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Preliminary Straightening of Thick Steel Sheet in a Seven-Roller Machine

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Abstract—A mathematical model is proposed for determining the forces and torques in the preliminary cold straightening of thick steel sheet in a seven-roller machine. On that basis, the bearing reaction of the working rollers, the residual stress in the wall of the steel sheet, the proportion of plastic strain over the sheet thickness, and the relative strain of longitudinal surface fibers of the sheet in straightening may be determined as a function of the working-roller radius, the spacing between rollers of the straightening machine, the reduction of the sheet by the upper rollers, and the sheet thickness, as well as the Young's modulus, yield point, and strengthening modulus of the sheet. The results may be used at manufacturing and metallurgical plants.

Keywords: steel sheet, street straightening, multiroller straightening machines, elastoplastic media, linear strengthening

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Rolling mills and multiroller straightening machines are widely used in the production of steel sheet in Russia and elsewhere [1–16].

A method of determining the geometry and curvature ε (radius of curvature ρ) of steel sheet on straightening in a seven-roller machine has already been proposed. Therefore, we assume here that, in straightening steel sheet, its curvature, radius of curvature, and points of contact with the rollers are known.

In the present work, we consider in detail the determination of the bending moments and residual stress and also the bearing reaction of the working rollers in a seven-roller straightening machine.

In the straightening of steel sheet, it is important to calculate the forces and torques in multiroller machines. In particular, we need to calculate the bending moments of the steel sheet in straightening and the total bearing reaction of the machine's working rollers (the forces exerted by the upper and lower roller assemblies).

If the bending moment is insufficient, it is impossible to eliminate the harmful residual stress in its wall and the surface defects. If the force exerted by the upper roller assembly is insufficient, it is impossible to ensure the sheet reduction required for satisfactory straightening.

Extreme values of the roller torques and the forces exerted by the roller assemblies often lead to defects of the sheet, fracture of the working and supporting rollers, and failure of the whole sheet-straightening machine.

Note that the assessment of the forces in various methods of sheet flexure and shaping at steel plates was considered in [10–16].

BENDING MOMENTS IN STRAIGHTENING

Suppose that H_i ($i = 1, ..., 7$) is the reduction of the sheet by the working rollers. Without loss of generality, we may assume that the lower four working rollers are immobile ($H_1 = H_3 = H_5 = H_7 = 0$ mm), while the upper three working rollers are characterized by independent vertical displacement.

Suppose that Π_{te} and Π_{co} are the strengthening moduli in tension and compression, respectively; E is Young's modulus; σ_y is the yield point; R is the radius of the working rollers; φ_i are the angles of the points of sheet–roller contact ($i = 1, ..., 7$); t is the spacing of the working rollers ; $R_0 = R + h/2$; $\varepsilon_i = 1/\rho_i$ is the curvature of the sheet at the contact points; ρ_i is the radius of curvature of the sheet at the contact points; h is the sheet thickness.

In elastic flexure ($\rho \geq \rho_y = hE/2\sigma_y$), the springback coefficient of the steel sheet is $\beta(\rho) = \infty$. In plastic flexure ($\rho < \rho_y = hE/2\sigma_y$), the springback coefficient of the sheet is determined from then formula

$$\beta(\rho) = \frac{1}{\left(1 - \dfrac{\Pi_{te} + \Pi_{co}}{2E}\right)\left(1 - 2\dfrac{\rho\sigma_y}{hE}\right)^2\left(1 + \dfrac{\rho\sigma_y}{hE}\right)}.$$

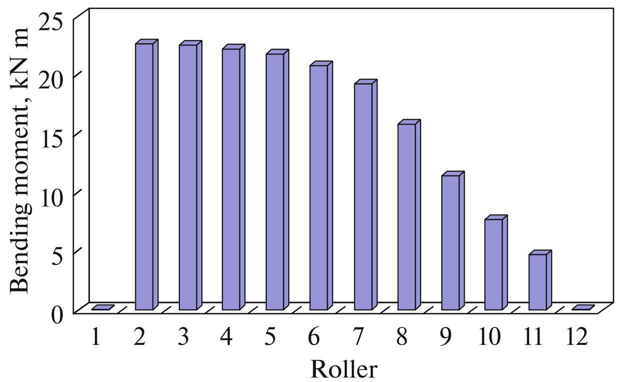

Fig. 1. Bending moments of the sheet at contact points with the rollers.

In plastic flexure of steel sheet, the bending moment is as follows [10–12]

$$M(\rho) = \frac{bh^2\sigma_y}{12}\left[3 - 4\left(\frac{\sigma_y\rho}{Eh}\right)^2\right] + \frac{bh^3(\Pi_{te} + \Pi_{co})}{24\rho}\left(1 - 2\frac{\sigma_y\rho}{Eh}\right)^2\left(1 + \frac{\sigma_y\rho}{Eh}\right),$$

where b is the width of the sheet .

For high-strength steel, the strengthening modulus will be practically the same in tension and compression: $\Pi_{te} \approx \Pi_{co} = \Pi$.

In elastic flexure, the bending moment is

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

Suppose that M_i is the bending moment of the steel sheet at contact point i

$$M_1 = 0, M_2 = M(\rho_2), M_3 = -M(\rho_3),$$
$$M_4 = M(\rho_4), M_5 = -M(\rho_5), M_6 = M(\rho_6), M_7 = 0.$$

In Fig. 1, we show the bending moments of the sheet at the contact points when

$$E = 2\times10^{11}\text{ Pa},\ R = 125\text{ mm},\ \sigma_y = 5\times10^8\text{ Pa},$$
$$h = 10\text{ mm},\ t = 270\text{ mm},\ \rho_1 = -1\text{ m},$$
$$H_2 = 12\text{ mm},\ H_4 = 6\text{ mm and } H_6 = 1\text{ mm}.$$

The extremal residual stresses are

$$\sigma^1_{res} = \sigma_y + \Pi(\varepsilon_{max} - \varepsilon_y) - 6\left(\frac{M}{bh^2}\right);$$

$$\sigma^2_{res} = \sigma_y - 12\left(\frac{M}{bh^2}\right)\frac{\sigma_y\rho}{Eh},$$

where $\varepsilon_y = E/\sigma_y$.

The distance from the neutral line to the plasticity zone (the boundary between the elastic and plastic zones) in the sheet cross section is $y_y = \sigma_y\rho/E$.

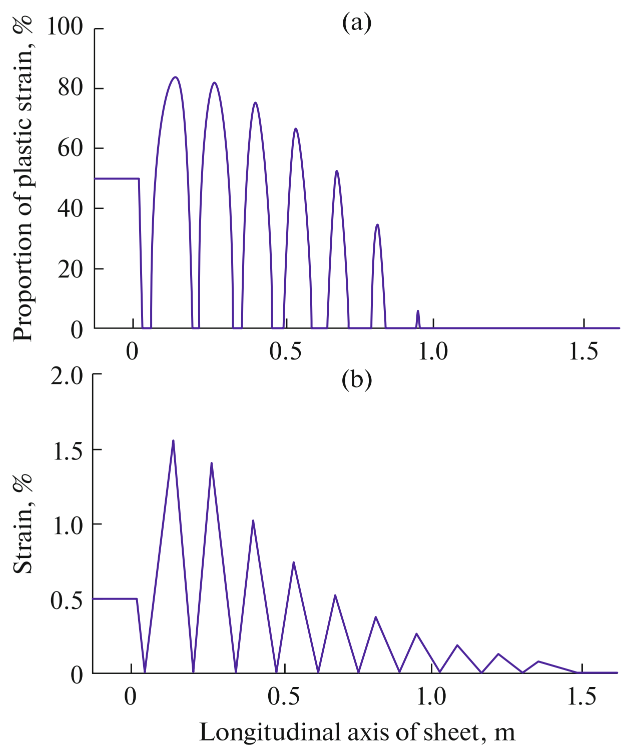

Fig. 2. Proportion of plastic strain over the sheet thickness (a) and strain of the longitudinal surface fibers of the sheet (b).

PLASTIC STRAIN OVER THE SHEET THICKNESS IN STRAIGHTENING

Over the sheet thickness, the proportion of plastic strain is

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

The strain of the longitudinal surface fibers of the sheet is

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

In Fig. 2, we show numerical values for the proportion of plastic strain over the sheet thickness and the strain of the longitudinal surface fibers of the sheet in a seven-roller straightening machine when

$$E = 2\times10^{11}\text{ Pa},\ R = 0.125\text{ mm},\ \sigma_y = 5\times10^8\text{ Pa},$$
$$h = 10\text{ mm},\ t = 270\text{ mm},\ \rho_1 = -1\text{ m},$$
$$H_2 = 12\text{ mm},\ H_4 = 6\text{ mm and } H_6 = 1\text{ mm}.$$

FORCES AND TORQUES IN THE SHEET-STRAIGHTENING MACHINE

Suppose that N_i, M_{gi}, and F_{dri} are, respectively, the bearing reaction, the torque (transmitted from the

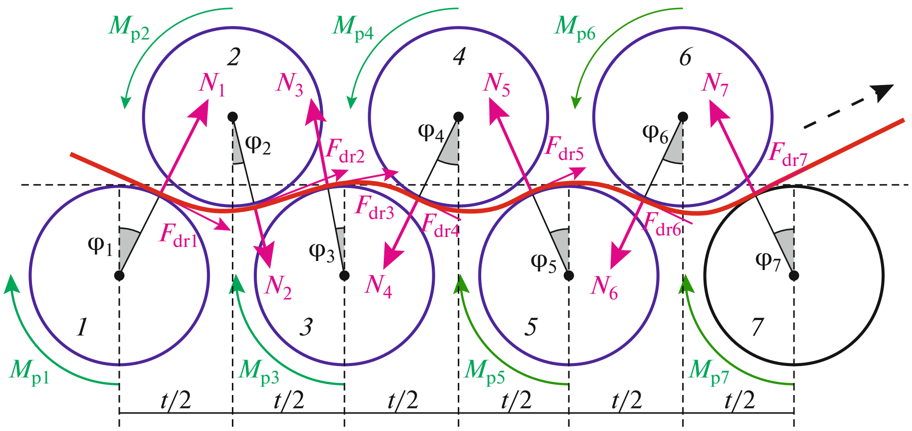

Fig. 3. Forces and moments acting on the steel sheet.

gear), and the drive force of roller i (i = 1, ..., 7), as shown in Fig. 3. (Note that $F_{dri} = M_{gi}/R$.)

We now find the seven coordinate systems y–z at the sheet–roller contact points. The y axis runs along the roller radius toward its center; the z axis runs from left to right over the tangent to the roller surface.

Suppose that y_{ji} and z_{ji} are the coordinates of the contact points of the sheet with roller j in coordinate system i, while $\Delta y_{(i+1)i}$ and $\Delta z_{(i+1)I}$ are the vertical and horizontal distances between adjacent sheet–roller contact points.

Then the auxiliary distances are

$$\Delta z_{21} = \frac{t}{2} - R_0 \sin\varphi_1 + R_0 \sin\varphi_2;$$
$$\Delta y_{21} = H_2 - R_0(1-\cos\varphi_1) - R_0(1-\cos\varphi_2);$$
$$z_{21} = \Delta z_{21}\cos\varphi_1 + \Delta y_{21}\sin\varphi_1;$$
$$y_{21} = -\Delta z_{21}\sin\varphi_1 + \Delta y_{21}\cos\varphi_1;$$

$$\Delta z_{32} = \frac{t}{2} - R_0 \sin\varphi_2 - R_0 \sin\varphi_3;$$
$$\Delta y_{32} = H_2 - R_0(1-\cos\varphi_2) - R_0(1-\cos\varphi_3);$$
$$z_{32} = \Delta z_{32}\cos\varphi_2 + \Delta y_{32}\sin\varphi_2;$$
$$y_{32} = -\Delta z_{32}\sin\varphi_2 + \Delta y_{32}\cos\varphi_2;$$

$$\Delta z_{43} = \frac{t}{2} + R_0 \sin\varphi_3 - R_0 \sin\varphi_4;$$
$$\Delta y_{43} = H_4 - R_0(1-\cos\varphi_3) - R_0(1-\cos\varphi_4);$$
$$z_{43} = \Delta z_{43}\cos\varphi_3 - \Delta y_{43}\sin\varphi_3;$$
$$y_{43} = \Delta z_{43}\sin\varphi_3 + \Delta y_{43}\cos\varphi_3;$$

$$\Delta z_{54} = \frac{t}{2} + R_0 \sin\varphi_4 - R_0 \sin\varphi_5;$$
$$\Delta y_{54} = H_4 - R_0(1-\cos\varphi_4) - R_0(1-\cos\varphi_5);$$
$$z_{54} = \Delta z_{54}\cos\varphi_4 - \Delta y_{54}\sin\varphi_{54};$$
$$y_{54} = \Delta z_{54}\sin\varphi_4 + \Delta y_{54}\cos\varphi_4;$$

$$\Delta z_{65} = \frac{t}{2} + R_0 \sin\varphi_5 - R_0 \sin\varphi_6;$$
$$\Delta y_{65} = H_6 - R_0(1-\cos\varphi_5) - R_0(1-\cos\varphi_6);$$
$$z_{65} = \Delta z_{65}\cos\varphi_5 - \Delta y_{65}\sin\varphi_5;$$
$$y_{65} = \Delta z_{65}\sin\varphi_5 + \Delta y_{65}\cos\varphi_5;$$

$$\Delta z_{76} = \frac{t}{2} + R_0 \sin\varphi_6 - R_0 \sin\varphi_7;$$
$$\Delta y_{76} = H_6 - R_0(1-\cos\varphi_6) - R_0(1-\cos\varphi_7);$$
$$z_{76} = \Delta z_{65}\cos\varphi_6 - \Delta y_{76}\sin\varphi_6;$$
$$y_{76} = \Delta z_{65}\sin\varphi_6 + \Delta y_{76}\cos\varphi_6.$$

The projections of the primary force vectors at the sheet–roller contact points take the form

$$F_{01y} = N_1\cos\varphi_1 - F_{dr1}\sin\varphi_1;$$
$$F_{01z} = N_1\sin\varphi_1 - F_{dr1}\cos\varphi_1;$$

$$F_{02y} = F_{01y} - N_2\cos\varphi_2 + F_{dr2}\sin\varphi_2;$$
$$F_{02z} = F_{01z} + N_2\sin\varphi_2 + F_{dr2}\cos\varphi_2;$$

$$F_{03y} = F_{02y} + N_3\cos\varphi_3 + F_{dr3}\sin\varphi_3;$$
$$F_{03z} = F_{02z} - N_3\sin\varphi_3 + F_{dr3}\cos\varphi_3;$$

$$F_{04y} = F_{03y} - N_4\cos\varphi_4 - F_{dr4}\sin\varphi_4;$$
$$F_{04z} = F_{03z} - N_4\sin\varphi_4 + F_{dr4}\cos\varphi_4;$$

$$F_{05y} = F_{04y} + N_5\cos\varphi_5 + F_{dr5}\sin\varphi_5;$$
$$F_{05z} = F_{04z} - N_5\sin\varphi_5 + F_{dr5}\cos\varphi_5.$$

The supplements to the reactions at the sheet–roller contact points are as follows

$$\Delta N_2 = -F_{01y}\cos\varphi_2 + F_{01z}\sin\varphi_2;$$
$$\Delta F_{dr2} = F_{01y}\sin\varphi_2 + F_{01z}\cos\varphi_2;$$

$$\Delta N_3 = F_{02y}\cos\varphi_3 - F_{02z}\sin\varphi_3;$$
$$\Delta F_{dr3} = F_{02y}\sin\varphi_3 + F_{02z}\cos\varphi_3;$$

$$\Delta N_4 = -F_{03y}\cos\varphi_4 - F_{03z}\sin\varphi_4;$$
$$\Delta F_{dr4} = -F_{03y}\sin\varphi_4 + F_{03z}\cos\varphi_4;$$
$$\Delta N_5 = F_{04y}\cos\varphi_5 - F_{04z}\sin\varphi_5;$$
$$\Delta F_{dr5} = F_{04y}\sin\varphi_5 + F_{04z}\cos\varphi_5;$$
$$\Delta N_6 = -F_{05y}\cos\varphi_6 - F_{05z}\sin\varphi_6;$$
$$\Delta F_{dr6} = -F_{05y}\sin\varphi_6 + F_{05z}\cos\varphi_6.$$

The normal reactions of the working rollers at the contact points are described by the equations

$$N_1 = \frac{M_2 - F_{dr1}y_{21}}{z_{21}};$$
$$N_2 = \frac{-M_3 - M_2 - F_{dr2}y_{32} - \Delta N_2 z_{32} - \Delta F_{dr2}y_{32}}{z_{32}};$$
$$N_3 = \frac{M_4 - M_3 - F_{dr3}y_{43} - \Delta N_3 z_{43} - \Delta F_{dr3}y_{43}}{z_{43}};$$
$$N_4 = \frac{-M_5 + M_4 - F_{dr4}y_{54} - \Delta N_4 z_{54} - \Delta F_{dr4}y_{54}}{z_{54}};$$
$$N_5 = \frac{M_6 - M_5 - F_{dr5}y_{65} - \Delta N_5 z_{65} - \Delta F_{dr5}y_{65}}{z_{65}};$$
$$N_6 = \frac{M_6 - F_{dr6}y_{76} - \Delta N_6 z_{76} - \Delta F_{dr6}y_{76}}{z_{76}};$$
$$N_7 = \frac{M_6 - F_{rf7}\left[z_{76}\sin(\varphi_6+\varphi_7) - y_{76}\cos(\varphi_6+\varphi_7)\right]}{z_{76}\cos(\varphi_6+\varphi_7) + y_{76}\sin(\varphi_6+\varphi_7)}.$$

In Fig. 4, we show the normal reactions of the working rollers at the contact points in a seven-roller straightening machine when

$$E = 2\times10^{11}\ \text{Pa},\ R = 125\ \text{mm},\ \sigma_y = 5\times10^{8}\ \text{Pa},$$
$$h = 10\ \text{mm},\ t = 270\ \text{mm},\ \rho_1 = -1\ \text{m},$$
$$H_2 = 12\ \text{mm},\ H_4 = 6\ \text{mm and}\ H_6 = 1\ \text{mm}.$$

The vertical force exerted by the upper roller assembly on the steel sheet is calculated as

$$F_{upp} = N_2\cos\varphi_2 - F_{dr2}\sin\varphi_2 + N_4\cos\varphi_4 - F_{dr4}\sin\varphi_4 + N_6\cos\varphi_6 - F_{dr6}\sin\varphi_6.$$

Likewise, the vertical force exerted by the lower roller assembly on the steel sheet is

$$F_{low} = N_1\cos\varphi_1 - F_{dr1}\sin\varphi_1 + N_3\cos\varphi_3 - F_{dr3}\sin\varphi_3 + N_5\cos\varphi_5 - F_{dr5}\sin\varphi_5 + N_7\cos\varphi_7 - F_{dr7}\sin\varphi_7.$$

The force exerted by the upper roller assembly on the steel sheet in the seven-roller straightening machine is $F_{upp} = F_{low} = 1636.86$ kN = 166.856 t when

$$E = 2\times10^{11}\ \text{Pa},\ R = 125\ \text{mm},\ \sigma_y = 5\times10^{8}\ \text{Pa},$$
$$h = 10\ \text{mm},\ t = 270\ \text{mm},\ \rho_1 = -1\ \text{m},$$
$$H_2 = 12\ \text{mm},\ H_4 = 6\ \text{mm and}\ H_6 = 1\ \text{mm}.$$

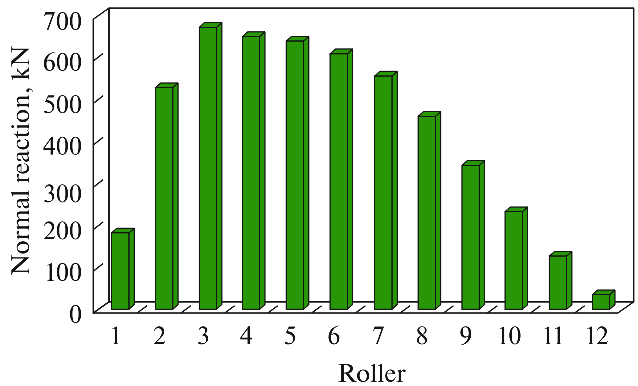

Fig. 4. Normal reactions of the working rollers.

STRAIGHTENING OF SHEET BY DEFORMATION OF THE ROLLER AXES

The undulation and warping of steel sheet may largely be attributed to its nonuniform reduction over the width in hot rolling, on account of the unequal spacing between the rollers. Nonuniform reduction results in different extension of individual sections of the sheet: the extension is greater for sections of the sheet where the reduction is greater. The interaction of longitudinal sections of sheet with different extension produces a large internal residual compressive stress in the sections with greater extension and a large residual tensile stress in the sections with less extension. As a result of those stresses, the plane form of the sheet becomes unstable, and local undulation and warping of the surface will be observed.

The undulation and warping of the sheet may only be corrected by equalizing the longitudinal extent of sections with different degrees of reduction. To correct local defects of the sheet, the axes of the lower working rollers in the straightening machine may be distorted by means of individual displacements of the lower supporting rollers, which rest on five mobile bearings. That results in nonuniform flexure of the sheet over its width in straightening.

The less extended sections are subjected to greater flexure. For each distribution of undulation and warping over the width of the sheet, special adjustment of the machine is required: the axes of the working rollers must be distorted in the corresponding sections.

CONCLUSIONS

An analytical model is proposed for determining the bearing reaction of the working rollers, the bending moments, the residual stress in the wall of the steel sheet during cold straightening in a seven-roller machine.

The results may be used at metallurgical enterprises in the production of thick steel sheet, as well as large-and moderate-diameter steel pipe for oil and gas pipelines [1–16].

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