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ARITHMETICAL METHOD OF CALCULATION OF POWER PARAMETERS OF 2N-ROLLER STRAIGHTENING MACHINE UNDER FLATTENING OF STEEL SHEET

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ABSTRACT

The main task of the technology of the steel sheet flattening is to calculate the optimal reduction of a sheet billet by the working rollers of straightening machines so that the sheet at the outlet from the machine has the minimum residual stress and curvature. In the mathematical and numerical modeling of the flattening process of the steel sheet in the multiroll straightening machines, in the beginning we calculate the curvature and bending moments of the steel sheet at the points of the tangency with the machine's working rollers, and then we calculate the energy-power parameters of the sheet's flattening. The calculation of energy-power parameters of the multiroll sheet-straightening machines is an important technological estimation at the steel sheet's flattening. The basis of energy-power calculation includes the estimation of the support reactions of working rollers and the efforts of the upper and lower rollers' cassettes of straightening machine at the sheet flattening. When there is an insufficient bending moment of steel sheet, it is impossible to eliminate the harmful residual stresses in the sheet wall and the surface defects of the sheet. If the force of the upper cassette rollers is insufficient, then to achieve the required reduction of the sheet for the quality flattening is impossible. The excessive values of the rollers' torque moments and the efforts of rollers' cassettes often lead to the sheet defects, the breakage of the working and supporting rollers and the breakage of whole sheet-straightening machine. The approximate method for the determining of the optimal technological parameters of the cold flattening of the steel sheet on the 2N-roller sheet-straightening machine is proposed in this paper. The calculations allow us to determine the type and curvature of the neutral plane of the steel sheet under the flattening, the residual curvature of the sheet after the flattening, the sheet's bending moments, the support reactions of working rollers, the residual stresses in the wall of the steel sheet, the proportion of plastic deformation on the sheet thickness and the relative deformation of the longitudinal surface fibers of the sheet under the flattening depending on the rollers' radius, the pitch between the straightening machines' working rolls, the magnitude of the sheet reduction by the upper rollers, the sheet thickness, as well as the elastic modulus, the yield stress and the hardening modulus of the sheet metal. The research results can be widely used at the engineering and metallurgical plants.

1. Introduction

The rolling mills and the multi-roller straightening machines are widely used in the manufacture of steel sheet in the Russian and foreign metallurgical industry [1–35]. For example, the five- and nine-roller straightening machines of the company "SMS Siemag" are used at the metallurgical complex mill-5000, and the five-, six-, eleven-, fourteen- and fifteen-roller straightening machines of the company "Fagor Arrasate" are used at the metallurgical lines of transverse cutting of steel sheet.

After the hot rolling [6, 7], the steel sheets are deforming during cooling due to the residual stresses and often have the surface defects in cold condition (for example, buckles, wavy edges, camber, crossbow, coil set and so on). Therefore, the steel sheets are flattened in the multi-roller straightening machines [12–15].

The process of sheet's straightening in the multi-roller flattening machines is mandatory (required) process for the technological processes of metallurgical production. The sheet flattening are widely used at Russian metallurgical plants (for example, in Vyksa, Chelyabinsk, Magnitogorsk, Izhora and so on) and at overseas metal-

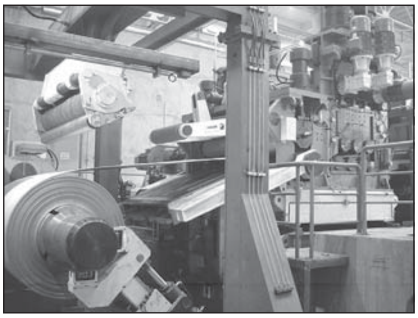

Fig. 1. The sixth-roller sheet-straightening machine by Fagor Arrasate

lurgical plants (in U.S., Germany, Spain, China, India and so on) [1, 12–15].

The sixth-roller straightening machine of the Spanish company "Fagor Arrasate" is shown in **fig. 1**.

Earlier in the author's papers [12–15] was developed the exact mathematical model of the calculation of technological parameters of the multi-roller sheet-straightening machine, based on a cubic approximation of the longitudinal line of the sheet between the adjacent working rollers. However in this case, it is necessary to solve numerically the transcendental system of nonlinear equations, which cannot be solved analytically, with a large number of unknowns (the number of unknowns is equal to the number of the working rollers of the straightening machine).

The technologists of metallurgical plants have suggested to simplify the above mentioned model, so that it was not necessary to solve numerically the complex non-linear system of equations in the calculation of the technological parameters of the straightening machine, and it was enough to perform only the basic arithmetic operations – the addition, subtraction, multiplication, division, exponentiation, and root extraction. At that, the precision of such arithmetic model should be sufficient for the practical calculations at metallurgical plant and should not much different from the precision of the exact mathematical model.

This paper is devoted to the decision of this problem.

2. The bending moment of steel sheet

Let h and b be the thickness and width of steel sheet, σ_y and E be the yield stress and the young's modulus of steel, P_t and P_c be the modules of hardening of steel under tension and compression.

In the pure elastic bending ($\rho \geq \rho_y = hE/(2\sigma_y)$), the bending moment of the steel sheet is equal to [1, 12–19]

$$M = \frac{bh^3 E}{12\rho}.$$

We transform the expression for the bending moment under a pure elastic bending of a a sheet ($\rho \geq \rho_y = hE/(2\sigma_y)$) to a dimensionless form

$$\frac{12M}{bh^2\sigma_y} = \frac{Eh}{\sigma_y \rho}.$$

In the pure elastic bending of a round beam and $\rho = \rho_y = Eh/(2\sigma_y)$, we obtain

$$\frac{12M}{bh^2\sigma_y} = 2.$$

In the elastoplastic bending ($\rho < \rho_y = hE/(2\sigma_y)$), the bending moment of the steel sheet is equal to

$$M(\rho) = \frac{bh^2\sigma_y}{12}\left(3 - 4\left(\frac{\sigma_y\rho}{Eh}\right)^2\right) + $$

$$+ \frac{bh^3(P_t + P_c)}{24\rho}\left(1 - 2\frac{\sigma_y\rho}{Eh}\right)^2\left(1 + \frac{\sigma_y\rho}{Eh}\right),$$

where ρ is the curvature's radius of the longitudinal neutral axis of the sheet.

For the high-strength steels, the hardening modules in tension and compression equal to each other practically: $P_t \approx P_c = P$.

We transform the expression for the bending moment under the elastoplastic bending of a sheet ($\rho < \rho_y = hE/(2\sigma_y)$) to a dimensionless form

$$\frac{12M(\rho)}{bh^2\sigma_y} = \left(3 - 4\left(\frac{\sigma_y\rho}{Eh}\right)^2\right) + $$

$$+ \left(\frac{P_t + P_c}{2E}\right)\frac{Eh}{\sigma_y\rho}\left(1 - 2\frac{\sigma_y\rho}{Eh}\right)^2\left(1 + \frac{\sigma_y\rho}{Eh}\right),$$

In the elastoplastic bending ($\rho < \rho_y = hE/(2\sigma_y)$) and $\rho = \rho_y = Eh/(2\sigma_y)$, we obtain

$$\frac{12M}{bh^2\sigma_y} = 2.$$

3. The springback coefficient of steel sheet

In the basis of determining of the residual strains after the elastoplastic deformations, the Genki's theorem of unloading (1924 year) have a place [12–15]: the residual stresses are equal to the difference between the true stresses in the elasto-plastic body and the stresses which would be created in the body under the assumption of the ideal elasticity of the body's material.

Using the Genki's theorem of unloading, we obtain the equation for determining the residual radius of curvature ρ_{res} of the steel sheet:

$$\frac{12M}{bh^2\sigma_y} = \frac{Eh}{\sigma_y}\left(\frac{1}{\rho} - \frac{1}{\rho_{res}}\right).$$

The springback coefficient under bending of the steel sheet is equal to

$$\beta(\rho) = \frac{\rho_{res}}{\rho} = \frac{1}{1 - \dfrac{12M\rho}{bh^3E}} = \frac{1}{1 - \dfrac{12M}{bh^2\sigma_y}\dfrac{\sigma_y\rho}{Eh}},$$

$$\rho_{res} = \beta(\rho)\rho.$$

In the pure elastic bending of a steel sheet ($\rho \geq \rho_y = hE/(2\sigma_y)$), the springback coefficient is equal to

$\beta(\rho) = \infty.$

In the elastoplastic bending of a sheet ($\rho < \rho_y = hE/(2\sigma_y)$), the springback coefficient is equal to

$$\beta(\rho) = \frac{1}{\left(1 - \frac{P_t + P_c}{2E}\right)\left(1 - 2\frac{\sigma_y \rho}{Eh}\right)^2\left(1 + \frac{\sigma_y \rho}{Eh}\right)},$$

$$\beta(0) = \frac{1}{1 - \frac{P_t + P_c}{2E}}, \quad \beta(\rho_y) = \infty.$$

In the elastoplastic bending of a sheet ($\rho < \rho_y = hE/(2\sigma_y)$), for the Prandtl's diagram (the modulus hardening $P_t = P_c = 0$) we have

$$\beta(\rho) = \frac{1}{\left(1 - 2\frac{\sigma_y \rho}{Eh}\right)^2\left(1 + \frac{\sigma_y \rho}{Eh}\right)},$$

$$\beta(0) = 1, \quad \beta(\rho_y) = \infty.$$

The proportion of plastic deformation through the steel sheet's thickness (the degree of penetration of plastic deformation into the sheet) is equal to

$$\eta = \left\{1 - \frac{2\sigma_y|\rho|}{Eh}, \ \ if \ |\rho| \le \frac{Eh}{2\sigma_y}; \ \ 0, \ \ if \ |\rho| > \frac{Eh}{2\sigma_y}\right\}.$$

4. Flattening of sheet in 2*N*-roller straightening machine

The flattening of steel sheet is carried out by means of $2N$ drive working rollers — N top working rollers and N lower working rollers. The working rollers are provided with the separate systems of the adjustment of their vertical position with the help of the wedge pairs and hydraulic cylinders [1, 12–15].

Let t be the step between the lower working rollers; H_i be the value of the compression of the neutral surface of the steel sheet at i-th working roller, N_i be the reactions of the working rollers at the points of tangency with the sheet, R be the radius of working rollers, $R_0 = R + h/2$; ρ_i and $\varepsilon_i = 1/\rho_i$ be the radii of curvature and the curvature of the longitudinal neutral line of the sheet at the points of tangency of the sheet with the working rollers, φ_i be the angles of the touch points of the sheet with the rollers ($i = 1, \dots 2N$) (**fig. 2**).

Remark 1. The connection between the real compression H_{real} and the compression of the neutral surface of the steel sheet H has the form

$$H = H_{real} + h.$$

The value of the maximum compression H is equal to

$$H_{max} = 2R_0\left(1 - \sqrt{1 - \left(\frac{t}{4R_0}\right)^2}\right).$$

Without limiting generality, further we suppose that the lower (odd) working rollers lie on the same horizontal level:

$$H_{2j+1} = 0, \quad j = 0, \dots, N-1;$$

and the upper working rollers have the independent vertical displacements (the compressions).

At the flattening of the steel sheet at the steel mills, the real angles of touching of the sheet with the working rollers of the straightening machine, starting from the second roller to the last roller, have small values (up to 1°–3°). Therefore, further we assume that all angles of touching of the working rollers with the steel sheet are equal to zero:

$$\varphi_i = 0, \quad i = 1, \dots, 2N.$$

The approximate radii of curvature of the longitudinal neutral axis of the steel sheet at the points of its tangency with the even working rollers of the sheet-straightening machine we put equal to

$$\rho_{2k} = \frac{t^2}{24H_{2k}}, \qquad k = 1, \dots, N-1.$$

The approximate radii of curvature of the longitudinal neutral axis of the steel sheet at the points of its tangency with the odd working rollers of the sheet-straightening machine we put equal to

$$\rho_{2k+1} = -\frac{t^2}{12(H_{2k} + H_{2k+2})}, \quad k = 1, \dots, N-1.$$

The approximate value of the curvature's radius on the last working roller is equal to

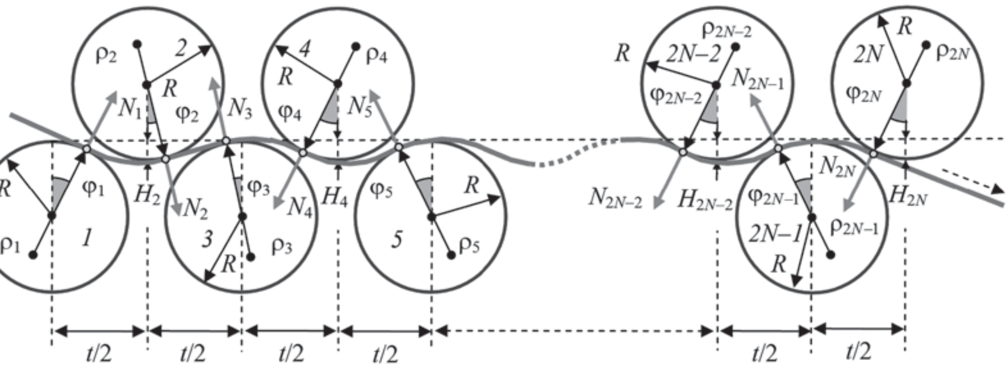

Fig. 2. The flattening of steel sheet by 2*N* working rollers

$$\rho_{2N} = \beta(\rho_{2N-1})\,\rho_{2N-1}.$$

Remark 2. If the compression

$$H_{2k} \ge \frac{t^2}{24R_0}, \quad k = 1,\ldots,N-1,$$

then the sheet's surface flows around the surface of the working roller. Therefore, $\rho_{2k} = R_0$.

Similarly, if

$$H_{2k} + H_{2k+2} \ge \frac{t^2}{12R_0}, \quad k = 1,\ldots,N-1,$$

then $\rho_{2k+1} = -R_0$.

Remark 3. We can also put the approximate odd radii of curvature are equal to

$$\rho_{2k+1} = -\frac{t^2}{48}\left(\frac{1}{H_{2k}} + \frac{1}{H_{2k+2}}\right), \quad k = 1,\ldots,N-1.$$

However in this case of approximation, the accuracy of calculating of the odd radii of curvature is reduced (especially in the last odd rollers, where the radii of sheet's curvature have the large values).

Remark 4. Note, that $2H_{2k}/t << 1$. Therefore,

$$\rho_{2k} = \frac{t^2}{24H_{2k}} \approx \frac{t^2}{24H_{2k}}\left(1 + \left(\frac{2H_{2k}}{t}\right)^2\right) = \frac{\sqrt{\left(\frac{t}{2}\right)^2 + H_{2k}^2}}{6\cos\left(\operatorname{arctg}\frac{t}{2H_{2k}}\right)}.$$

At the points of tangency of the steel sheet with the working rollers of the straightening machine, the bending moments of the sheet are equal to

$$M_1 = 0; \quad M_{2k} = M(\rho_{2k}), \quad k = 1,\ldots N-1;$$

$$M_{2k+1} = -M(|\rho_{2k+1}|), \quad k = 1,\ldots N-1; \quad M_{2N} = 0.$$

The reaction of the working rollers at its contact points with the sheet are equal to

$$N_1 = \frac{2}{t}M_2, \quad N_2 = \frac{2}{t}(-M_3 + 2M_2),$$

$$N_{2k-1} = \frac{2}{t}(M_{2k} - 2M_{2k-1} + M_{2k-2}), \quad k = 2,\ldots,N-1;$$

$$N_{2k-2} = \frac{2}{t}(-M_{2k-1} + 2M_{2k-2} - M_{2k-3}), \quad k = 3,\ldots,N;$$

$$N_{2N-1} = \frac{2}{t}(-2M_{2N-1} + M_{2N-2}), \quad N_{2N} = \frac{2}{t}M_{2N-1}.$$

The vertical force of the upper rollers' pressure on the sheet is equal to

$$F_{\text{upper}} = \sum_{k=1}^{N} N_{2k} = \frac{4}{t}\sum_{k=2}^{2N-1}(-1)^k M_k.$$

The vertical force of the lower rollers' pressure on the sheet is equal to

$$F_{\text{lower}} = \sum_{k=0}^{N-1} N_{2k+1} = \frac{4}{t}\sum_{k=2}^{2N-1}(-1)^k M_k = F_{\text{upper}}.$$

The total force of the pressure of all the upper and lower rollers on the sheet is equal to

$$F_{\text{sum}} = F_{\text{upper}} + F_{\text{lower}} = \sum_{k=1}^{2N} N_i = \frac{8}{t}\sum_{k=2}^{2N-1}(-1)^k M_k.$$

5. Numerical calculation for the fourteen-roller straightening machine

For the fourteen-roller straightening machine of the company "Fagor Arrasate", $N = 7$ ($2N = 14$), $t = 81.67$ mm, $R = 37.5$ mm. The results of calculations at the flattening of the steel sheet in $h = 4$ mm, $b = 1.8$ m, $E = 2 \cdot 10^{11}$ Pa, $\sigma_y = 500 \cdot 10^6$ Pa, $P_t = P_c = 8.8\times10^9$ Pa, $H_2 = 4$ mm, $H_4 = 3.33$ mm, $H_6 = 2.67$ mm, $H_8 = 2$ mm, $H_{10} = 1.33$ mm, $H_{12} = 0.67$ mm, $H_{14} = 0$ mm (the upper rollers are located of on the upper flat cassette) and $\rho_1 = -1$ m are shown in **fig. 3 – 6**.

The pressure forces of the upper and lower working rollers on the steel sheet at the exact solution are equal to $F_{\text{upper}} = F_{\text{lower}} = 2309$ kH.

The suggested above arithmetical method of the calculation give us the value equal to $F_{\text{upper}} = F_{\text{lower}} = 2315$ kN (the difference from the exact solution is equal to 0.4% or 6 kN), but the Korolev's method [1] gives us the value equal to $F_{\text{upper}} = F_{\text{lower}} = 1834$ kN (the difference from the exact solution is equal to 20.6% or 475 kN).

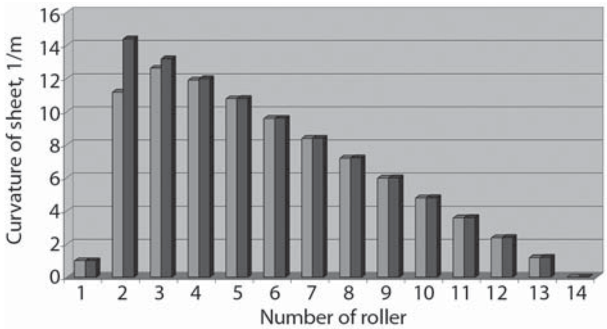

Fig. 3. The module of sheet's curvature at flattening

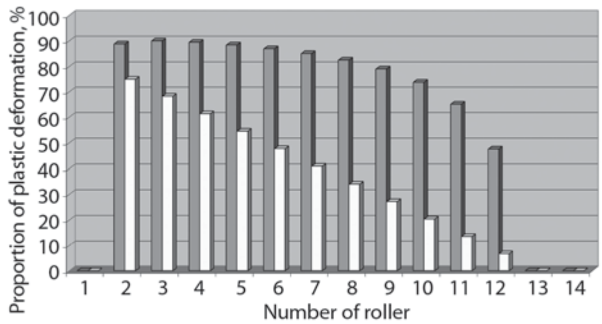

Fig. 4. The proportion of plastic deformation on the sheet thickness

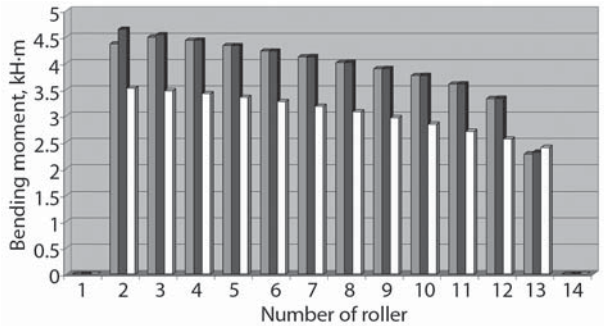

Fig. 5. The module of bending moments of sheet at flattening

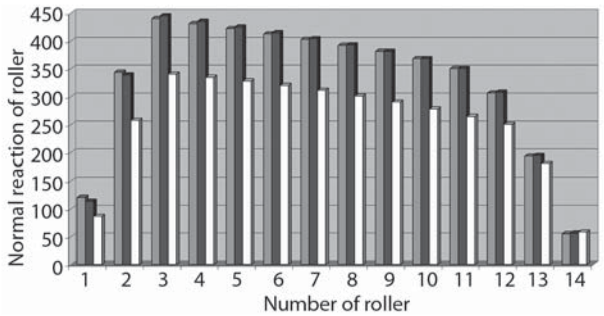

Fig. 6. The normal reactions of working rollers

In fig. 3, the left columns correspond to the exact solution of the problem, and the right columns correspond to the approximate solution of this paper.

From fig. 3 it is seen, that in the case of the location of the upper rollers on the flat upper cassette the curvature's module of the sheet at the points of the tangency with the working rollers is changing almost on the straight-line law from the third roller to the second to last roller.

If the upper working rollers have the individual settings for their compression, then the module of the curvature of the sheet at the points of tangency with the working rollers can be changed according to the nonlinear law.

6. Comparative analysis of different methods of calculations

One of the methods of calculating the bending moments of the sheet and the forces of the sheet-straightening machines is the Korolev's method [1].

In the Korolev's method the bending moments of the steel sheet are calculated by means of the coefficient of the penetration of the plastic deformation deep into the steel sheet in the assumption that this coefficient varies on the straight-line law from the second working roller to the second to last working roller (the first and last working rollers do not bend the sheet). This assumption is clearly false (see **fig. 4**).

In fig. 4, the left columns correspond to the exact solution of the problem, but the right columns correspond to the solution according to the Korolev's method.

In reality (in the case when the upper rollers are located on the flat upper cassette), the proportion of plastic deformation through the thickness of the steel sheet (from the third to the second to last working roller) resembles us in appearance the inverted parabola and with the top (the maximum) on the third roller (fig. 4).

The curvature and radii of curvature of the steel sheet are not calculated in the Korolev's method, and that prevents to appreciate more or less accurately the bending moments of the sheet, which depend on the curvature of the sheet.

For the modern multi-roller sheet-straightening machines with the independent reduction of the working rollers, the Korolev's method is not applicable, as it is initially assumed in it, that the upper and lower rollers, respectively, belong to the upper and lower flat cassettes of rollers.

The main disadvantage of the Korolev's method is that the hardening module of the metal sheet in bending is assumed to be zero (the Prandtl's diagram), which leads to very significant errors (up to 20%) in the calculation of the force parameters of the straightening machine (see **fig. 5** and **fig. 6**), and this can lead to the breakage of the straightening machine.

In fig. 5 and fig. 6, the left columns correspond to the exact solution of the problem, the middle columns correspond to the approximate solution of this work, and the right columns correspond to solution of the Korolev's method.

7. Conclusions

The arithmetical method of calculating of the curvature of the longitudinal neutral line of the sheet, the bending moments of the sheet and the reactions of the working rollers under the cold flattening of the steel sheet at the multi-roller sheet-straightening machine is proposed. It is shown, that the proposed arithmetical method of the calculation is significantly more exact than the Korolev's method. The research results can be used in the production of the steel sheet at metallurgical plants [1–35].

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