{y},\ E, -E\cdot b\cdot \ln(a)\cdot a^{\left(\frac{\varepsilon}{\varepsilon_{y}}-1\right)}\right], \qquad (4)$$

$$\lambda(\varepsilon)=\frac{E'(\varepsilon)}{E}= if\left[\varepsilon<\varepsilon_{y},\ 1, -b\cdot \ln(a)\cdot a^{\left(\frac{\varepsilon}{\varepsilon_{y}}-1\right)}\right]. \qquad (5)$$

The flowchart of the general algorithm is shown in Figure 4. It includes several one-type cycles executed in consecutive order, their number being equal to the number of alternating bending stages. Data files of internal bending moment, curvature and normal stresses are formed in the course of calculation. After program finishing, the files can be read and processed using built-in functions of standard mathematical program packages.

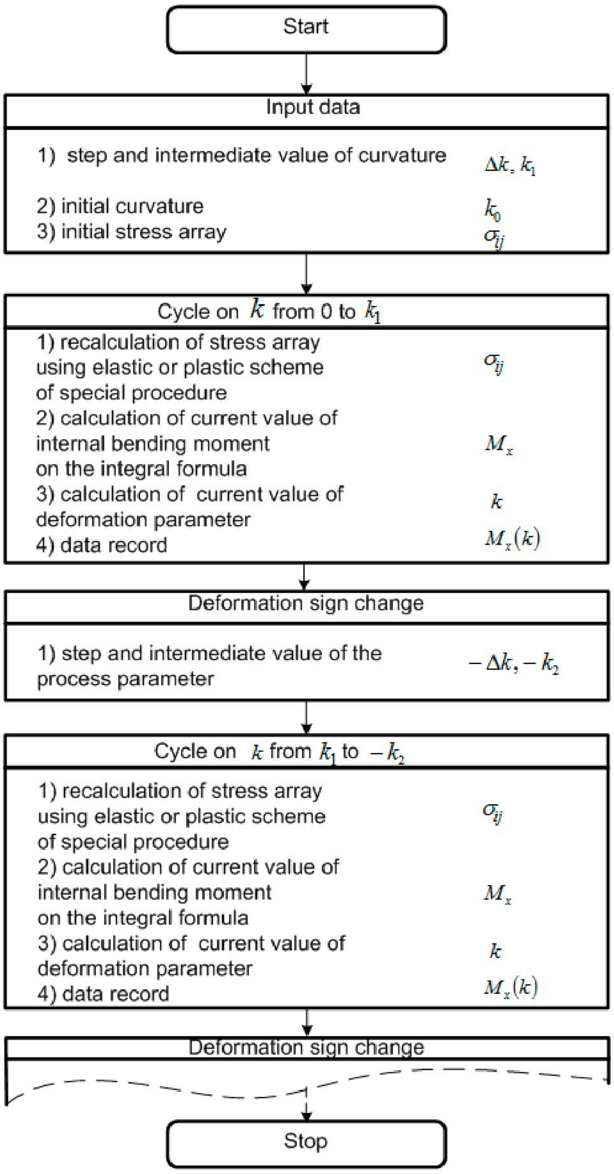

Fig. 4. Flowchart of the general algorithm for solving the problem of alternating bending.

V. RESULTS AND DISSCUSION

Figures 5 and 6 represent an example of simulating the fourfold straightening process for a steel wire of 1,1 mm in diameter. Calculations and data file forming have been carried out for three values of initial curvature of a wire ($k0 = 2{,}5$ m^{-1}, $k0 = 5$ m^{-1}, $k0 = 10$ m^{-1}) using the procedure developed in Microsoft Visual Basic. The curvature value at the end of a single stage of straightening is unknown. It should be determined by means of the condition that internal bending moment M_x and residual wire curvature at the end of the process would be equal to zero under optional value of the initial curvature $k0$. In this example, the deformation value for all three initial curvatures remained the same at the separate step of bending.

The data files with the calculated arrays of normal stress, bending moment and curvature were processed using the mathematical package MathCad. As it is shown in Figure 5, in this numerical calculation the function $M_x(k)$ comes to the coordinate origin with the accuracy sufficient for practical calculations when initial curvature $k0 = 2{,}5$ m^{-1}, $k0 = 5$ m^{-1}. For $k0 = 10$ m^{-1} the final value of the moment is not zero. In this case, it is necessary either to increase the value of the bending deformation at the first stage, or add one more step of bending to ensure the output condition $M_x = 0$.

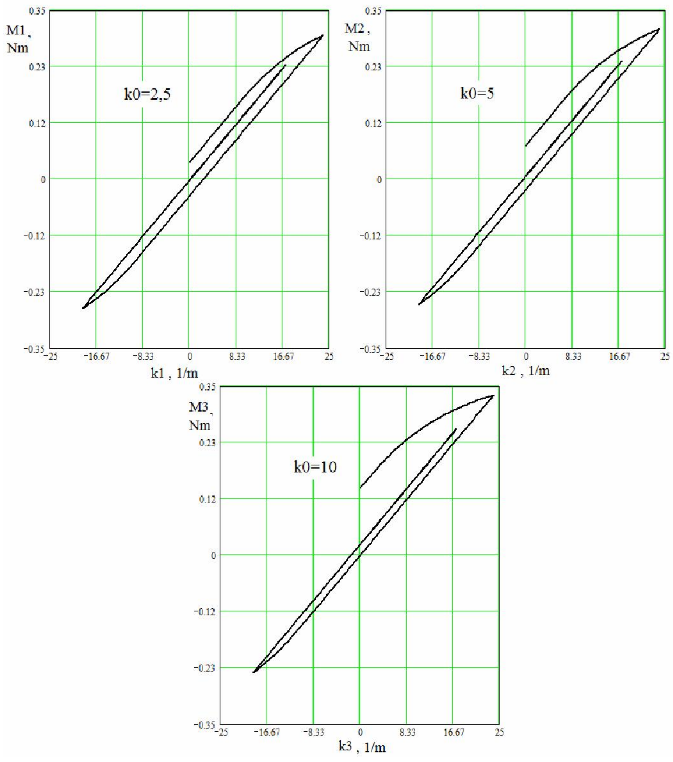

Fig. 5. Dependence $M_x(k)$ calculated for three values of initial curvature

Figure 6 represents diagrams for $\sigma(x, y)$ stress distribution along the cross section of a wire for three values of initial curvature. The left part of it shows initial stresses when curvilinear wire is straightened at the entrance to the straightener. Stress diagram is linear, outer fiber stresses reach maximum values. After straightening normal stresses are redistributed, stress diagram becomes complex. However, initial maximum stresses are reduced 2-3 times. Even for the case of $k0 = 10$ m^{-1} residual stresses do not exceed 300 MPa and this value could be decreased more by adding one more stage of bending.

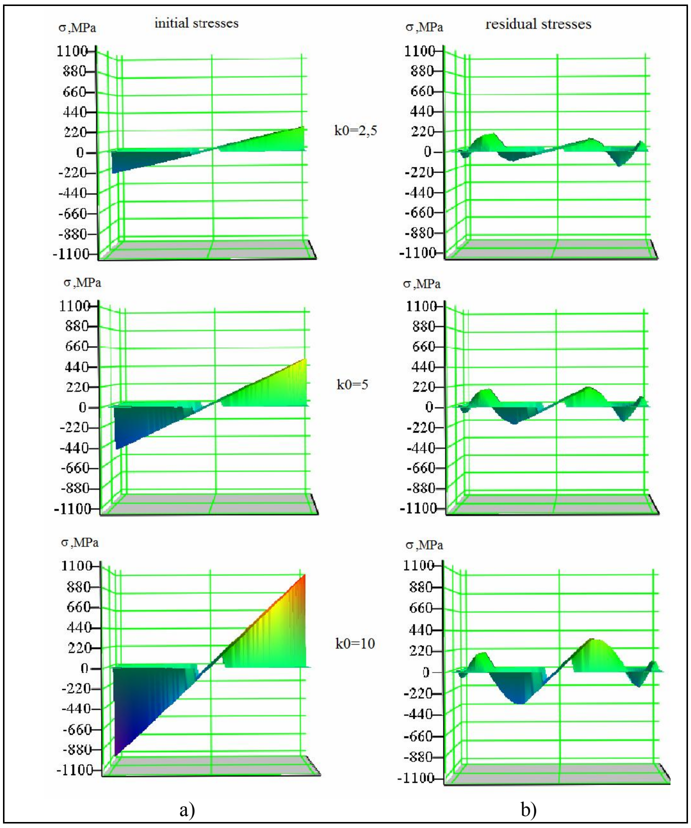

Fig. 6. Graphical stress analysis of a wire when a) entering and when b) leaving the straightener

VI. CONCLUSION

The technique developed provides a method for choosing the necessary number of bending cycles at the stage of technological procedure designing based on real properties of a material as well as for visual evaluation of distribution of stresses in cross section of a wire at different stages of deformation. Further the different elements described can be used for modeling one of the perspective operations of machining which is a rotating straightening.

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