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THE MATHEMATICAL MODEL OF THE THICK STEEL SHEET FLATTENING ON THE TWELVE-ROLLER SHEET-STRAIGHTENING MACHINE. MESSAGE 2. FORCES AND MOMENTS

V. N. Shinkin[1]

[1] *National University of Science and Technology "MISIS", Moscow, Russia*
E-mail: shinkin-korolev@yandex.ru

AUTHOR'S INFO

V. N. Shinkin, DSc. Phys.-Math., Prof.

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steel sheet, sheet-straightening machines, curvature of sheet, springback coefficient, elastoplastic continuous medium

ABSTRACT

The mathematical method for the determining of the technological parameters of the cold straightening of the thick steel sheet on the twelve-rolled sheet-straightening machine is proposed. The calculations allow us to determine the support reaction 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 straightening depending on the rollers' radius, the pitch between the straightening machines' working rollers, 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 results of the research can be used at the metallurgical plants.

Introduction

The rolling mills and the multi-roller straightening machines (**fig. 1**) are widely used for the steel sheet production in Russian and overseas metallurgical industry [1–24].

In the first part of the paper the technique of determining the shape and curvature ε (radius of curvature ρ) of the steel sheet at flattening on the twelve-roller straightening machine was suggested.

In the second part of the paper we consider in detail the method of determining the bending moments and residual stresses, as well as the support reactions of the working rollers in the twelve-roller straightening machine.

We note that the estimation of the force parameters for the different methods of bending and forming in metallurgy are investigated in papers [10–21].

The bending moments at the steel sheet flattening

Let H_i ($i = 1, ..., 12$) be the sheet's reductions by the working rollers. Without limiting the generality, further we assume that the lower six working rollers are fixed ($H_1 = H_3 = H_5 = H_7 = H_9 = H_{11} = 0$ mm) and the upper six working rollers have the independent vertical movement.

Let P_t and P_c be the hardening modules of steel in tension and compression, E and σ_y be the young's modulus and yield strength, R be the radius of the working rollers, φ_i be the angles of the contact points of rollers with the steel sheet ($i = 1, ..., 12$), t be the step of the lower working rollers, $R_0 = R + h/2$, $\varepsilon_i = 1/\rho_i$ and ρ_i be the sheet's curvature and the radii of sheet's curvature at the contact points of rollers with the steel sheet, h be the sheet's thickness.

Under the elastic bending ($\rho \geq \rho_y = hE/(2\sigma_y)$), the springback coefficient of steel sheet is equal to $\beta(\rho) = \infty$.

Under the plastic bending ($\rho < \rho_y = hE/(2\sigma_y)$), the springback coefficient of steel sheet is equal to

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

Under the plastic bending of steel sheet, the bending moment is equal to [10–12]

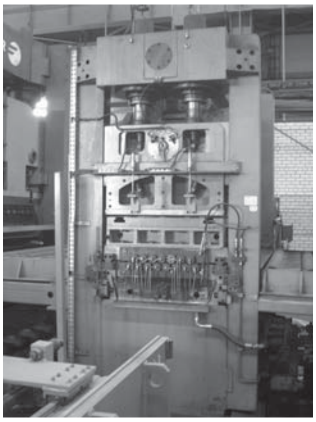

Fig. 1. The multi-roller straightening machine by Fagor Arrasate

$$M(\rho)=\frac{bh^2\sigma_y}{12}\left(3-4\left(\frac{\sigma_y\rho}{Eh}\right)^2\right)+$$
$$+\frac{bh^3(P_t+P_c)}{24\rho}\left(1-2\frac{\sigma_y\rho}{Eh}\right)^2\left(1+\frac{\sigma_y\rho}{Eh}\right),$$

where b is the sheet width.

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

Under the elastic bending of steel sheet, the bending moment is equal to

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

The dependence of the bending moment M on the curvature radius ρ of the sheet is shown in **fig. 2**.

Let M_i be the bending moments of the steel sheet at the contact points of working rollers with the sheet:

$$M_1=0,\ M_2=M(\rho_2),\ M_3=-M(\rho_3),\ M_4=M(\rho_4),$$
$$M_5=-M(\rho_5),\ M_6=M(\rho_6),\ M_7=-M(\rho_7),$$
$$M_8=M(\rho_8),\ M_9=-M(\rho_9),\ M_{10}=M(\rho_{10}),$$
$$M_{11}=-M(\rho_{11}),\quad M_{12}=0.$$

The bending momets of the sheet at the contact points of the sheet with the rollers at $E = 2\cdot10^{11}$ Pa, $R = 125$ mm, $\sigma_y = 500\cdot10^6$ Pa, $h = 10$ mm, $t = 270$ mm, $\rho_1 = -1$ m, $H_2 = 12$ mm, $H_4 = 6$ mm, $H_6 = 3$ mm, $H_8 = 1.5$ mm, $H_{10} = 0.75$ mm and $H_{12} = 0.375$ mm are shown in **fig. 3**.

The residual stresses of the sheet after springbacking are shown in **fig. 4**, where $\varepsilon_y = E/\sigma_y$, $y_y = \sigma_y\rho/E$ is the boundary between the elastic and plastic zones in the sheet wall.

The extremal residual stresses are equal to

$$\sigma^1{}_{res}=\sigma_y+P(\varepsilon_{max}-\varepsilon_y)-6\left(\frac{M}{bh^2}\right),$$
$$\sigma^2{}_{res}=\sigma_y-12\left(\frac{M}{bh^2}\right)\frac{\sigma_y\rho}{Eh}.$$

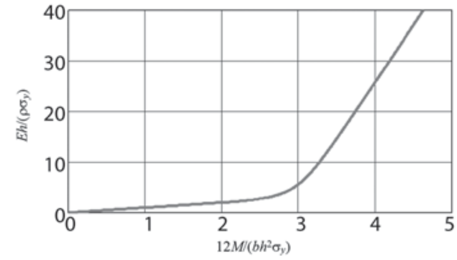

Fig. 2. The graph of the bending moment $M(\rho)$

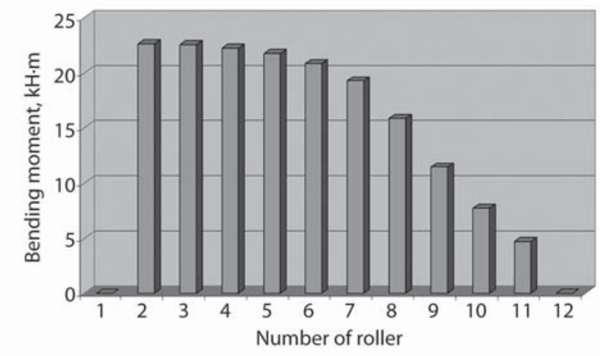

Fig. 3. The bending moments of sheet at contact points with rollers

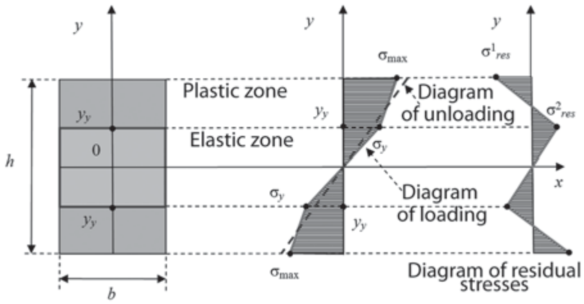

Fig. 4. The residual stresses in the wall of the sheet

The proportion of plastic deformation on the sheet thickness under bending

The proportion of plastic deformation on the sheet thickness is equal to

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

The relative deformation of the longitudinal surface fibers of the sheet is equal to

$$\eta_{lsf}=\frac{h}{2|\rho|}.$$

The numerical calculations for the proportion of plastic deformation on the sheet thickness and the relative deformation of the longitudinal surface fibers of the sheet in the twelve-roller straightening machine at $E = 2\cdot10^{11}$ Pa, $R = 125$ mm, $\sigma_y = 500\cdot10^6$ Pa, $h = 10$ mm, $t = 270$ mm, $\rho_1 = -1$ m, $H_2 = 12$ mm, $H_4 = 6$ mm, $H_6 = 3$ mm, $H_8 = 1.5$ mm, $H_{10} = 0.75$ mm and $H_{12} = 0.375$ mm are shown in **fig. 5** and **fig. 6**.

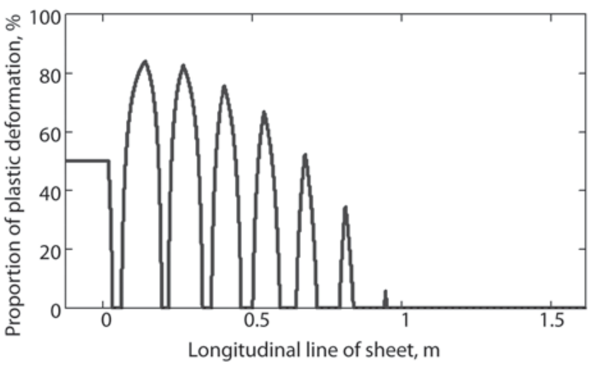

Fig. 5. The proportion of plastic deformation on the sheet thickness

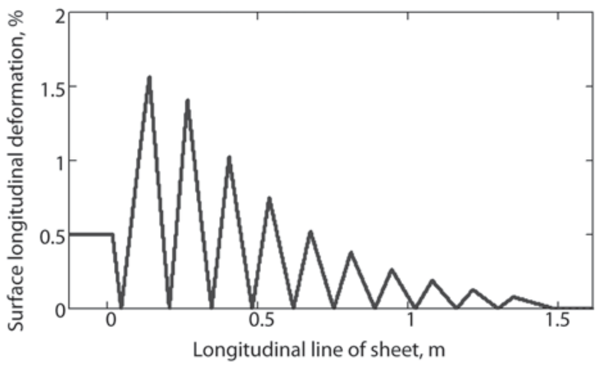

Fig. 6. The relative deformation of the longitudinal surface fibers of the sheet

The calculation of the power parameters of the twelve-roller straightening machine

Let N_i, M_{ri} and F_{rfi} ($F_{rfi} = M_{ri}/R$) be, respectively, the support reaction, the rotational moment (transmitted from the gearbox) and the feed force of the i-th roller ($i = 1, ..., 12$) (**fig. 7**).

We build the twelve coordinate systems $y–z$ at the contact points of the sheet with the rollers. The axes y will direct along the radius of the rollers to their center, but the axes z will direct tangent to the rollers' surface from left to right.

Let y_{ji} and z_{ji} be the coordinates of the points of sheet tangency with the j-th roller in the i-th coordinate system.

We introduce auxiliary distances:

$$\Delta z_{21} = \frac{t}{2} - R_0 \sin\varphi_1 + R_0 \sin\varphi_2,$$
$$\Delta y_{21} = H_2 - R_0\left(1-\cos\varphi_1\right) - R_0\left(1-\cos\varphi_2\right),$$
$$z_{21} = \Delta z_{21}\cos\varphi_1 + \Delta y_{21}\sin\varphi_1,$$
$$y_{21} = -\Delta z_{21}\sin\varphi_1 + \Delta y_{21}\cos\varphi_1,$$
$$\Delta z_{32} = \frac{t}{2} - R_0 \sin\varphi_2 - R_0 \sin\varphi_3,$$
$$\Delta y_{32} = H_2 - R_0\left(1-\cos\varphi_2\right) - R_0\left(1-\cos\varphi_3\right),$$
$$z_{32} = \Delta z_{32}\cos\varphi_2 + \Delta y_{32}\sin\varphi_2,$$
$$y_{32} = -\Delta z_{32}\sin\varphi_2 + \Delta y_{32}\cos\varphi_2,$$
$$\Delta z_{43} = \frac{t}{2} + R_0 \sin\varphi_3 - R_0 \sin\varphi_4,$$
$$\Delta y_{43} = H_4 - R_0\left(1-\cos\varphi_3\right) - R_0\left(1-\cos\varphi_4\right),$$
$$z_{43} = \Delta z_{43}\cos\varphi_3 - \Delta y_{43}\sin\varphi_3,$$
$$y_{43} = \Delta z_{43}\sin\varphi_3 + \Delta y_{43}\cos\varphi_3,$$
$$\Delta z_{54} = \frac{t}{2} + R_0 \sin\varphi_4 - R_0 \sin\varphi_5,$$
$$\Delta y_{54} = H_4 - R_0\left(1-\cos\varphi_4\right) - R_0\left(1-\cos\varphi_5\right),$$
$$z_{54} = \Delta z_{54}\cos\varphi_4 - \Delta y_{54}\sin\varphi_4,$$
$$y_{54} = \Delta z_{54}\sin\varphi_4 + \Delta y_{54}\cos\varphi_4,$$
$$\Delta z_{65} = \frac{t}{2} + R_0 \sin\varphi_5 - R_0 \sin\varphi_6,$$
$$\Delta y_{65} = H_6 - R_0\left(1-\cos\varphi_5\right) - R_0\left(1-\cos\varphi_6\right),$$
$$z_{65} = \Delta z_{65}\cos\varphi_5 - \Delta y_{65}\sin\varphi_5,$$
$$y_{65} = \Delta z_{65}\sin\varphi_5 + \Delta y_{65}\cos\varphi_5,$$
$$\Delta z_{76} = \frac{t}{2} + R_0 \sin\varphi_6 - R_0 \sin\varphi_7,$$
$$\Delta y_{76} = H_6 - R_0\left(1-\cos\varphi_6\right) - R_0\left(1-\cos\varphi_7\right),$$
$$z_{76} = \Delta z_{76}\cos\varphi_6 - \Delta y_{76}\sin\varphi_6,$$
$$y_{76} = \Delta z_{76}\sin\varphi_6 + \Delta y_{76}\cos\varphi_6,$$
$$\Delta z_{87} = \frac{t}{2} + R_0 \sin\varphi_7 - R_0 \sin\varphi_8,$$
$$\Delta y_{87} = H_8 - R_0\left(1-\cos\varphi_7\right) - R_0\left(1-\cos\varphi_8\right),$$
$$z_{87} = \Delta z_{87}\cos\varphi_7 - \Delta y_{87}\sin\varphi_7,$$
$$y_{87} = \Delta z_{87}\sin\varphi_7 + \Delta y_{87}\cos\varphi_7,$$
$$\Delta z_{98} = \frac{t}{2} + R_0 \sin\varphi_8 - R_0 \sin\varphi_9,$$
$$\Delta y_{98} = H_8 - R_0\left(1-\cos\varphi_8\right) - R_0\left(1-\cos\varphi_9\right),$$

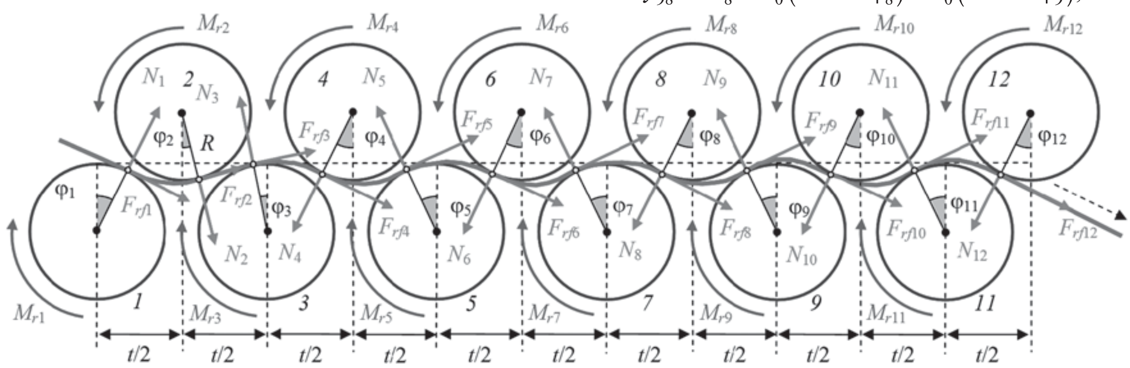

Fig. 7. Forces and moments acting on the steel sheet

$$z_{98} = \Delta z_{98} \cos\varphi_8 - \Delta y_{98} \sin\varphi_8,$$
$$y_{98} = \Delta z_{98} \sin\varphi_8 + \Delta y_{98} \cos\varphi_8,$$
$$\Delta z_{109} = \frac{t}{2} + R_0 \sin\varphi_9 - R_0 \sin\varphi_{10},$$
$$\Delta y_{109} = H_{10} - R_0(1-\cos\varphi_9) - R_0(1-\cos\varphi_{10}),$$
$$z_{109} = \Delta z_{109} \cos\varphi_9 - \Delta y_{109} \sin\varphi_9,$$
$$y_{109} = \Delta z_{109} \sin\varphi_9 + \Delta y_{109} \cos\varphi_9,$$
$$\Delta z_{1110} = \frac{t}{2} + R_0 \sin\varphi_{10} - R_0 \sin\varphi_{11},$$
$$\Delta y_{1110} = H_{10} - R_0(1-\cos\varphi_{10}) - R_0(1-\cos\varphi_{11}),$$
$$z_{1110} = \Delta z_{1110} \cos\varphi_{10} - \Delta y_{1110} \sin\varphi_{10},$$
$$y_{1110} = \Delta z_{1110} \sin\varphi_{10} + \Delta y_{1110} \cos\varphi_{10},$$
$$\Delta z_{1211} = \frac{t}{2} + R_0 \sin\varphi_{11} - R_0 \sin\varphi_{12},$$
$$\Delta y_{1211} = H_{12} - R_0(1-\cos\varphi_{11}) - R_0(1-\cos\varphi_{12}),$$
$$z_{1211} = \Delta z_{1211} \cos\varphi_{11} - \Delta y_{1211} \sin\varphi_{11},$$
$$y_{1211} = \Delta z_{1211} \sin\varphi_{11} + \Delta y_{1211} \cos\varphi_{11}.$$

The projections of the main vectors of the forces at the contact points of the sheet with rollers are equal to

$$F_{01y} = N_1 \cos\varphi_1 - F_{rf1} \sin\varphi_1,$$
$$F_{01z} = N_1 \sin\varphi_1 + F_{rf1} \cos\varphi_1,$$
$$F_{02y} = F_{01y} - N_2 \cos\varphi_2 + F_{rf2} \sin\varphi_2,$$
$$F_{02z} = F_{01z} + N_2 \sin\varphi_2 + F_{rf2} \cos\varphi_2,$$
$$F_{03y} = F_{02y} + N_3 \cos\varphi_3 + F_{rf3} \sin\varphi_3,$$
$$F_{03z} = F_{02z} - N_3 \sin\varphi_3 + F_{rf3} \cos\varphi_3,$$
$$F_{04y} = F_{03y} - N_4 \cos\varphi_4 - F_{rf4} \sin\varphi_4,$$
$$F_{04z} = F_{03z} - N_4 \sin\varphi_4 + F_{rf4} \cos\varphi_4,$$
$$F_{05y} = F_{04y} + N_5 \cos\varphi_5 + F_{rf5} \sin\varphi_5,$$
$$F_{05z} = F_{04z} - N_5 \sin\varphi_5 + F_{rf5} \cos\varphi_5,$$
$$F_{06y} = F_{05y} - N_6 \cos\varphi_6 - F_{rf6} \sin\varphi_6,$$
$$F_{06z} = F_{05z} - N_6 \sin\varphi_6 + F_{rf6} \cos\varphi_6,$$
$$F_{07y} = F_{06y} + N_7 \cos\varphi_7 + F_{rf7} \sin\varphi_7,$$
$$F_{07z} = F_{06z} - N_7 \sin\varphi_7 + F_{rf7} \cos\varphi_7,$$
$$F_{08y} = F_{07y} - N_8 \cos\varphi_8 - F_{rf8} \sin\varphi_8,$$
$$F_{08z} = F_{07z} - N_8 \sin\varphi_8 + F_{rf8} \cos\varphi_8,$$
$$F_{09y} = F_{08y} + N_9 \cos\varphi_9 + F_{rf9} \sin\varphi_9,$$
$$F_{09z} = F_{08z} - N_9 \sin\varphi_9 + F_{rf9} \cos\varphi_9.$$
$$F_{010y} = F_{09y} - N_{10} \cos\varphi_{10} - F_{rf10} \sin\varphi_{10},$$
$$F_{010z} = F_{09z} - N_{10} \sin\varphi_{10} + F_{rf10} \cos\varphi_{10}.$$

The supplementations to the support forces at the contact points of the sheet with the rollers are equal to

$$\Delta N_2 = -F_{01y} \cos\varphi_2 + F_{01z} \sin\varphi_2,$$
$$\Delta F_{rf2} = F_{01y} \sin\varphi_2 + F_{01z} \cos\varphi_2,$$
$$\Delta N_3 = F_{02y} \cos\varphi_3 - F_{02z} \sin\varphi_3,$$
$$\Delta F_{rf3} = F_{02y} \sin\varphi_3 + F_{02z} \cos\varphi_3,$$
$$\Delta N_4 = -F_{03y} \cos\varphi_4 - F_{03z} \sin\varphi_4,$$
$$\Delta F_{rf4} = -F_{03y} \sin\varphi_4 + F_{03z} \cos\varphi_4,$$
$$\Delta N_5 = F_{04y} \cos\varphi_5 - F_{04z} \sin\varphi_5,$$
$$\Delta F_{rf5} = F_{04y} \sin\varphi_5 + F_{04z} \cos\varphi_5,$$
$$\Delta N_6 = -F_{05y} \cos\varphi_6 - F_{05z} \sin\varphi_6,$$
$$\Delta F_{rf6} = -F_{05y} \sin\varphi_6 + F_{05z} \cos\varphi_6,$$
$$\Delta N_7 = F_{06y} \cos\varphi_7 - F_{06z} \sin\varphi_7,$$
$$\Delta F_{rf7} = F_{06y} \sin\varphi_7 + F_{06z} \cos\varphi_7,$$
$$\Delta N_8 = -F_{07y} \cos\varphi_8 - F_{07z} \sin\varphi_8,$$
$$\Delta F_{rf8} = -F_{07y} \sin\varphi_8 + F_{07z} \cos\varphi_8,$$
$$\Delta N_9 = F_{08y} \cos\varphi_9 - F_{08z} \sin\varphi_9,$$
$$\Delta F_{rf9} = F_{08y} \sin\varphi_9 + F_{08z} \cos\varphi_9,$$
$$\Delta N_{10} = -F_{09y} \cos\varphi_{10} - F_{09z} \sin\varphi_{10},$$
$$\Delta F_{rf10} = -F_{09y} \sin\varphi_{10} + F_{09z} \cos\varphi_{10},$$
$$\Delta N_{11} = F_{010y} \cos\varphi_{11} - F_{010z} \sin\varphi_{11},$$
$$\Delta F_{rf11} = F_{010y} \sin\varphi_{11} + F_{010z} \cos\varphi_{11}.$$

The normal reactions of the working rollers at the contact points with the sheet are equal to

$$N_1 = \frac{M_2 - F_{rf1} y_{21}}{z_{21}},$$
$$N_2 = \frac{-M_3 + M_2 - F_{rf2} y_{32} - \Delta N_2 z_{32} - \Delta F_{rf2} y_{32}}{z_{32}},$$
$$N_3 = \frac{M_4 - M_3 - F_{rf3} y_{43} - \Delta N_3 z_{43} - \Delta F_{rf3} y_{43}}{z_{43}},$$
$$N_4 = \frac{-M_5 + M_4 - F_{rf4} y_{54} - \Delta N_4 z_{54} - \Delta F_{rf4} y_{54}}{z_{54}},$$
$$N_5 = \frac{M_6 - M_5 - F_{rf5} y_{65} - \Delta N_5 z_{65} - \Delta F_{rf5} y_{65}}{z_{65}},$$
$$N_6 = \frac{-M_7 + M_6 - F_{rf6} y_{76} - \Delta N_6 z_{76} - \Delta F_{rf6} y_{76}}{z_{76}},$$
$$N_7 = \frac{M_8 - M_7 - F_{rf7} y_{87} - \Delta N_7 z_{87} - \Delta F_{rf7} y_{87}}{z_{87}},$$
$$N_8 = \frac{-M_9 + M_8 - F_{rf8} y_{98} - \Delta N_8 z_{98} - \Delta F_{rf8} y_{98}}{z_{98}},$$
$$N_9 = \frac{M_{10} - M_9 - F_{rf9} y_{109} - \Delta N_9 z_{109} - \Delta F_{rf9} y_{109}}{z_{109}},$$
$$N_{10} = \frac{-M_{11} + M_{10} - F_{rf10} y_{1110} - \Delta N_{10} z_{1110} - \Delta F_{rf10} y_{1110}}{z_{1110}},$$
$$N_{11} = \frac{-M_{11} - F_{rf11} y_{1211} - \Delta N_{11} z_{1211} - \Delta F_{rf11} y_{1211}}{z_{1211}},$$

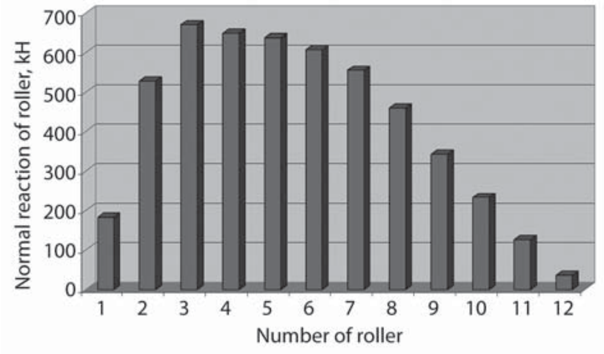

Fig. 8. Normal reactions of the working rollers

$$N_{12} = \frac{-M_{11} - F_{rf12}\left(z_{1211}\sin\left(\varphi_{11}+\varphi_{12}\right) - y_{1211}\cos\left(\varphi_{11}+\varphi_{12}\right)\right)}{z_{1211}\cos\left(\varphi_{11}+\varphi_{12}\right) + y_{1211}\sin\left(\varphi_{11}+\varphi_{12}\right)}.$$

The normal reactions of the working rollers of the twelve-roller straightening machine at $E = 2\cdot10^{11}$ Pa, $R = 125$ mm, $\sigma_y = 500\cdot10^6$ Pa, $h = 10$ mm, $t = 270$ mm, $\rho_1 = -1$ m, $H_2 = 12$ mm, $H_4 = 6$ mm, $H_6 = 3$ mm, $H_8 = 1.5$ mm, $H_{10} = 0.75$ mm and $H_{12} = 0.375$ mm are shown in **fig. 8**.

The vertical force (the force of the upper cassette of rollers) acting from the upper cassette of rollers to the steel sheet is equal to

$$F_{up} = N_2\cos\varphi_2 - F_{rf2}\sin\varphi_2 + N_4\cos\varphi_4 - F_{rf4}\sin\varphi_4 + $$
$$+N_6\cos\varphi_6 - F_{rf6}\sin\varphi_6 + N_8\cos\varphi_8 - F_{rf8}\sin\varphi_8 +$$
$$+N_{10}\cos\varphi_{10} - F_{rf10}\sin\varphi_{10} + N_{12}\cos\varphi_{12} - F_{rf12}\sin\varphi_{12}.$$

The vertical force from the sheet on the lower cassette of rollers is equal to

$$F_{down} = N_1\cos\varphi_1 - F_{rf1}\sin\varphi_1 + N_3\cos\varphi_3 -$$
$$-F_{rf3}\sin\varphi_3 + N_5\cos\varphi_5 - F_{rf5}\sin\varphi_5 +$$
$$+N_7\cos\varphi_7 - F_{rf7}\sin\varphi_7 + N_9\cos\varphi_9 -$$
$$-F_{rf9}\sin\varphi_9 + N_{11}\cos\varphi_{11} - F_{rf11}\sin\varphi_{11}.$$

Conclusions

The analytical method for the determining of the support reaction of working rollers and the residual stress in the steel sheet wall under the cold straightening on the twelve-rolled sheet-straightening machine is suggested.

The results of the research can be widely used at metallurgical plants in the production of thick steel sheet, and the manufacture of the steel large- and medium-diameter tubes for the gas-oil main pipelines [1–24].

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