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CALCULATION OF TECHNOLOGICAL PARAMETERS OF O-FORMING PRESS FOR MANUFACTURE OF LARGE-DIAMETER STEEL PIPES

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ABSTRACT

The trunk pipeline transport of oil and gas is the crucial part of Russian economy and the focus of the latest achievements of domestic and foreign science and technology. In 2008, the length of Russian trunk pipelines exceeds 223 thousand km, of which 160 thousand km of gas-pipelines and 63 thousand km of oil-pipelines. The pipeline transport was pumped more than 488 mln tonnes of oil and oil products and 565 million tons of gas. The freight turnover of pipeline transport amounted to 1.156 trillion tonne-km of oil and oil products and 1.317 trillion tonne-km of gas.
To ensure the high requirements to the trunk pipeline exploitation, the forming process of pipe billet according to the scheme JCOE is established on the market of production of welded large-diameter pipes.
In this paper, the mathematical model for the calculation of the steel billet' form after the O-forming press is obtained. At a forming process the elastoplastic medium model of steel is used. The research results mean for the calculation of the press's optimal calibration in the production of the thick-walled straight-line-single-seam large-diameter welded steel pipes according to the scheme JCOE for main gas and oil pipelines.

1. The manufacture of large-diameter pipes for main gas and oil pipelines

In the first stage of the process of the manufacture of the large-diameter pipes according to the scheme JCOE [1–25], 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. Next to obtain the open O-profile of pipe billets, the main part of sheet billet is forming simultaneously by the step-by-step method on the O-forming press (OFP) along the entire length of the billet from the bent edges to the middle of the billet. Then the assemblage of the pipe is taken place by means of the gas welding of pipe's outer seam and the four-arc welding of the internal and external seams of the pipe. After welding the necessary transverse diameter and 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 [8–10].

The production of the single-joint straight-line-seam welded pipes according to the scheme JCOE for the gas and oil pipelines with a diameter of ≥1220 mm take place in Russia on JSC "Vyksa Steel Works" (JSC VSW), ZAO "Izhora Pipe Mill" (ZAO ITZ) and JSC "Chelyabinsk Pipe-Rolling Plant" (JSC ChelPipe), and also take place on the pipe factories in Germany, China and India (**tab. 1**).

The formation of a corrugation defect of the longitudinal edges of a pipe billet on a flanging press, the harmful effect of the residual stresses of the pipe metal after the O-forming press on the process of pipe's expanding, the faulty fusion defect in the welded longitudinal seam during the pipe assembly, the defect from the rolled burnt-on with the hairline on the pipe surface, the processes of flattening of steel sheet on the multiroller sheet-straightening machines under a pipe production, the processes of a steel sheet rolling under the production of pipes were studied in [8–12, 20, 21].

2. The step-by-step bending of the steel sheet billets on the O-forming press

The deformation resistance of steel $\sigma_s = \mu_1\sigma_y$, where σ_y is the yield strength of steel, μ_1 is the dimensionless coefficient that takes into account the velocity of billet's deformation on the O-forming press ($\mu_1 \approx 1$).

For describing of the metal's mechanical properties, we will use the model of elastoplastic medium with a linear hardening.

Table 1. **The comparative characteristics of the straight-line-seam single-weld large-diameter welded pipes made by the scheme JCOE**

Characteristics	Foreign producers		Native producers		
	Europe	Japan	JSC VSW	ZAO ITZ	JSC ChelPipe
Diameter, mm	530–1420	406–1420	508–1422	630–1420	508–1422
Wall thickness, mm	7.0–40	6.0–44.5	8.0–50	8.0–37.9	9.5–48
Length, m	10.5–11.6, 18	10.5–11.6, 18.0	10.5–12.4	10.5–18.3	12.7–18.3
Strength class	X60–X100	X60–X100	K34–K65 X42–X80	K52–K65 X56–X70	≤ K80 ≤ X100

Then the residual curvature radius ρ_0 of the billet's neutral plane after a springback and the springback coefficient β of the billet are equal to [8–10]

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

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

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

The pipe's steel billet after the deformation in the O-forming press is springy back.

Let H_{red} and $H = H_{red} + h$ be respectively the value of the reduction by the punch (the forming knife) of sheet billet and its median plane, L_m be the distance between the dies (the matrixes), Δ_m be the dies parameter, r_p and r_m be respectively the radii of the working surfaces of the punch and matrix, φ be the angle of the border of the contact zone of the punch with the sheet billet (**fig. 1**).

To describe the shape of the neutral plane of the billet outside the contact zone of the billet with the punch (in the lower position of the punch under a forming), we introduce two Cartesian rectangular coordinate system. The origin of the first coordinate system x–y we dispose at the point of the neutral plane of the billet, which is corresponding to the bottom point of the working cylindrical surface of the punch. We direct the axis x horizontally and direct the axis y vertically.

The beginning of the second coordinate system x_2–y_2 we dispose at the point of the neutral plane of the billet, which is corresponding to the point of separation of the billet from the punch. The axis x_2 we direct parallel to a tangent to the cylindrical surface of punch at the separation point, and the axis y_2 we direct perpendicular to the axis x_2.

The shape of the neutral surface of the steel billet between the punch and the die (outside the contact area the billet with the punch) we will approximate with the cubic polynomial of the form $y_2(x_2) = ax_2^2 - bx_2^3$. Note that the first two coefficients of the polynomial equal to zero, because the billet surface touches with the cylindrical surface of the punch at the point, which is corresponding to the origin of the coordinate system x_2–y_2.

The coordinates of the center of the working cylindrical surface of the right matrix in the coordinate system x_2–y_2 are equal to

$$x_{2m}(\varphi) = \left(\frac{L_m}{2} + \Delta_m - \left(r_p + \frac{h}{2}\right)\sin\varphi\right)\cos\varphi + \left(H + \frac{h}{2} - r_m - \left(r_p + \frac{h}{2}\right)(1-\cos\varphi)\right)\sin\varphi,$$

$$y_{2m}(\varphi) = -\left(\frac{L_m}{2} + \Delta_m - \left(r_p + \frac{h}{2}\right)\sin\varphi\right)\sin\varphi + \left(H + \frac{h}{2} - r_m - \left(r_p + \frac{h}{2}\right)(1-\cos\varphi)\right)\cos\varphi.$$

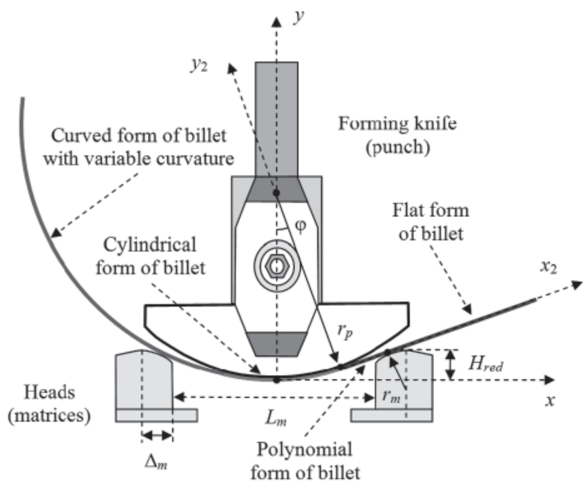

Fig. 1. The bending of a steel billet on the O-forming press

Let us denote the coordinates of the point of the neutral plane of the billet, which is corresponding to the tangent point of the billet with the right matrix, in the coordinate systems x–y and x_2–y_2 respectively by (x_0, y_0) and (x_{20}, y_{20}).

The values φ and x_{20} satisfy the system of two nonlinear equations:

$$\left(x_{2m}(\varphi) - x_{20}\right)^2\left(1 + \frac{4\left(r_p + \dfrac{h}{2}\right)^2}{x_{20}^{\,2}}\right) = \left(r_m(\varphi) + \frac{h}{2}\right)^2,$$

$$\frac{x_{20}}{2r_p}\left(\frac{x_{20}^{\,2}}{3r_p} - y_{2m}(\varphi)\right) = x_{2m}(\varphi) - x_{20}.$$

Solving the system of equations, we find the numerical values φ and x_{20}.

Then we find the coefficients of the cubic polynomial and the shape of the neutral surface of the billet in the coordinate system x_2–y_2:

$$a = \frac{1}{2\left(r_p + \dfrac{h}{2}\right)}, \quad b = \frac{1}{6x_{20}\left(r_p + \dfrac{h}{2}\right)},$$

$$y_2(x_2) = ax_2^2 - bx_2^3,$$

$$y_{20} = y_2(x_{20}) = ax_{20}^2 - bx_{20}^3, \quad 0 \le x_2 \le x_{20}.$$

The dependences of x_0 and y_0 from the x_{20} and y_{20} have the form

$$x_0 = x_{20}\cos\varphi - y_{20}\sin\varphi + \left(r_p + \frac{h}{2}\right)\sin\varphi,$$

$$y_0 = x_{20}\sin\varphi + y_{20}\cos\varphi + \left(r_p + \frac{h}{2}\right)(1-\cos\varphi).$$

In the area of contact of the billet with the punch, the radius of curvature of the neutral plane of the billet in the coordinate system x–y is equal to

$$\rho(x) = r_p + \frac{h}{2} = \text{const}, \quad \varepsilon(x) = \frac{1}{r_p + \frac{h}{2}} = \text{const},$$

$$0 \le x \le \left(r_p + \frac{h}{2} \right) \sin\varphi.$$

The radius of curvature and the parametric equation of the neutral line of the billet between the punch and the die outside the contact area of the billet with the punch in the coordinate system x–y have the form

$$\rho(x_2) = \frac{\left[1 + \left(2ax_2 - 3bx_2^2 \right) \right]^{\frac{3}{2}}}{2a - 6bx_2}, \quad \varepsilon(x_2) = \frac{1}{\rho_2(x_2)},$$

$$x(x_2) = x_2 \cos\varphi - \left(ax_2^2 - bx_2^2 \right) \sin\varphi + \left(r_p + \frac{h}{2} \right) \sin\varphi,$$

$$y(x_2) = x_2 \sin\varphi + \left(ax_2^2 - bx_2^2 \right) \cos\varphi + \left(r_p + \frac{h}{2} \right) (1 - \cos\varphi),$$

$$0 \le x_2 \le x_{20}, \quad \left(r_p + \frac{h}{2} \right) \sin\varphi \le x \le x_0.$$

Outside the contact area of the billet with the right matrix, the radius of curvature of the neutral plane of the billet in the coordinate system x–y equal to infinity (the plain form of the billet):

$$\rho(x) = \infty, \quad \varepsilon(x) = 0, \quad x_0 \le x.$$

Knowing the curvature radius $\rho(x)$ of the neutral plane of the billet during a forming, we find the radius of curvature and the curvature of the neutral plane of the billet after a springback:

$$\rho_0(x) = \beta(\rho(x)) \cdot \rho(x), \quad \varepsilon_0(x) = \frac{1}{\rho_0(x)}.$$

Under the step-by-step forming, the same infinitely small section of the billet may be deformed twice. In this case, as the final value of the curvature of such section we select the maximum value from two values of curvature under the various forming of the billet.

3. The calculations' results of the shape of the steel billet after its bending on the O-forming press

We denote the final height of the pipe billet after springback by H_β, and the final deviation of the billet edge from a vertical line, which is passing through the middle of the billet's width, by l_β.

We can obtain the exact value of the profile of the neutral plane of the steel sheet billet ($x\beta$, $y\beta$), the values H_β and l_β of the billet after a springback by means of the numerical multiradius calculation scheme for the O-forming press, in which the origin of the coordinate system x–y is selected in the point of the middle surface of the billet corresponding to the middle of billet's width:

$$j = 1 \ldots N \ (N = 1000), \quad x_j = \frac{\pi D}{2N} j, \quad \rho_{0j} = \rho_0(x_j),$$

$$\Delta S_0 = 0, \quad \Delta S_j = \frac{\pi D}{2N},$$

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

$$y\beta_0 = 0, \quad y\beta_N + \frac{h}{2}\left(1 - \cos\psi_N \right) = H_\beta,$$

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

Let L_m = 461.5 mm, Δ_m = 25 mm, but the forming step of the punch under the step-by-step bending of the billet on the O-forming press is equal to half of the length between the top points of the matrixes:

$\Delta L_{OFP} = (L_m + 2\Delta_m)/2$ = 255.75 mm. The outer perimeter of the pipe with the diameter D = 1420 mm is equal to $P_D = \pi D$ = 4461.06 mm. Then we obtain that $(P_D/2 - \Delta L_{OFP})/\Delta L_{OFP}$ = 7.72. Therefore, when the billet's left side is forming on the O-forming press we need eight blows of the punch.

The same number of blows of the punch (eight blows) is required for the forming of the right side of the billet.

After that, the billet's center is deforming by the last seventeenth blow of the punch.

Making calculations for the pipe with the diameter D = 1420 mm at $E = 2{\cdot}10^{11}$ Pa, σ_y = 500 MPa, $P_s = P_c = 8.8{\cdot}10^9$Pa, r_p = 500 mm, r_m = 50 mm, Δ_m = 25 mm, L_m = 461.5 mm, h = 19 mm, H = 50 mm, $H_{red} = H - h$ = 31 mm, we obtained H_β = 1505.51 mm ($H_\beta - D$ = 85.51 mm) and l_β = 78.86 mm ($2l_\beta$ = 157.72 mm).

Note that in the calculations we took into account the bending of the edges of the steel billet on the flanging press and we put the radius of the evolvent surface of the matrix of the flanging press [8–10] is equal to r = 561.0 mm.

The curvature of the springback steel billet after the O-forming press is shown in **fig. 2**.

4. The inflection point defect under the bending of a billet on the O-forming press

When the billet is forming on the O-forming press, an inflection point defect (the plastic bending of the billet in the

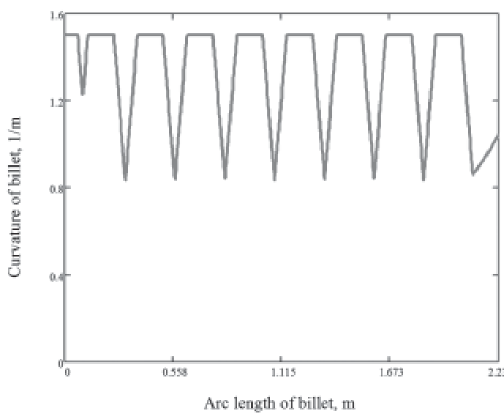

Fig. 2. The curvature of the right half of a billet after the O-forming press

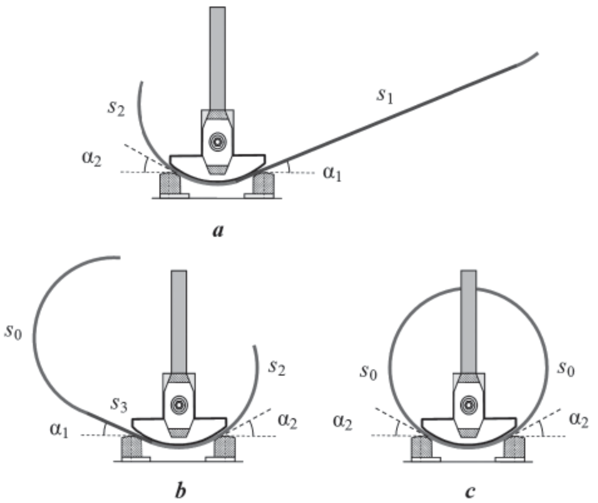

Fig. 3. The step-by-step forming of a steel billet on the O-forming press:
a — the forming of the billet's left part from left to right; *b* — the forming of the billet's right part from right to left; *c* — the final blow of the punch at the billet's center

direction opposite to the normal bending of the billet) may occur because of the large bending moments from the billet's part, hanging freely in the air.

The first case — the inflection of the straightforward free part of the billet during its forming from left to right (**fig. 3,** *a*).

In this case, the billet's inflection across the dies in the opposite direction occurs if the transverse length of the billet's free part s_1 is greater than s_{1y}, which is determined from the equation:

$$s_{1y} = \frac{1}{\mu_2}\sqrt{\frac{h\sigma_y}{3\gamma g\cos\alpha_1}},$$

where μ_2 is the dimensionless coefficient that takes into account the inertial forces under bending; γ is the specific weight of steel, g is the acceleration of gravity ($g = 9.81$ m/s²).

The second case — the inflection of the cylindrical free part of the billet in the opposite direction when the billet is formed from left to right or from right to left (**fig. 3,** *b*).

In this case, the billet's inflection across the dies in the opposite direction occurs if the length of the cylindrical portion of the billet's free part s_2 is greater than s_{2y}, which is determined from the nonlinear equation:

$$\frac{h\sigma_y}{6} = \gamma g\frac{\mu_2 s_{2y}^{\;2}}{2}\frac{1}{\left(\frac{\alpha_s}{2}\right)}\left[\frac{\sin\left(\frac{\alpha_s}{2}\right)}{\left(\frac{\alpha_s}{2}\right)}\sin\left(\alpha_2+\frac{\alpha_s}{2}\right)-\sin\alpha_2\right],$$

$$\alpha_s = \frac{\mu_2 s_{2y}}{\beta r_p}.$$

The third case — the inflection of the billet's curved free part, consisting of the straight portion of length s_3 and the cylindrical portion of length s_0 (**fig. 3,** *c*).

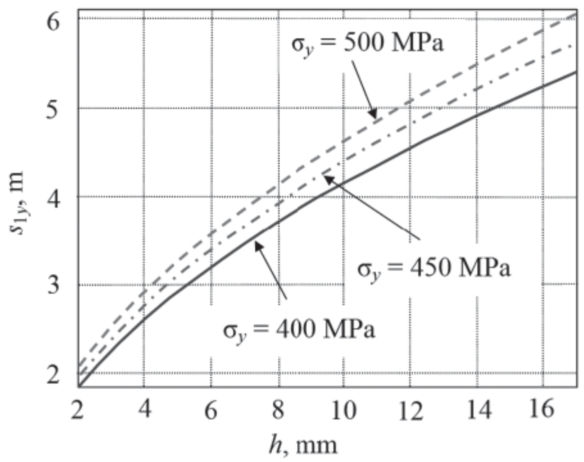

Fig. 4. The maximum transverse length of the free part of a billet under the bending on the O-forming press without the inflection point defect

In this case, the billet's inflection across the dies in the opposite direction occurs if the length s_3 is greater than s_{3y}, which is determined from the quadratic equation:

$$\frac{h\sigma_y}{6\gamma g} = \frac{\mu_2^2 s_{3y}^2\cos\alpha_1}{2} + \mu_2 s_{3y} s_0\cos\alpha_1 + \frac{s_0^2}{\alpha_{s0}}\left[\frac{\sin\left(\frac{\alpha_{s0}}{2}\right)}{\left(\frac{\alpha_{s0}}{2}\right)}\sin\left(\alpha_1+\frac{\alpha_{s0}}{2}\right)-\sin\alpha_1\right],$$

$$\alpha_{s0} = \pi - 2\alpha_1, \quad s_0 = \alpha_{s0}\beta r_p.$$

The most dangerous is the first step of the billet's bending from left to right on the O-forming press, in which there is the maximum bending moment from the free part of the billet.

The dependence of the maximum transverse length of the billet's free part s_{1y} on the thickness h for the different modules of plasticity is shown in **fig. 4**.

Note that the perimeter length of the cross-section of the pipe with the diameter of 1020 mm, 1220 mm and 1420 mm is equal respectively to 3.204 m, 3.833 m and 4.461 m.

The value of billet's bended edge L_{edg} on the flanging press depending on the instrument's calibrations can vary from 187.6 mm to 503.7 mm.

Put 'diameter' $D = b/\pi$, where b is the billet's width.

The length of the billet's free part s_1 in the first step of its bending on the O-forming press is equal to $s_1 = b - \Delta S = \pi D - \Delta S$, where $\Delta S = k\, L_m / 2 + L_{edg}$, $0 < k \le 1$.

The maximum diameter D_{max}, which can be obtained on the O-forming press without the inflection point defect of the billet, is equal to

$$D_{max} = \frac{1}{\pi}\left(\frac{1}{\mu_2}\sqrt{\frac{\sigma_т h}{3\gamma g\cos\alpha}} + \Delta S\right).$$

Table 2. **The maximum pipe diameter during the billet's bending on the O-forming press without the inflection point defect**

h, mm	D_{max}, mm		
	σ_y = 400 MPa	σ_y = 450 MPa	σ_y = 500 MPa
2	802.4	838.3	872.2
3	935.3	979.2	1020.8
4	1047.4	1098.1	1146.1
5	1146.1	1202.8	1256.5
6	1235.3	1297.5	1356.3
7	1317.4	1384.5	1448.0
8	1393.8	1465.6	1533.4
9	1465.6	1541.7	1613.7

The values of D_{max} at L_m = 461.5 mm, L_{edg} =432 mm, k = 1 (ΔS = 662.75 mm) are given in **tab. 2**.

The minimum thickness of the billet's wall h_{min}, at which it is possible to obtain the pipe billet with a diameter D on the O-forming press without the inflection point defect, is equal to

$$h_{min} = \frac{3\mu_2^2 \gamma g \cos\alpha \left(\pi D - \Delta S\right)^2}{\sigma_y}.$$

The values of h_{min} at ΔS = 662.75 mm are given in **tab. 3**.

Table 3. **The minimum thickness of the billet's wall during the bending on the O-forming press without the inflection point defect**

D, mm	h_{min}, mm		
	σ_y = 400 MPa	σ_y = 450 MPa	σ_y = 500 MPa
1020	3.74	3.33	2.99
1220	5.82	5.17	4.66
1420	8.36	7.43	6.69

5. Conclusions

The mathematical model for the calculation of the form of the steel billet after the O-forming press is obtained.

The investigation results can be used for the calculation of the optimal calibrations of the O-forming press under the manufacture the thick-walled large-diameter welded pipes for the main gas and oil pipelines [1–25].

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