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 million 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’s 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-staightening machines under a pipe production, the processes of a steel sheet rolling under the production of pipes were studied in [8–12, 20, 21].


The deformation resistance of steel \( \sigma_y = \mu \sigma_s \), where \( \sigma_y \) is the yield strength of steel, \( \mu \) 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>
<thead>
<tr>
<th>Characteristics</th>
<th>Foreign producers</th>
<th>Native producers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, mm</td>
<td>530–1420</td>
<td>606–1420</td>
</tr>
<tr>
<td>Wall thickness, mm</td>
<td>7.0–40</td>
<td>6.0–44.5</td>
</tr>
<tr>
<td>Length, m</td>
<td>10.5–11.6, 18</td>
<td>10.5–11.6, 18.0</td>
</tr>
<tr>
<td>Strength class</td>
<td>X60–X100</td>
<td>X60–X100</td>
</tr>
</tbody>
</table>
Then the residual curvature radius \( \rho_0 \) of the billet’s neutral plane after a springback and the springback coefficient \( \beta \) of the billet are equal to [8–10]

\[
\rho_0 = \beta(\rho)\rho,
\]

\[
\beta(\rho) = \frac{1}{1 - P_t + P_r} \left( 1 - 2 \frac{\sigma_s}{hE} \right)^2 \left( 1 + \frac{\sigma_s}{hE} \right),
\]

where \( h \) and \( \rho \) are the thickness and curvature radius of the neutral plane of the steel sheet billet; \( E \) is the young’s modulus; \( P_t \) and \( P_r \) are respectively the hardening modules in tension and compression; \( \sigma_s \) is the deformation resistance of steel.

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

Let \( H_{neo} \) and \( H = H_{neo} + h \) 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), \( \Delta_m \) be the dies parameter, \( r_p \) and \( r_m \) be respectively the radii of the working surfaces of the punch and matrix, \( \varphi \) be the angle of the border of the contact zone of the punch and matrix, \( \beta \) 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 \( y_2(x_2) = ax_2^3 - bx_2^2 \). 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

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

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

The values \( x_{20} \) and \( y_{20} \) have

\[
x_{20} = \frac{x_{2m}(\varphi = 0)}{2} \left( \frac{r_p + h}{2} \right) \left( 1 - \cos \varphi \right),
\]

\[
y_{20} = \frac{y_{2m}(\varphi = 0)}{2} \left( \frac{r_p + h}{2} \right) \sin \varphi.
\]

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

![Fig. 1. The bending of a steel billet on the O-forming press](image-url)
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
\[
\rho(x) = \frac{r_p + \frac{h}{2}}{} = \text{const}, \quad \epsilon(x) = \frac{1}{r_p + \frac{h}{2}} = \text{const}, \quad 0 \leq x \leq \left( r_p + \frac{h}{2} \right) \sin \varphi.
\]

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 $O$-forming press, in which the origin of the coordinate system $O$ corresponds to the middle of the billet's width:
\[
\rho(x) = \frac{[1 + (2ax_x - 3bx_x^2)]^3}{2a - 6bx_x}, \quad \epsilon(x) = \frac{1}{\rho_0(x)},
\]
\[
x(x_2) = x_2 \cos \varphi - (ax_x^2 - bx_x^2) \sin \varphi + \left( r_p + \frac{h}{2} \right) \sin \varphi,
\]
\[
y(x_2) = x_2 \sin \varphi + (ax_x^2 - bx_x^2) \cos \varphi + \left( r_p + \frac{h}{2} \right) (1 - \cos \varphi),
\]
\[
0 \leq x_2 \leq x_20, \quad \left( r_p + \frac{h}{2} \right) \sin \varphi \leq x \leq x_0.
\]

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):
\[
\rho(x) = \infty, \quad \epsilon(x) = 0, \quad x_0 \leq x.
\]

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:
\[
\rho_0(x) = \beta_0(p(x)) \cdot p(x), \quad \epsilon_0(x) = \frac{1}{\rho_0(x)}.
\]

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 $H_0$, and the final deviation of the billet edge from a vertical line, which is passing through the middle of the billet’s width, by $l_0$.

We can obtain the exact value of the profile of the neutral plane of the steel sheet billet $(x\beta, y\beta)$, the values $H_0$ and $l_0$ 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 the billet’s width:
\[
j = 1…N (N = 1000), \quad x_j = \frac{\pi D}{2N} j, \quad \rho_{0j} = \rho_0(x_j),
\]
\[
\Delta S_0 = 0, \quad \Delta S_j = \frac{\pi D}{2N}.
\]
\[
\psi_0 = 0, \quad \Delta \psi_j = \frac{\Delta S_j}{\rho_{0j}}, \quad \psi_j = \Delta \psi_0 + \ldots + \Delta \psi_j,
\]
\[
y\beta_0 = 0, \quad y\beta_N + \frac{h}{2} (1 - \cos \psi_N) = H_0,
\]
\[
x\beta_j = x\beta_{j-1} + \rho_{0j-1} (\sin \psi_j - \sin \psi_{j-1}).
\]

Let $L_m = 461.5$ mm, $\Delta_m = 25$ 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:
\[
\Delta L_{OFP} = \left( L_m + 2\Delta_m \right)/2 = 255.75 \text{ mm}.
\]

The outer perimeter of the pipe with the diameter $D = 1420$ mm is equal to $P_0 = \pi D = 4461.06$ mm. Then we obtain that $(P_0/2 - \Delta L_{OFP})/\Delta L_{OFP} = 7.72$. 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 $E = 2 \times 10^{11}$ Pa, $\sigma_y = 500$ MPa, $P_s = P_c = 8.8 \times 10^9 \text{Pa}$, $r_p = 500$ mm, $r_m = 50$ mm, $\Delta_o = 25$ mm, $L_m = 461.5$ mm, $h = 19$ mm, $H = 50$ mm, $H_{ed} = H - h = 31$ mm, we obtained $H_0 = 1505.51$ mm ($H_0 - D = 85.51$ mm) and $l_0 = 78.86$ mm ($2l_0 = 157.72$ 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
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:

\[
\frac{\sigma_y}{6}\frac{\sqrt{\frac{h\sigma_y}{\gamma\cos\alpha}}}{2} = \mu_2\frac{s_{1y}}{3}\frac{\alpha_1}{\cos\alpha_1},
\]

where \(\mu_2\) is the dimensionless coefficient that takes into account the inertial forces under bending; \(\gamma\) 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:

\[
\frac{h\sigma_y}{6}\frac{\sqrt{\frac{\mu_2s_{2y}}{2}\frac{\alpha_2}{\cos\alpha_2}}}{(\frac{\alpha_2}{2})\sin\left(\alpha_2 + \frac{\alpha_1}{2}\right) - \sin\alpha_2} = \mu_2\frac{s_{2y}}{2}\frac{\alpha_1}{\cos\alpha_1} + \frac{s_{2y}}{\alpha_1}\frac{\sin\left(\frac{\alpha_1}{2}\right)}{\left(\frac{\alpha_1}{2}\right)}\sin\left(\frac{\alpha_1 + \alpha_{10}}{2}\right) - \sin\alpha_1,
\]

\(\alpha_{10} = \pi - 2\alpha_1, s_0 = \alpha_{10}\beta_p\).

The third case — the inflection of the billet’s curved free part, consisting of the straight portion of length \(s_1\) and the cylindrical portion of length \(s_0\) (fig. 3, c).

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 < \(k\) ≤ 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

\[
D_{max} = \frac{1}{\pi}\left(\frac{1}{\mu_2}\sqrt{\frac{\sigma_yh}{3\gamma\cos\alpha} + \Delta S}\right).
\]
The values of \( D_{\text{max}} \) at \( L_s = 461.5 \text{ mm} \), \( L_{\text{adj}} = 432 \text{ mm} \), \( k = 1 \) (\( \Delta S = 662.75 \text{ mm} \)) are given in Table 2.

The minimum thickness of the billet’s wall \( h_{\text{min}} \), 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

\[
h_{\text{min}} = \frac{3\mu \gamma \alpha \pi D - \Delta S}{\sigma_y}.
\]

The values of \( h_{\text{min}} \), at \( \Delta S = 662.75 \text{ mm} \) are given in Table 3.

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].

REFERENCES


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

<table>
<thead>
<tr>
<th>( h ), mm</th>
<th>( D_{\text{max}} ), mm</th>
<th>( \sigma_y = 400 \text{ MPa} )</th>
<th>( \sigma_y = 450 \text{ MPa} )</th>
<th>( \sigma_y = 500 \text{ MPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>802.4</td>
<td>838.3</td>
<td>872.2</td>
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<tr>
<td>3</td>
<td>935.3</td>
<td>979.2</td>
<td>1020.8</td>
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<tr>
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<td>1047.4</td>
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</tr>
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<td>9</td>
<td>1465.6</td>
<td>1541.7</td>
<td>1613.7</td>
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</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>( D ), mm</th>
<th>( \sigma_y = 400 \text{ MPa} )</th>
<th>( \sigma_y = 450 \text{ MPa} )</th>
<th>( \sigma_y = 500 \text{ MPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1020</td>
<td>3.74</td>
<td>3.33</td>
<td>2.99</td>
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<tr>
<td>1220</td>
<td>5.82</td>
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</tr>
<tr>
<td>1420</td>
<td>8.36</td>
<td>7.43</td>
<td>6.69</td>
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</table>