The method for determining the profile of large diameter pipes and the optimal technological mode during calibration-bending in the weld zone

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Abstract. The article presents the results of finite-element modeling of the local calibration-bending process of large-diameter pipes in the weld zone with control of the dynamics changes in the geometry of the inner and outer surfaces of the workpiece, the base diameter, the total deformation of the perimeter and ovalization of the contours. The author has developed the technique of determining the coordinates of surface grid nodes based on an algorithm implemented in a special LUA-program for the QForm complex. The developed modeling technique allows us to determine the optimal working stroke of the tool and other parameters of the local calibration of the tube billet to minimize its degree of ovalization. An example of the implementation of the local calibration method and the predicted change in the geometry of the contour of the pipe billet with diameter ϕ1420х40 made of K60 steel with the initial shape defects after welding is given. The technical implementation of the method of local correction and prediction of the tube billet profile is complemented by the possibility of editing it by expansion. Improving the accuracy of geometry in the end zones of pipes will directly increase the possibility of high quality butt-welding during installation of pipeline systems.

1. Introduction
Currently, large-diameter pipes (LDP) are produced in large quantities in the world by using modern methods of forming according to the JCOE, UOE schemes, as well as forming by rolling on presses and roll bending machines. After forming operations from a steel sheet, the pipe is welded with internal and external seams. A characteristic defect of a pipe [1-3] is the deviation of its transverse profile from the correct circle of a given diameter in the form of an ovality or a polyhedron with smooth angles, as well as the longitudinal curvature of the pipe. A common sore point is the shape of the pipe in the area of the longitudinal seam after welding the edges, where it is possible to offset the edges, form edges at the wrong angle, and have flat sections on both edges, wrinkled edges, as well as the presence of sheet thickness in the weld zone [4-7]. The process of mechanical calibration of welded pipes by internal pressure with a composite tool called expansion or distribution usually completes the shaping of the LDP [8-15], significantly reducing the level of defects associated with the specifics of the previous operations of shaping and multi-pass welding with a longitudinal seam. However, with a strong distortion of the initial geometry in the weld zone, the possibility of expansion is not enough, especially in the case discussed below.

Today, pipe blanks with a profile always come in for expansion, on which in the welding zone there are two flat sections welded either by the roof, or by a common plane. Edge crushing is not permitted.
The increased risk of crushing the edges of thick-walled pipes is specific for the method of forming the edges of thick-walled pipes with rollers. The profile after welding of the “roof” type is shown in figure 1.

In the present work, we study the LDP calibration scheme based on radial compression, or local bending of metal in the weld zone. The proposed scheme is an alternative to the expansion process or its addition in order to obtain high-quality pipes. The ideal profile in the end zones of the LDP is especially important, this determines the strength of the butt welds during the installation of gas and oil pipelines.

The above diagram (figure 1) gives the initial position of the tool and the pipe, welded in the form of a “roof” and with external reinforcement before starting calibration using the local bending method.

![Diagram](image)

Figure 1. Calibration-bending scheme of LDP in the weld zone. 1-pipe billet; 2-upper punch; 3-lower punch; 4-weld.

The presence of external reinforcement of the weld shown in figure 1 on the pipe billet is a possible special case. Welding techniques may differ, there may be no reinforcement of the weld on the workpiece by the time this operation starts, however, the presence of flat sections in the weld zone that together form one or another angle between the planes to be welded are today a characteristic feature of the configuration of pipe blanks after welding operations. The local calibration scheme under study is based on the creation of bilateral radial pressure in the weld zone created by the convergence of two instruments. The force of the upper punch 2 is applied to the outer surface of the workpiece 1, which moves downward with a speed v in the direction of the workpiece and the weld 4, the lower punch 3 can be fixed.

In the work, we used the method of finite element modeling of the calibration process of the LDP according to the studied scheme and the QForm software package. Additionally, a special data processing algorithm has been developed, implemented in a program in the LUA language, designed to control the perimeter of the contour, the external and internal profiles of the tube billet, and scan the value of the deviation of the profile from the correct circle. The algorithm allows us to determine the optimal moment of stopping the working stroke of the tool to achieve the optimal product profile in accordance with the specified specifications for the geometry of the product.

The described local calibration of the critical zone can be considered both as a preliminary operation before expansion, and as a means of correcting the end zones of products after calibration of the body by the expansion process, when the limit for increasing the perimeter has already been exhausted and ovalization has not yet been eliminated.

2. The method for determining the pipe profile parameters during calibration

The model uses a 2D modeling apparatus for the elastic-plastic deformation of metal based on the QForm complex. The assumption is true if the longitudinal dimension of the punches along the axis of the pipe is significantly greater than the width of the weld. Given the complex transverse profile of the pipe in the weld zone, a fine mesh was generated to increase the accuracy and convergence of the solution. The grid consists of nodes inside the workpiece and surface nodes on the inner and outer surfaces of the workpiece, or the contours of the body are formed by surface nodes. According to the QForm regulation, normal vectors for volume nodes are always equal to the zero vector $\vec{0}$, and will
differ from the zero vector \( \bar{0} \) for surface nodes. This is the basis for the algorithm for controlling the geometry of the inner and outer surfaces of the tube billet.

At each step of the deformation modeling process, there are \( m \) and \( n \) surface nodes on the external and internal contours of the body, respectively. Figure 2a shows the coordinates for the inner surface nodes \( P_i(x_i, z_i) \), where the normal vectors in them are \( \bar{n}_i(x_i, z_i) \); and where \( i = 1…m \). For external surface nodes \( Q_j(x_j, z_j) \), the normal vectors in them are \( \bar{n}_j(x_j, z_j) \), \( j = 1…n \). It is easy to see that the scalar product of the vectors \( \bar{O}P \) and \( \bar{n}_i \) is greater than zero, i.e. \( \bar{O}P \cdot \bar{n}_i > 0 \) or \( x_i x + z_i z > 0 \); and the scalar product of the vectors \( \bar{O}Q_j \) and \( \bar{n}_j \) is less than zero, i.e. \( \bar{O}Q_j \cdot \bar{n}_j < 0 \) or \( x_j x + z_j z < 0 \).

These mathematical conditions were used to determine the coordinates of the internal and external surface nodes formed by the LUA subroutine after modeling in the post-processor of the main QForm program. The obtained data with the coordinates of the surface nodes are recorded in the Data.txt file. Information on the geometric parameters of the external and internal contours of the tube stock, such as the diameter of the base circle, the perimeter of the contours, the deformation of the contours and the deviation of the contours from the correct circle, are converted as a MATLAB program code.

To calculate the base circle (the best suitable circle) of the contour under study (see figure 2b) having the central coordinate \( Q_{st}(x_{st}, z_{st}) \), the radius \( R_{st} \) is determined by the least squares method for the set of all points (nodes) on this circuit. According to the "best circle fit" algorithm, \( X = \frac{-a}{2} \) ; and \( Z = \frac{-b}{2} \); and

\[
R_{st} = \sqrt{\frac{a^2 + b^2}{a} - c} - c,
\]

where \( a, b, c \) - coefficients depend on the coordinates of the surface nodes of the tube billet. The diameter of the base circle as a conditional diameter is defined as \( D_{st} = 2R_{st} \).

The radius at the \( i \)-th node from the center of the base circle is \( R_i = \sqrt{(x_i - X)^2 + (z_i - Z)^2} \), where \( i=1…m \) for the inner surface, and \( i=1…n \) for external.

The perimeter of the surface is determined \( C = \sum_k \sqrt{(x_{k+1} - x_k)^2 + (z_{k+1} - z_k)^2} \), with the hypothesis \( k = m, x_{m+1} = x_1 \), and \( z_{m+1} = z_1 \) for the inner surface; \( k = n, x_{n+1} = x_1 \), and \( z_{n+1} = z_1 \) for the external.

The average tangential deformation of the contours, which is limited when calibrating the pipes, is calculated here using the formula \( \varepsilon = \frac{c - c_1}{c_1} \times 100\% \), where \( C_1 \) is the perimeter of the inner or outer surface of the original workpiece.

The maximum deviation of the contour from the correct circle in millimeters (ovalization) is determined by the expression \( \Delta = R_{max} - R_{min} \), where \( R_{max} = \max(R_i) \), \( R_{min} = \min(R_i) \).

Figure 2. Surface nodes (a), the scheme for determining the best suitable circle (b).
A diagram of the algorithm for calculating the geometric parameters of the LDP profile is given in figure 2c. The simulation results are presented in graphical form in the form of a relationship of the conditional diameter $D_{st}$, the profile perimeter $C$, ovalization $\Delta_k$, and the total plastic deformation $\varepsilon_c$ with the movement of the upper tool $u$. Some special values of these parameters are given in tabular form as a means of searching for optimal movements of the upper tools (technological process parameters), at which the minimum deviation of the contours from the correct circle $\Delta e_{min}$ or the best shape of the calibrated product is achieved is a condition for stopping the calibration process.

3. Results and discussion

An example of the work is presented to demonstrate how to build geometric models of the workpiece, upper and lower punches, to simulate the solution of the problem of elastic-plastic deformation during calibration of the material in the QForm complex, then apply the developed mathematical methodology and the algorithm above to analyze the dynamics of changes in the geometry of the pipe workpiece during calibration and then determine the optimal working stroke of the punch with a minimum value of ovalization of the pipe billet.

In the example, we took a pipe billet with one longitudinal weld, the pipe wall thickness $s = 40$ mm, the width of the flat sections in the weld zone $L = 136.5$ mm; estimated outer diameter of the pipe $D = 1420$ mm; the angle in the zone of the weld $\alpha = 153^\circ$ and the thickness of the metal in the zone of the weld $h = 60$ mm (figure 1). In the model, we assume that the rest of the blank contour has a profile in the form of a regular circle. The workpiece material is K60 steel with an elastic modulus $E = 186000$ MPa, change in deformation resistance during tensile testing of standard samples: $\sigma_p = 720 \times (10^{-17} + \varepsilon_p)\times 0.05186$ MPa, where $\varepsilon_p$ is the plastic deformation. 2D geometric models of the workpiece and tool are built on AutoCad 2014 software. The initial temperature of the workpiece in the above version is accepted $20^\circ$C.

An adaptive finite element mesh is used for modeling according to the QForm program algorithm. The maximum mesh element size is 0.6 mm (1,142,138 triangular elements and 577,413 nodes, including 12,688 surface nodes, figure 3). The radius of curvature of the contact surface of the upper punch $R_v = 710$ mm, and the lower $R_n = 670$ mm. The material of the punches is 9HVG steel, the tool is adopted by a rigid body. The lowering speed of the upper tool on the workpiece $v = 1$ mm / s, the lower punch is stationary. The Coulomb friction model is selected with a coefficient $\mu = 0.17$. Stop condition - with the unloading of the workpiece after completion of the stroke of 20 mm.

Figure 3. Modeling the calibration-bending process in the weld zone in the QForm complex.
The change in the conditional diameter $D_n$, the perimeter of the body contour $C$, ovalization $\Delta_k$ and the total deformation $\varepsilon_c$ for the inner and outer surfaces of the tube billet when moving the upper tool $u$ are shown in figures 4 and 5.

![Figure 4. Change in the parameters of the external contour of the body during the movement of the upper punch $u$.](image)

For the outer contour of the workpiece (figure 4), when $u$ is moved from 0 to 6.7 mm, ovalization decreases to the minimum value, it is accompanied by a decrease in both the nominal diameter and perimeter. At this stage, the surface is compressed with a negative value of the total deformation along the contour of the perimeter of the outer surface. With a change in $u$ from 6.7 mm to 10.3 mm, the dimensions of the tube billet are reduced to minimum values, the ovalization $\Delta_k$ increases. When moving $u > 10.3$ mm, the dimensions and ovalization of the pipe further increase, and the outer surface stretches. In the unloading stage after deformation at $u = 20$ mm, ovalization decreases by about 3 mm, and the nominal diameter, perimeter and pipe deformation increase slightly. Therefore, the stage determined by the displacement of the upper punch by $u = 6.7$ mm can be considered the optimal time to stop the process to achieve a better outer pipe contour, when ovalization takes a minimum value, decreasing by 6.6 mm from its initial value (initial pipe billet). The calculated parameters of the external contour for the initial ($u = 0$ mm) and final ($u = 6.7$ mm) states are presented in table 1.

| Parameter | Before calibration | With a minimum value of ovalization |
|-----------|--------------------|-----------------------------------|
| $u$ [mm]  | 0                  | 6.7                               |
| $D_n$ [mm] | 1421.6             | 1420.9                            |
| $C$ [mm]  | 4478.6             | 4478.4                            |
| $\Delta_k$ [mm] | 30.0              | 23.4                              |
| $\varepsilon_c$ [%] | 0            | -0.0051                           |
Changing the parameters of the geometry of the inner surface is shown in figure 5. During the calibration process, the perimeter of the inner contour always increases, the workpiece is stretched by a positive strain value. Ovalization of the inner contour reaches its minimum value when moving \( u = 3.2 \) mm, and the nominal diameter will be minimal when \( u = 10.3 \) mm. After unloading the product at \( u = 20 \) mm, ovalization decreases slightly (by about 2.5 mm), while the base diameter, perimeter and pipe deformation increase slightly. Therefore, the optimal mode for stopping the calibration process should be selected according to the movement of the upper tool \( u = 3.2 \) mm to obtain the best shape of the internal surface of the pipe, then the ovalization decreases by 3.3 mm from its initial state. The calculated parameters of the internal contour for the initial \( (u = 0 \text{ mm}) \) and final \( (u = 3.2 \text{ mm}) \) states are presented in table 2.

| Parameter | Before calibration | With a minimum value of ovalization |
|-----------|--------------------|-------------------------------------|
| \( u \) [mm] | 0                  | 3.2                                 |
| \( D_n \) [mm] | 1341.1             | 1340.9                              |
| \( C \) [mm]  | 4216.2             | 4216.2                              |
| \( \Delta_k \) [mm] | 14.8               | 11.5                                |
| \( \varepsilon_c \) [%] | 0                  | 0.011                               |

The calculation method described above allows one to study the change in the workpiece profile before and after calibration in the form of a scan of the values of the radius \( R \) by a full angle \( \theta \) of 360 degrees (figure 6). The final state here corresponds to a displacement of \( u = 3.2 \) mm for a better internal surface or \( u = 6.7 \) mm for a better external. The weld corresponds to the central angle \( \theta = 90^\circ \). It can be seen that after calibration with a minimum value of ovalization, the “roof” defect was significantly reduced from the initial tube billet, that is, the quality of the surface profiles of large-diameter pipes was increased.
4. Conclusion
In this paper, we considered the finite-element modeling of the calibration process of the pipe billet in the weld zone according to the local bending scheme. Results of the research developed the methodology and algorithm for detecting the coordinates of the surface nodes of the dispersed grid, which determine the geometry of the external and internal contours of the product during calibration, by using a subroutine in the LUA language for the QForm complex. Based on the identified dynamics of the change in the pipe contours, the optimal value of the tool stroke corresponding to the minimum ovalization of the product profile is determined. The proposed methods for calibrating pipes and predicting the geometry of the product can be used to optimize process conditions in the production of large diameter pipes in order to improve their quality.

References
[1] Yong Bai and Ruxin Song 1997 International Journal of Pressure Vessels and Piping 74(3) 221–9
[2] Jepson W P and Taylor R E 1993 International Journal of Multiphase Flow 19(3) 411 – 20
[3] Oddie G, Shi H, Durlofsky L J, Aziz K, Pfeffer B and Holmes J A 2003 International Journal of Multiphase Flow 29(4) 527–58
[4] Ngo G V 2018 Journal of Physics: Conference Series 1015 032090
[5] Ngo G V 2018 IOP Conference Series: Materials Science and Engineering 537 032076
[6] Ngo G V and Tham B C 2019 IOP Conference Series: Materials Science and Engineering 537 032079
[7] Ngo G V 2019 IOP Conference Series: Materials Science and Engineering 537 032084
[8] Shinkin V N and Kolikov A P 2012 Metallurgist 55 833–40
[9] Jiang W Y, Lin Y, Chen M anh Yu Y Y 2015 Ocean Engineering 102 63–70
[10] Palumbo G and Tricarico L 2005 Journal of Materials Processing Technology 164-165 1089-98
[11] Anatoly Dubov and Sergey Kolokolnikov 2010 Welding in the World 54 241–8
[12] Lindgren M and Lepistö T 2002 Materials Science and Technology 18(11) 1369–76
[13] Blackman S A and Dorling D V 2000 Proceedings of the 3rd international pipeline technology conference 2 371–87
[14] Fletcher L, Stubbs C and Stecher G. 2004 Proceedings of the 4th international pipeline technology conference 1 315–23
[15] Zhao M C, Yang K and Shan Y 2002 Mater Sci Eng A. 335 14–20