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MATHEMATICAL MODEL OF TECHNOLOGICAL PARAMETERS' CALCULATION OF FLANGING PRESS AND THE FORMATION CRITERION OF CORRUGATION DEFECT OF STEEL SHEET'S EDGE

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ABSTRACT

In the modern production of the large-diameter thick-walled steel welded pipes on the presses, the main part of the steel pipe' billet (about 90% of the billet's surface) is deformed on the O-forming press by means of the movable punch and the fixed matrices. However, it is impossible to make the bending of the sheet's longitudinal edges on this press. Therefore, before the forming of the billet on the O-forming press, the edges of the steel sheet billet are always bent on the flanging press. The low-quality calibration of the instrument of the flanging press and the wrong choice of the technological modes of the bending of the billet's edges lead to the formation of the numerous defects of the sheet billet (the corrugation defect of the billet's edges, the offset edges of the billet, and so on) that makes it impossible in the next for a good quality weld of the pipe billet's edges on the pipe-welding machine.

Under the edge's transversal bending of the thick-leaved blank the analytical method of the calculation of the main technological parameters is suggested in this paper. The shape and size of the thick-leaved blank during and after the forming in the flanging press, the spring coefficient and the residual curvature of the blank are obtained. During every molding stage the elasto-plastic material model is considered. The condition of the corrugation's origin for the longitudinal edge of the sheet blank is obtained. The results of the investigation are important for the working out of the manufacturing technique of the steel major-diameter tubes for the main pipelines.

1. Introduction

In the market of the production of the steel welded large-diameter pipes for the main gas and oil pipelines, the process of the forming of the tube billet according to the scheme JCOE is established [1–32].

In the first stage of the process, the edge bending of sheet billet on the flanging press by means of the step-by-step method is taken place simultaneously from two sides (**fig. 1** and **fig. 2**). Next the main part of a sheet billet is forming simultaneously by the step-by-step method on the O-forming press along the entire length of the billet from the bent edges to the middle of the billet. Then the assemblage of the pipe by the welding of the pipe's longitudinal seam is taken place. After welding, the necessary transverse diameter and transverse roundness of the pipe is achieved by using the expander. Thereafter the process of the hydraulic testing of the pipe and the process of applying insulation on the inner and outer surface of the pipe are followed [14–16].

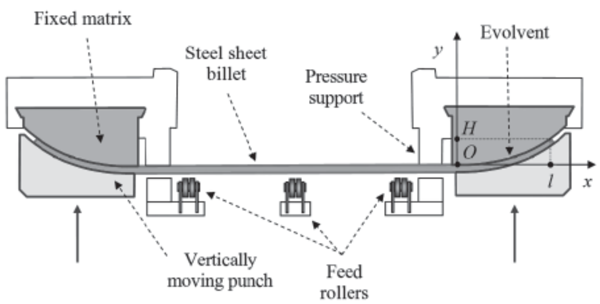

Fig. 1. Bending of the edges of a sheet billet in the flanging press

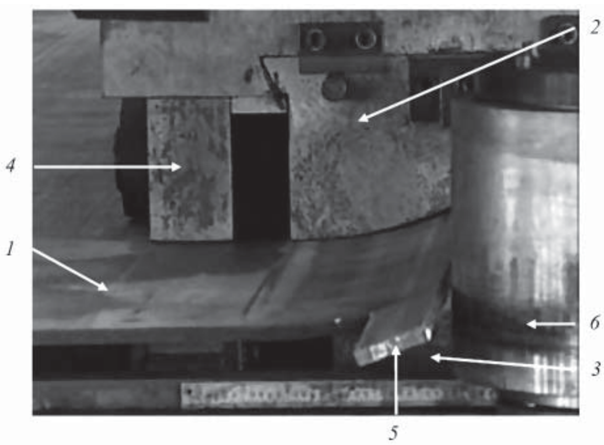

Fig. 2. Deformation of sheet billet in the flanging press: *1* **– sheet billet,** *2* **– punch,** *3* **– matrix,** *4* **– pressure support,** *5* **– technological plank,** *6* **– guide roller**

2. Calculation of punch's profile of the flanging press

We introduce the rectangular coordinate system *Oxy*, the beginning of which is located at the point of contact of a sheet billet with the matrix.

Let H and l be respectively the height and length of the edge of the deformable parts of the billet during the forming, H_1 and l_1 be the values H and l after the forming (after the springback).

The contact profile of the matrix is set in the flanging press by means of the evolvent equation (**fig. 3**):

$$b(\varphi) = r\cos\varphi + r\varphi\sin\varphi,$$

$$a(\varphi) = r\sin\varphi - r\varphi\cos\varphi, \quad \frac{\mathrm{d}a(b)}{\mathrm{d}b} = \mathrm{tg}\,\varphi,$$

where φ is the angle of evolvent, $r = \mathrm{const}$.

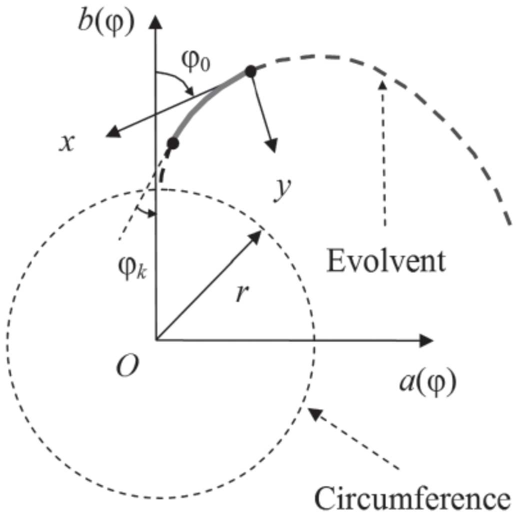

Рис. 3. Coordinate system for calculation of the matrix's working profile of the flanging press

The arc length and the curvature radius of evolvent are equal to $S(\varphi) = r\varphi^2/2$ and $\rho_{ev}(\varphi) = r\varphi$.

Denote by φ_0 the angle, corresponding to the beginning of the evolvent surface of the matrix, and by φ_k the angle, corresponding to the end of this surface.

Then the dependence of the real coordinates $x(\varphi)$ and $y(\varphi)$ of the evolvent surface of the matrix (the upper surface of the non-springbacking billet) from the coordinates $a(\varphi)$ and $b(\varphi)$ has the form

$$b_0 = r\cos\varphi_0 + r\varphi_0 \sin\varphi_0, \quad a_0 = r\sin\varphi_0 - r\varphi_0\cos\varphi_0,$$

$$\rho_{ev}(\varphi) = r\varphi,$$

$$x(\varphi) = -\left(a(\varphi) - a_0\right)\sin\varphi_0 - \left(b(\varphi) - b_0\right)\cos\varphi_0,$$

$$x(\varphi_k) = l,$$

$$y(\varphi) = \left(a(\varphi) - a_0\right)\cos\varphi_0 - \left(b(\varphi) - b_0\right)\sin\varphi_0,$$

$$y(\varphi_k) = H.$$

We introduce the angle of inclination of the matrix surface's profile to the horizontal line $\alpha(\varphi) = \varphi_0 - \varphi$, $\alpha(\varphi_k) = \alpha_k$. Then $dy(\varphi)/dx(\varphi) = \mathrm{tg}\,\alpha(\varphi)$.

The calculation results of the parameters of the matrix's evolvent surface under the bending of the edges of the steel sheet billet for the pipe diameter $D = 1420$ mm ($r = 561{,}0$ mm, $\varphi_0 = 88°$, $\varphi_k = 43°$) is shown in **tab. 1**.

The radius of the curvature of the neutral plane of steel billets during forming on the flanging press is equal to $\rho = r\varphi + h/2$.

3. The springback coefficient of a steel sheet

To describe the mechanical properties of metals, we will use the model of elastoplastic medium with the linear hardening.

Table 1. **Calculation of the profile of matrix's surface of the flanging press**

x, mm	0	100	200	300	400	462.03
y, mm	0	5.98	24.94	59.49	115.39	167.24
ρ, mm	861.6	793.7	718.1	629.9	517.8	421.0
S, mm	0	100.2	202.1	308.0	422.8	503.7
α_k, degree	0	6.94	14.66	23.66	35.12	45.00

After the deformation in the flanging press, the edges of the steel sheet billet spring backwards. Then the residual radius of curvature of the billet's neutral plane of after springbacking ρ_0 and the springback coefficient of billet β are equal to [14–18]

$$\rho_0 = \beta(\rho)\rho,$$

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

where h and ρ are respectively the thickness and the radius of the neutral plane's curvature of the steel sheet's billet; E is the young's modulus; P_t and P_c are respectively the hardening modules in a tension and a compression; σ_s is the deformation resistance of steel.

The deformation resistance of steel $\sigma_s = \mu_{FP}\sigma_y$, where σ_y is the yield strength of steel, $\mu_{FP} = \text{const} \approx 1$ is a dimensionless coefficient that takes into account the strain rate of the billet.

Note that the speed of the vertical movement of the punch on the flanging press can be up to 22 mm/s up and 50 mm/s down.

If $\varphi \geq hE/(2(r + h/2)\sigma_s) = \varphi_{el}$, then it is necessary to put $\rho_0 = \infty$ (the case of the full elastic springbacking of the sheet billet's section to a flat state).

As for the flanging press $\varphi < \varphi_{el}$, then under the forming it is only observed the plastic deformation of the billet.

The bending of the edges of the sheet billet takes place simultaneously and symmetrically relative to the central longitudinal axis of the sheet, and the value of φ_0 is set to always.

Let ΔL_{FP} be the length of the bended edge on the involute at one side of the billet. Then

$$\varphi_k = \frac{-\frac{h}{r} + \sqrt{\left(\frac{h}{r}\right)^2 + 4\left(\varphi_0^2 + \frac{h}{r}\varphi_0 - 2\frac{\Delta L_{FP}}{r}\right)}}{2} \approx$$

$$\approx \sqrt{\varphi_0^2 - 2\frac{\Delta L_{FP}}{r}}, \quad \frac{h}{r} << 1.$$

4. Numerical miltiradius scheme of calculation of the form of the sprinbacking steel sheet

To obtain the exact value of the profile of the billet's neutral plane ($x\beta$, $y\beta$), the values H_1 and l_1 after the springbacking of the steel sheet billet, we can by means of the numerical multiradius scheme of the calculation for the flanging press (**fig. 4**):

$$j = 1 \ldots N \ (N = 1000), \quad \varphi_j = \varphi_0 - \frac{(\varphi_0 - \varphi_k)j}{N},$$

$$\rho_{0j} = \rho_0(\varphi_j),$$

$$\Delta S_0 = 0, \quad \Delta S_j = \frac{r\varphi_j^2 + h\varphi_j}{2} - \frac{r\varphi_{j+1}^2 + h\varphi_{j+1}}{2},$$

$$\psi_0 = 0, \quad \Delta\psi_j = \frac{\Delta S_j}{\rho_{0j}}, \quad \psi_j = \Delta\psi_0 + \ldots \Delta\psi_j,$$

$$y\beta_0 = 0, \quad y\beta_j = y\beta_{j-1} + \rho_{0j-1}\left(\cos\psi_{j-1} - \cos\psi_j\right),$$

$$y\beta_N + \frac{h}{2}\left(\cos\psi_N - 1\right) = H_1,$$

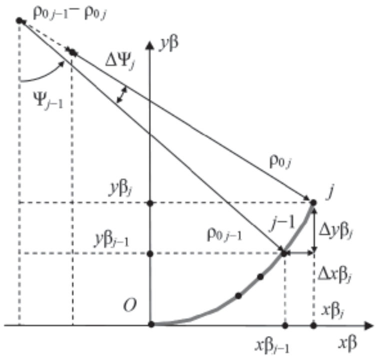

Fig. 4. Multuradius scheme of calculation of profile of the billet's neutral plane after springback

$$x\beta_0 = 0, \quad x\beta_j = x\beta_{j-1} + \rho_{0\,j-1}\left(\sin\psi_j - \sin\psi_{j-1}\right),$$

$$x\beta_N - \frac{h}{2}\sin\psi_N = l_1.$$

For the pipe with the diameter $D = 1420$ mm, the calculation results of the height of the steel billet' edge ($r = 561,0$ mm, $\varphi_0 = 88°$, $E = 2\times10^{11}$ Pa) after a springbacking are given in **tab. 2**.

5. Shape of steel sheet under forming in the flanging press

When the steel sheet billet is forming into the flanging press, the residual plastic deformations in the longitudinal direction of the billet may occur due to the difference between the heights of the billet at the points of its contact with the punch and the roller conveyor. If these plastic deformations are too large, then the corrugation defect of the billet's edges on the phase transition between the punch's steps can take place.

We find the form of the sheet billet in the longitudinal direction at the time of its bending in the flanging press (**fig. 5**).

Let H and H_{ev} be the longitudinal elevation and the height of the bended flank edges of the sheet billet during forming on at the flanging press, l be the unknown length of billet's separation from the plane of the roll-table, E be the young's modulus of the metal, b and h be the width and the thickness of the billet, J_x be the moment of inertia of the sheet's cross section ($J_x = bh^3/12$), γ be the specific weight of steel, $q = \gamma bh$ be the linear weight of the sheet in the longitudinal direction.

Let O_1 be the point of separation of the sheet from the plane of the roll-table in a Cartesian rectangular coordinate system O_1yu and Oyz: $u = l - z$.

The differential equation of the longitudinal neutral axis of the sheet billet has the form

$$EJ_x \frac{d^4 y(u)}{du^4} = -q,$$

After the integration with respect to u, taking into account the boundary conditions

Table 2. **Height of billet's edge after springback**					
Grade of steel	σ_y, N/mm²	h, mm	ΔL_{FP}, mm	$H_1 + h$, mm	
				Standard	Calculation
14ХГС	350	25	430	120±5	120.03
16Г2САФ	420	24	442	120±5	119.93

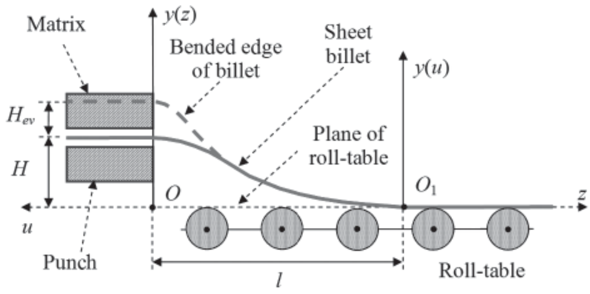

Fig. 5. Form of the longitudinal edge of sheet billet in the flanging press

$$y(0) = 0, \quad y(l) = H, \quad \left.\frac{dy(u)}{du}\right|_{u=0} = 0, \quad \left.\frac{dy(u)}{du}\right|_{u=l} = 0,$$

we get

$$EJ_x \frac{d^2 y(u)}{du^2} = \left(-\frac{ql}{12} + \frac{6EJ_x H}{l^3}\right) + \left(\frac{ql}{2} + \frac{12EJ_x H}{l^3}\right)u - \frac{qu^2}{2} = M_x(u),$$

$$EJ_x \frac{dy(u)}{du} = \left(-\frac{ql}{12} + \frac{6EJ_x H}{l^3}\right)u + \left(\frac{ql}{2} + \frac{12EJ_x H}{l^3}\right)\frac{u^2}{2} - \frac{qu^3}{6},$$

$$EJ_x y(u) = \left(-\frac{ql}{12} + \frac{6EJ_x H}{l^3}\right)\frac{u^2}{2} + \left(\frac{ql}{2} + \frac{12EJ_x H}{l^3}\right)\frac{u^3}{6} - \frac{qu^4}{24},$$

where $M_x(u)$ is the bending moment of the sheet billet.

The non-deformed edge of the sheet billet touching the plane of the roll-table is a straight line, so the bending moment at the point O_1 of the separation of the billet from the plane of the roll-table is equal to zero:

$$M_x(0) = \left(-\frac{ql}{12} + \frac{6EJ_x H}{l^3}\right) = 0.$$

From the last equation, we find the length l of the separation of the billet from the plane of the roll-table:

$$l = \sqrt[4]{\frac{72EJ_x H}{q}}.$$

To take into account the effect of the bending of sheet edges in the transverse direction during forming is possible by introducing the constant dimensionless coefficient μ of the reduced length, which is determined experimentally.

Passing from z to u and substituting l and μ, we obtain

$$l = \frac{1}{\mu}\sqrt[4]{\frac{6Eh^2 H}{\gamma}},$$

$$y(z) = H\left(1 - \mu z\sqrt[4]{\frac{\gamma}{6Eh^2 H}}\right)^3\left(1 + 3\mu z\sqrt[4]{\frac{\gamma}{6Eh^2 H}}\right),$$

$$\frac{dy(z)}{dz} = -12H\mu^2 z\sqrt{\frac{\gamma}{6Eh^2H}}\left(1-\mu z\sqrt[4]{\frac{\gamma}{6Eh^2H}}\right)^2,$$

$$\frac{d^2y(z)}{dz^2} = -12H\mu^2\sqrt{\frac{\gamma}{6Eh^2H}}\left(1-\mu z\sqrt[4]{\frac{\gamma}{6Eh^2H}}\right)\times$$

$$\times\left(1-3\mu z\sqrt[4]{\frac{\gamma}{6Eh^2H}}\right).$$

The radius of the sheet curvature in the longitudinal direction is equal to

$$\rho(z) = \frac{\left(1+\left(\frac{dy(z)}{dz}\right)^2\right)^{\frac{3}{2}}}{\frac{d^2y(z)}{dz^2}}.$$

6. The criterion of the corrugation defect of the steel sheet's edge

The longitudinal residual plastic deformation, leading to the appearance of the corrugation defect, will occur if the normal stresses in the longitudinal direction of the sheet billet reaches the yield strength σ_y: $\rho \le \rho_{el} = (H_{ev} + h/2)E/\sigma_s$.

Therefore, the criterion of the origin of the corrugation defect in the longitudinal direction of the sheet billet on the flanging press has the form

$$|\rho_{\min}| = |\rho(0)| = \left(12H\mu^2\sqrt{\frac{\gamma}{6Eh^2H}}\right)^{-1} \le \rho_{el},$$

$$H \ge \frac{\sigma_s^2 h^2}{24\gamma\mu^4\left(H_{ev}+h/2\right)^2 E}.$$

7. Conclusions

The proposed model of the plastic forming of the thick-wall pipe's billet on the flanging press allows us to calculate the billet's profile during forming and after springbacking as close as possible to the form of the required profile of the pipe, in depending on the geometric sizes and mechanical properties of the billet, and also the geometrical sizes of the deforming tools.

The criterion of the emergence of the corrugation defect of the sheet edges in the longitudinal direction of the billet under the step-by-step forming by the scheme JCOE is obtained.

The results of the study can be used in the development of the technological regimes and in the successful development of the technology of the production of the large-diameter steel pipes with the diameter up to 1420 mm, the wall thickness up to 40 mm and the lengths up to 18.3 m, which are used for the construction of the modern gas and oil pipelines [1–32].

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