Increasing the strength of welded thin-walled axisymmetric vessels made of corrosion-resistant steel

M A Vasechkin¹, O Yu Davydov¹, V G Egorov¹, S V Egorov² and E V Matveeva¹

¹ Voronezh State University of Engineering Technologies, 19 Revolutsii Av., Voronezh, 394036, Russia
² Research Institute of Automated Means of Production and Control, 129A Tsialkovskogo St., Voronezh, 394076, Russia

E-mail: vmax77@mail.ru

Abstract. Structural elements of thin-walled vessels operating under internal pressure are mainly made from sheet blanks using welding operations. To reduce the negative impact of welds in the manufacture of thin-walled vessels, it is proposed to use separate calibration processes by compressing vessel parts with subsequent welding and their joint calibration by distribution and rotary rolling. Compression calibration ensures the accuracy of matching of the abutting annular edges of the vessel parts. During rotary rolling, the welds are simultaneously smoothed and the strength characteristics are improved due to plastic hardening caused by thinning and leveling the wall thickness of the vessel body. Based on the conducted research, technological recommendations have been developed for the manufacture of thin-walled vessels of increased strength from corrosion-resistant steels.

Thin-walled vessels are common components of various process equipment operating under internal pressure. The main structural elements of the vessels are a cylindrical body, bottom and lid, which are shells of various shapes. Depending on the purpose, the vessels are made of corrosion-resistant steels, titanium, aluminum and other alloys.

Thin-walled cylindrical shells with an outer diameter of up to 200 mm and a wall thickness of up to 1.5 mm are mainly made from sheet blanks, the cylindrical shape of which is obtained by folding it on a sheet bending machine followed by longitudinal welding of the joined edges.

When connecting several shells into a single structure, ring welding of the joined elements is often used, and it is necessary to ensure an exact match in the diameter of the joined ring edges, which is possible for pre-calibrated shells [1].

The main requirement for thin-walled shells under conditions of ensuring penetration over their entire thickness and the absence of defects in welded joints is their strength under the action of static and variable pressure [2].

Welds are stress concentrators, which significantly reduces the fatigue strength of any structures operating under variable stress conditions. One of the possible ways to reduce the negative impact of welds in thin-walled axisymmetric shells while increasing the strength is to introduce an operation into the technological process of their manufacture – rotary rolling with thinning of the wall [3, 4].
The figure 1 shows a diagram of manufacturing a welded thin-walled vessel consisting of a cylindrical body and bottom.
At the beginning, the elements of the vessel are made from the sheet: a cylindrical blank of the body and the bottom. The cylindrical billet of the body is obtained by folding a flat sheet billet on a sheet bending machine and then welding the longitudinal edges. The bottom of the vessel can be made by plastic shaping using pressing equipment designed for performing works related to deep drawing [5].

![Diagram of manufacturing a welded thin-walled vessel](image)

**Figure 1.** The scheme of manufacturing a welded thin-walled vessel: I – convolution of a sheet material into a cylinder and welding the abutting longitudinal edges; II – plastic shaping of the bottom; III – calibration of compression of the cylindrical body of the vessel; IV – calibration of compression cylindrical edge of the bottom; V – welding of the shell and bottom annular seam; VI – distribution of circular welding seam; VII rotary rolling: 1 – storage vessel; 2 – mandrel; 3 – rolling head.

As a result of separate manufacturing of vessel elements, mismatch of annular edges is inevitable during welding, which leads to a decrease in the quality of the annular seam. In order
to eliminate this defect, before Assembly, calibration is performed by compressing the jointed annular edges of the connected elements of the vessel. In addition, the use of compression calibration eliminates the deviation from roundness and provides centering of welded parts along the outer diameter, which allows getting a high-quality butt weld with limited penetration, which in the future will have a positive impact on the resource of the vessel as a whole [6, 7].

When sizing by compression, it is necessary to take into account the probability of loss of stability of the pipe wall and the formation of a corrugation [8-11]. The loss of stability is affected by factors such as the design of the crimping tool, the diameter, wall thickness, and material properties of the pipe billet, as well as the compression pressure created during calibration. The critical pressure \( [q] \) at which the pipe wall loses stability can be determined by the expression:

\[
[q] = \frac{E_k t_0 (1.234 \alpha + 0.775)}{R (1.571 \alpha + 1.645)},
\]

where \( E_k \) is the tangent hardening modulus; \( t_0 \) is the initial wall thickness of the bottom and cylindrical parts of the semi-finished vessel; \( R \) is the outer radius of the pipe; \( \alpha \) is half of the central angle of the crimping tool sector.

The value of the central angle \( 2 \alpha \) of the crimping tool sector is determined by the expression:

\[
2 \alpha = \frac{h + 1}{R},
\]

where \( h \) is the width of the crimping tool sector.

The value of the tangent hardening modulus \( E_k \) is determined from the hardening curve used to make a thin-walled vessel, a material. For 12X18H10T steel, the experimentally obtained dependence for determining the tangent hardening modulus \( E_k \) has the form:

\[
E_k = 317 e_u^{-0.738},
\]

where \( e_u \) is the strain intensity during compression calibration:

\[
e_u = |\ln \left( 1 - \frac{b}{R} \right)|,
\]

where \( b \) is the radial displacement of the welded pipe edges during calibration.

Using the dependencies (1)-(4), one can determine the radial displacement \( [b] \), at which the pipe wall loses stability at a given compression pressure \( q \).

After welding the body and bottom of the vessel, the joint distribution of the annular weld and the welded parts is performed until the value of the outer diameter \( D \) of the vessel at the distribution point is reached, mm:

\[
D = D_0 + (0.2 \ldots 0.4),
\]

where \( D_0 \) is the nominal outer diameter of the cylindrical part of the vessel.

This operation is necessary to restore the gap \( \xi \) between the mandrel 2 and the inner surface of the vessel body 1, since the gap \( \xi \) completely disappears during compression calibration and subsequent welding of the cylindrical part and the bottom.

When distributing the annular seam, it should be taken into account that distribution to a diameter less than \((D_0 + 0.2)\) mm leads to the appearance of bulges on the inner surface of the
cylindrical part of the vessel when it is removed from the mandrel at the end of the rotary rolling. In the case of distribution up to a diameter greater than \( (D_0 + 0.4) \) mm on the outer surface of the vessel at the distribution point, there is a loss of stability in the form of corrugations formed during rotary rolling.

Rotary rolling is performed in order to eliminate the ring protrusion formed on the surface of the vessel during the distribution process and increase the strength characteristics of the manufactured vessel. The quality of steel thin-walled axisymmetric vessels obtained using the rotary rolling operation depends on the combination of geometric parameters of the rolled pipe and the tool, the degree of thinning of the pipe wall and the mechanical characteristics of the material of the cylindrical blank [3, 4, 12-15].

In studies conducted to assess the impact of the power parameters of the process of rotational rolling on the lateral stability is roll out a thin-walled cylindrical shell obtained a expression determining the critical value of length \([L]\), in which the rolled out part of the cylindrical shell loses its stability:

\[
[L] = \frac{2\sqrt{Rt^2}}{[M]} \cdot E_c^2,
\]  

where \([M]\) is the permissible value of the torsion moment; \(E_c\) is the secant hardening modulus; \(t\) is the wall thickness of the cylindrical part of the vessel after rolling the annular and longitudinal welds.

The allowable value of \([M]\) torsion moment is a fraction of the critical torsion moment \(M_k\):

\[
[M] = \frac{M_k}{n} = \frac{3.97E_kRt^2}{n},
\]  

where \(n\) is the coefficient of stability margin. For steel 12X18H10T experimentally established \(n = 2,8\).

The secant hardening module for steel 12X18H10T can be defined by the expression:

\[
E_c = 1209,7e_u^{-0,738}.
\]  

The intensity of the cylindrical shell deformation during rotation is determined by the expression:

\[
e_u = 1,155\varepsilon \cdot 10^{-2},
\]  

where \(\varepsilon\) is the relative wall thickness deformation during rotational rolling of the cylindrical part of the vessel:

\[
\varepsilon = \left(1 - \frac{t}{t_0}\right) \cdot 100\%.
\]  

The choice of the value \(\varepsilon\) is made for the most complete elimination of undercuts on the fusion lines of the annular and longitudinal welds, as well as traces from the seams themselves. It should be borne in mind that corrosion-resistant steels are characterized by a monotonous increase in strength and a strong decrease in plasticity as the relative deformation \(\varepsilon\) increases. Re-hardening of the steel contributes to the loss of stability of the vessel wall in the form of formation of flappers first, and then corrugations.

Using the dependencies (6)-(10) makes it possible to determine, at a given value of the length \(L\) of the rolled cylindrical part of the vessel body, the relative deformation along the thickness \([\varepsilon]\), at which the vessel wall will lose stability.

To assess the strength and durability of manufactured vessels, depending on the relative deformation of the vessel along the wall thickness of the cylindrical part of the vessel during rotary rolling, a series of tests of prototypes was carried out, according to the results of which it was found that:
• at $\epsilon < 12\%$ the complete elimination (smoothing) of undercuts on the lines of fusion of welds is not provided, and in the process of cyclic loading of steel thin-walled axisymmetric vessels by internal pressure, this undercut, as a stress concentrator, significantly reduces the cyclic durability;

• at $\epsilon > 25\%$ the plasticity of the rolled cylindrical part of the steel vessel is reduced so much that there are defective signs in the form of flappers and corrugations.

Thus, selecting the relative strain value from the interval $12\% \leq \epsilon \leq 25\%$ provides stability of the wall of the cylindrical part of vessels of a wide size range during rolling. In addition, the choice of $\epsilon$ from the specified range allows you to produce thin-walled and extra-thin-walled vessels with high performance properties and reduced material consumption.

**Acknowledgements**

The research is performed with the financial support of the Government of the Russian Federation represented by the Ministry of Education and Science in the framework of the Federal Target Program “Research and development in the priority areas of development of the scientific and technological complex of Russia for 2014-2020” under the grant agreement No. 14.574.21.0042. The unique identifier of the agreement RFMEFI57414X0042.

**References**

[1] Zakharchenko N D, Salahetdinov Z H etc. 1988 The Leading Technical Material LTM 1,4.1638–86. Structurally and Technological Optimization of Pipeline Communications, Production and Control of Pipes and Branch Pipes (Moscow: NIAT) p 576

[2] Badaguyev B T 2010 Pressure Vessels. Safety in Operation: Orders, Instructions, Journals, Regulations (Moscow: Alfa Press) p 141

[3] Vasechkin M A, Egorov V G, Maslov I N and Kolomenskiy A B 2016 Determination of the optimum conditions at the processing of high-strength corrosion-proof Research Journal of Applied Sciences 11(2) 72-9

[4] Vasechkin M A, Davydov O Yu, Egorov V G and Maslov I N 2016 Shaping high-longevity components of corrosion-resistant pipes by rotary rolling Chemical and Petroleum Engineering 52(5-6) 392-7

[5] Forging and Stamping. Sheet Stamping 2010 4 edit. by Yakovlev S S (Moscow: Mashinostroyenie) p 731

[6] Vasechkin M A, Davydov O Yu, Kolomenskiy A B and Egorov S V 2016 Calibration of thin-walled precision pipe by transverse compression and expansion using a multisector tool Russian Engineering Research 36(5) 366-70

[7] Vasechkin M A, Shakhoiv S V, Maslov I N and Egorov S V 2015 Installation for calibration of thin-walled precision pipes Journal of Engineering and Applied Sciences 10(8) 208-13

[8] Chumadin A S and Zo Hein Win 2013 Calculation of power parameters at rotational compression of pipes Scientific Work MATI-RSTU 20 182-5

[9] Sosenushkin E N and Tretyakova E I 2010 Field research of stability of pipe preparation at a combination of operations of pressing and expansion (Moscow: Stankoinstrument) 313-8

[10] Demin V A and Buzhilov A L 2010 The distribution of pipe billets by conical punch with cylindrical projection for production of complex parts Machine building production 6 33–5

[11] Xie L, Peng C, Jin L and Shen H 2009 The analysis of the tool for increase in diameter of preparations Machine building production 11 25–7

[12] Yakovlev S S and Dudka D V 2011 The Condition of loss of stability of the wall of a pipe billet made of anisotropic material News of Tula State University Technical Science 1 14-21

[13] Yakovlev S S, Tregubov V I and Yakovlev S P 2009 Rotary Extension with Thinning of Wall of Axisymmetric Parts form Anisotropic Pipe Billets (Moscow: Mashinostroyenie) p 256

[14] Tkachev A V and Korol’kov V I 2010 Study of shell stability in rotary extension operations News of Samara Scientific Center 12(1) 560–3
[15] Naumov D M 2012 *Rotary Extension with Wall Thinning by Ball Rolling Devices* (Tula: Tula State University) p 16