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DIAGNOSTICS OF TECHNOLOGICAL RESIDUAL STRESSES IN DIFFERENT THICKNESS CIRCUMFERENTIAL WELDED JOINTS OF PIPELINES

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Abstract. Using the calculation-experimental method based on solution of inverse problems of the theory of a shell with residual strains and utilizing the experimental data obtained by non-destructive test methods, the distribution of residual stresses near the circumferential weld in the different-thickness pipelines is defined and analyzed, the non-uniformity of their distribution under the measuring devices is considered.

Keywords. Diagnostics, residual stresses, welded joints, pipelines.

1. INTRODUCTION

While the transnational pipeline transport system is in use, a number of hardships arise; most of them are common to the oil and gas industries of Russia, Ukraine, Czech Republik, Poland, and other countries [1]. Therefore, it is benificial to exchange information concerning latest technologies. Comprehensive inspection of cross-country pipelines enables us to estimate their conditions, prompt reparation, and carring out preventive operations.

Nowadays, non-destructive methods, i.e. electromagnetic, ultrasonic, interferometry holography, and others are used for diagnostics of the stressed state in pipelines. However, [2] notices that in real operating conditions of oil and gas transport pipelines none of the aforesaid experimental non-destructive methods can provide complete and authentic information on stress-strain conditions in the welded pipeline joints.

Analysis of inner defectoscopy of pipelines has shown that ≈ 35 per cent of the detected corrosion defects are in the zones of welded joints. Especial attention should be paid to the welded joints of pipes of different thicknesses which are a cause of high stress concentration. Residual stresses in the zones of such welded joints are of alternating sings and non-uniformly distributed with the thickness, they are distributed non-symmetrical with respect to the plane of the welded joint.

Direct application of physical methods is not always fit for diagnosing stresses in welded joints because of incomplete information on their distribution in the element of a pipe [3]. To apply calculational methods, it is necessary to know the welding mode and ways to reduce the values of residual stresses after the welding (relaxation) in the welded joint, that essentially troubles or even makes it impossible to use these methods for finding such stresses in pipelines of long-term operation. Therefore, it is expedient to use calculational-experimental methods [4, 5], when diagnosing welded joints of pipeline of long-term operation.

2. CALCULATION-EXPERIMENTAL METHODS

To estimate the stressed state in the zone of circumferential welded joint of long-term operation pipes of different thickness, the calculation-experimental method is developed which is based on experimental data obtained by non-destructive or partially non-destructive methods and on solutions of inverse problems of shell theory. For this purpose, key equations of the theory of shells of different thickness under the action of local symmetric with respect to axis fields of non-compartible residual deformations are obtained with their solutions.

It is known [6, 7] that for welding pipes with circumferential beads when the difference between the thicknesses of their walls (maximal of which is of 12 mm) does not exceed 2.5 mm or does not exceed 3 mm when the maximal thickness exceeds 12 mm, the forms of work-outs of the butts are the same as for equal thickness pipes. But when the difference of thickness of the walls is greater than the mentioned values, butt work-outs of special forms should be used [7]. If the greater thickness of a wall does not exceed 0.5 of the less one, the recommended butt work-out is given in Fig. 1.

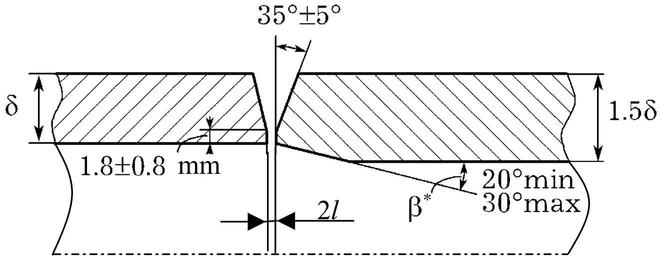

Fig. 1. Work-out of butts for wall thickness δ≤16 mm

The mathematical model for calculation-experimental diagnosing of stresses in welded joints for the case when the difference between thicknesses of the pipe walls does not exceed 3 mm is suggested in [8]. Further, consider the case when the ratio of the wall thicknesses does not exceed 1.5 (Fig. 1). In this case, the pipes of different thicknesses welded by multilayer circumferential welded bead with the work-out of their butts given in Fig.1 are modeled by a circular shell consisting of the parts whose thicknesses are 2 h_l, 2 h_2, and 2 h_0 in the bevel zone of the greater thickness pipe wall (Fig. 2). This shell is referenced to the three-orthogonal coordinate system α, β, γ, where $\alpha = z / R_l$; z is the coordinate along the shell axis; R_l is the radius of the median surface of $2h_l$ – thick shell; β is the angular coordinate; γ is the coordinate along the onter normal to the median surfaces of the constituent parts of the different thickness shell; z^* is the coordinate describing the situation of the right butt of the intermediate thickness shell. This coordinate is expressed in terms of the difference of the pipes walls thicknesses, bevel angle β^* of the work – out of the greater thickness wall, and the clearence width $2l$ as follows $z^* = l + 2(h_2 - h_1)\cot\beta^*$.

After analising known from literature references data on the distribution of caused by residual plastic deformations in the welded joint zone (obtained by calculation and experimental methods),the expressions of the localized near the bead circumferential $e^{0}_{\beta\beta}$ and axial $e^{0}_{\alpha\alpha}$ non-compartible residual deformations which cause residual stresses are given in the form

$$e^0_{ll}(\alpha,\gamma)=\begin{cases} e^{01}_{ll}(\alpha,\gamma), & \alpha\le 0;\\ e^{02}_{ll}(\alpha,\gamma), & \alpha\ge 0;\end{cases}\qquad l=\alpha,\beta. \tag{1}$$

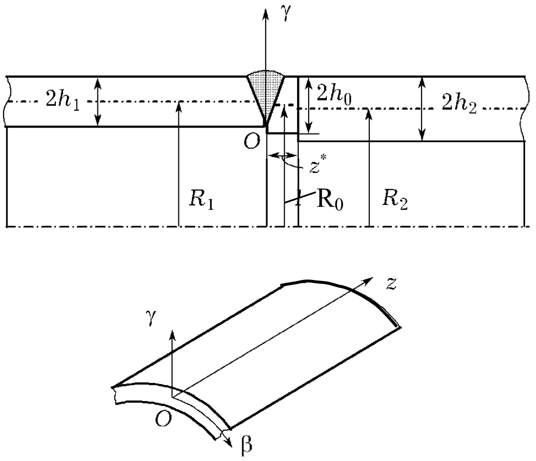

Fig. 2. Axial section of different thickness shell

Here $e^{0j}_{\beta\beta}(\alpha,\gamma)=-\mathbf{E}^*_{1j}\,f_{1j}(\gamma)\,\varphi_{1j}(\alpha)\,S^0_{1j}(\alpha)$, $e^{0j}_{\alpha\alpha}(\alpha,\gamma)=-\mathbf{E}^*_{2j}\,f_{2j}(\gamma)\,\varphi_{2j}(\alpha)\,S^0_{2j}(\alpha)$, (2)

where $$f_{ij}(\gamma)=1-m_{ij}\left(1-\frac{\gamma}{h_i}\right)^2,$$

$$\varphi_{ij}(\alpha)=1+s_{ij}\frac{\alpha^2}{\alpha^2_{ij}}-(3+2s_{ij})\frac{\alpha^4}{\alpha^4_{ij}}+(2+s_{ij})\frac{\alpha^6}{\alpha^6_{ij}},\quad i,j=1,2,$$

S^0_{ij} are the unit step functions: $S^0_{ij}(\alpha)=1$ for $|\alpha|\le|\alpha_{ij}|$; $S^0_{ij}(\alpha)=0,\ |\alpha|\ge|\alpha_{ij}|$ ($j=1$ for $\alpha\le 0$; $j=2$ for $\alpha\ge 0$); $\mathbf{E}^*_{1j}$, m_{ij}, S_{ij} are numerical parameters; $\alpha_{ij}=z_{ij}/R_1$, z_{ij} are coordinates of zone boundary of circumferential $e^0_{\beta\beta}$ and exial $e^0_{\alpha\alpha}$ deformations. With this, having denoted $m_{11}=m_1$, $m_{21}=m_2$, from the condition of continuity of these deformations with pipe thickness we establish the following relations between the parameters m_{ij}:

$$m_{12}=y_0^2m_1,\ m_{22}=y_0^2m_2,\ y_0=h_0/h_1,\ \text{if } z\le z^*$$
$$\text{and } m_{12}=y_2^2m_1,\ m_{22}=y_2^2m_2,\ y_2=h_2/h_1,\ \text{if } z\ge z^*.$$

The graphs the functions $\varphi_1(\alpha)=\varphi_{11}(\alpha)S^0_{11}(\alpha)+\varphi_{12}(\alpha)\times S^0_{12}(\alpha)$ and $\varphi_2(\alpha)=\varphi_{21}(\alpha)S^0_{21}(\alpha)+\varphi_{22}(\alpha)S^0_{22}(\alpha)$ for some values of parameters are given in Fig. 3., Fig. 4.

The application of Kirhhoff – Love hypotheses of classical theory of shells (in particular, the hypothesis of non-compression of fibers $\sigma_{jj} = 0$) enables us to obtain key equations for determining the function of deflection $w_3(\alpha)$ [9] in the form

$$\left(\frac{d^4}{d\alpha^4} + 4\lambda_i^4\right) w_i = -2R_i\, \mathbf{E}_1^* \left[2\lambda_i^4\left(1 - \frac{4}{3} y_i^2 m_1\right) - \mu\, y_i^2 m_1 \frac{R_i}{h_i}\right] \varphi_{1i}(\alpha) S_{1i}^0(\alpha) +$$

$$+2\mathbf{E}_2^*\, y_i^2\, m_2 \frac{R_i^2}{h_i} \frac{d^2}{d\alpha^2} \varphi_{2i}(\alpha)\, S_{2i}^0(\alpha)\ , \qquad (3)$$

where $\lambda_i^4 = 3R_i^2(1-\mu^2)\big/(4h_i^2)$; μ – Poiesson coefficient.

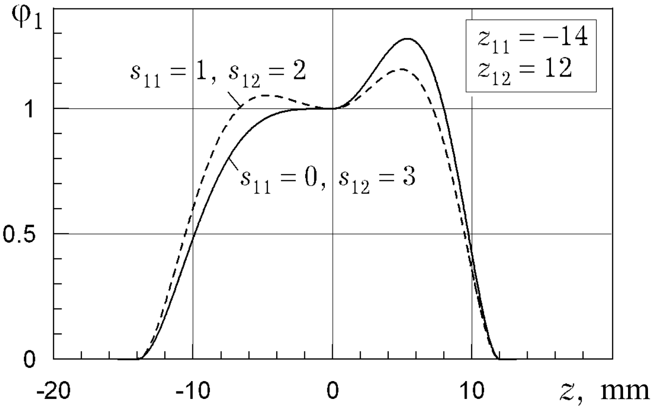

Fig. 3. Graphs of the function $\varphi_1(\alpha)$

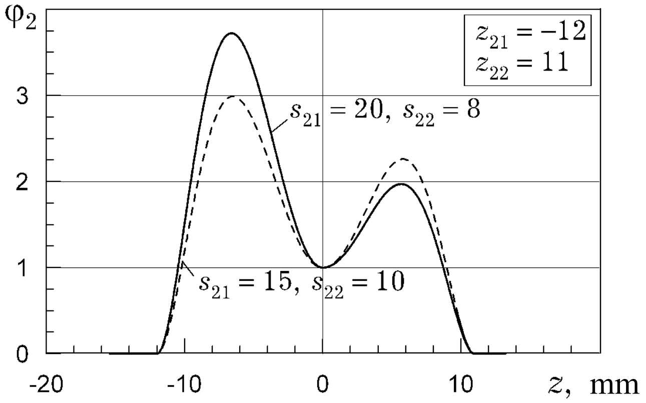

Fig. 4. Graphs of the function $\varphi_2(\alpha)$

Having used the fundamental solution of these equations and having applied operation of convolution [10], we obtain partial solutions and expressions for the functions $w_i(\alpha)$

$$\overline{w}_i(\alpha) = \Lambda_i(\alpha) - \lambda_i \left\{ \frac{1}{2}\left(1 - \frac{4}{3} y_i^2 m_1\right) F_{11}^{(i)}(\alpha) + \frac{y_i^2}{\sqrt{3(1-\mu^2)}} \left[\mu\, m_1 F_{21}^{(i)}(\alpha) + k\, m_2 F_{22}^{(i)}(\alpha)\right] \right., \quad (4)$$

where $A_i(\alpha)$ are the solutions of the homogeneous equations, and F_{11}, F_{21}, F_{22} are integral characteristics of non-compartible deformations field.

The expressions for axial $\sigma_{\alpha\alpha}$ and circumferential $\sigma_{\beta\beta}$ residual stresses in an arbitrary point of the welded bead zone of the pipe can be written as follows

$$\hat{\sigma}_{\alpha\alpha}^{(i)}(\alpha,\gamma) = -\sqrt{\frac{3}{1-\mu^2}}\frac{R_1}{R_i}\frac{\gamma}{h_i}\Omega_i(\alpha) + \frac{\lambda_i}{1-\mu^2}\frac{\gamma}{h_i}\left[-\frac{\sqrt{3(1-\mu^2)}}{2}\left(1-\frac{4}{3}y_i^2 m_1\right)F_{21}^{(i)}(\alpha) + \right.$$

$$\left. + y_i^2 \mu\, m_1 F_{11}^{(i)}(\alpha) + y_i^2 k\, m_2 F_{12}^{(i)}(\alpha)\right] + \frac{y_i^2}{1-\mu^2}\times$$

$$\times\left(\frac{1}{3}-\frac{\gamma^2}{h_i^2}\right)\left[\mu\, m_1 \varphi_{1i}(\alpha) S_{1i}^0(\alpha) + k\, m_2 \varphi_{2i}(\alpha) S_{2i}^0(\alpha)\right],$$

$$\hat{\sigma}_{\beta\beta}^{(i)}(\alpha,\gamma) = \frac{R_1}{R_i}\bar{w}_i(\alpha) + \mu\,\hat{\sigma}_{\alpha\alpha}^{(i)}(\alpha,\gamma) + \left[1 - y_i^2\left(1-\frac{\gamma}{h_i}\right)^2\right]\varphi_{1i}(\alpha) S_{1i}^0(\alpha), \tag{5}$$

where

$$\hat{\sigma}_{ij}(\alpha,\gamma) = \sigma_{ij}(\alpha,\gamma) \big/ (E\mathbf{E}_1^*),$$

$$\Omega_1 = -A_{11}\omega_{21}(\alpha) + A_{21}\omega_{11}(\alpha),\ \Omega_2 = A_{12}\omega_{22}(\alpha) - A_{22}\omega_{12}(\alpha),$$

$$\Omega_0 = -B_1\omega_{40}(\alpha) + B_2\omega_{30}(\alpha) - B_3\omega_{20}(\alpha) + B_4\omega_{10}(\alpha),$$

$$\varphi_{j1}(\alpha) = \varphi_{j2}(\alpha),\ S_{j0}^0(\alpha) = S_{j2}^0(\alpha),\ j = 1,2,$$

where A_{ji} $(i,j=1,2)$ and $B_l\left(l = 1-4\right)$ are constants integration.

In Expressions (5), numerical parameters $\mathbf{E}_1^*$, k, m_i, s_{ij}, α_{ij} $(i,j=1,2)$, characterising non-compartible residual deformations e_{ii}^0 $(i=\alpha,\beta)$ can take different values. To determine them while calculating stresses in specific welded joints, experimental information on residual stresses or their average characteristics have been used. Such information can be obtained by non-destructive methods [11].

For experimental evaluating of pipeline stressed state, electromagnetic and ultrasonic methods [11] are used most of all. With this, according to measured data from electromagnetic method , average (over a certain zone of outer surface of the pipe under the transformar-like transducer) difference between principal stresses σ_+^E, and the difference of principal stresses over the whole thickness of the pipe under the surface of its contact with piezelectric transducer are determined by ultrasonic method. Developed by Ye. Paton Institute of Electrowelding of Ukrainion Academy of Sciences method of holographic speckle-interferometry which is a modification of Matar's method is of prospect. Using "ECI – OH1001" – small size interferometer, principal residual stresses $\sigma_{\alpha\alpha}^E$, $\sigma_{\beta\beta}^E$ on the surface of a welded joint are determined [12]. Having used Formula (5) for calculating axial and circumferential stresses in an arbitrary point of the pipe, expressions for average characteristics σ_+^T, and σ_0^T which are being obtained on the basis of experimental data are received [8].

For, determine the parameters $\mathbf{E}_1^*, k, m_i, s_{ij}, \alpha_{ij}$ we make up a functional which is the measure of the agreement of calculated characteristics of the stressed state with the experimental data [9]. Minimizing the functional, we find the values of the parameters $\mathbf{E}_1^*, k, m_i, s_{ij}, \alpha_{ij}$ at which the divergence between the experimental and the theoretical characteristics of stressed state is mimimal. After this, according to Formulae (5), we calculate residual stresses in an arbitrary point of the pipe, in particula, these which cannot be obtained experimentally.

3. DETERMINATION OF RESIDUAL STRESSES IN DIFFERENT THICKNESS CIRCUMFERENTIAL WELDED JOINTS IN PIPELINE

To aprobate the proposed method, appropriate equipment has been developed (Fig.5). This testing set-up consistes of the reservoir 1 which is made of two pipes (of 17G1C steel) which are connected by the welded joints with welded spherical bottoms at the butt ends. To create necessary pressure in the reservoir, a pump is used that pushes fluid, for example water, from the expansion tank 2. Pressure in the reservoir is controlled by means of electrical manometer 3. The measuring equipment also consists of foil strain gauge 4, hardware/software system Uni Lab 5, matching device 6, strain measurement station 7, and personal computer 8.

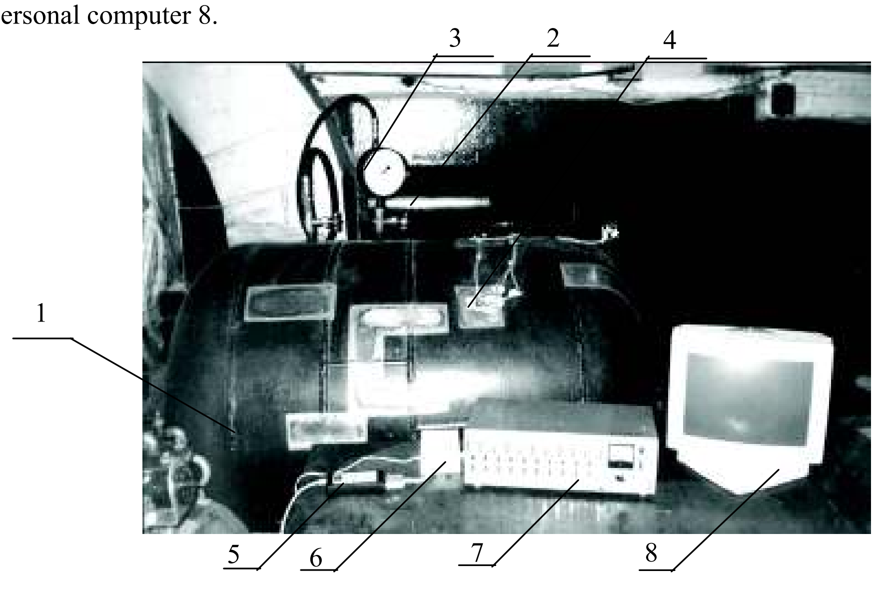

Fig. 5. Experimental set-up for modeling stress state in welded pipeline joints

Stress in different parts of the reservoir including welded joints is determined by means of calculation, “SMMT-3” and “MESTR-411” electromagnetic devices and electro-strain-measurement methods. The developed methodology gives the opportunity of checkout and calibration of the measuring equipment which is used for determination of stresses in the critical parts of the existing pipelines.

For the welded by multilager circumferential welded bead pipes 1020 mm in diameter and with thichnesses $2h_1 = 10\,\text{mm}$, $2h_2 = 14\,\text{mm}$, for characteristic distributions of residual non-compartible deformations $e^0_{\alpha\alpha}$ and $e^0_{\beta\beta}$ discribed by Expessions (1) and (2), circumferential $\sigma_{\beta\beta}$ and axial $\sigma_{\alpha\alpha}$ stresses are calculated. Measuring stressed state in industrial the pipeline is done by "MESTR-411" device. According to Formulae (5), circumferential $\sigma_{\beta\beta}$ and axial $\sigma_{\alpha\alpha}$ stresses are calculated. Numerical calculation for the values of parameters z_{ij} and s_{ij} $(i, j = 1,2)$ which are given in Fig. 6, Fig. 7 have been carried out. The material of the pipes is 17G1C steel ($E = 2 \cdot 10^5$ MPa), μ=0,3 bevel angle $\beta^* = 25°$, $z^* = 10\,\text{mm}$.

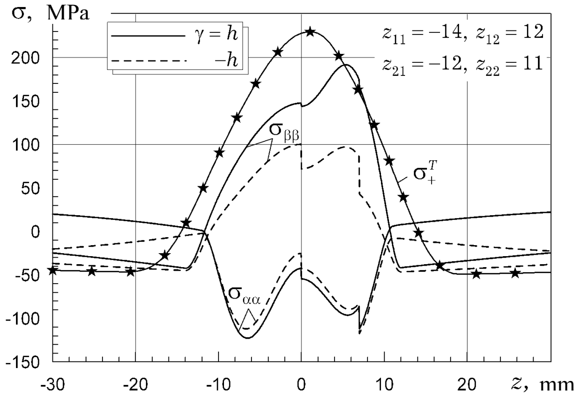

Fig. 6. Distribution of circumferential and axial residual stresses in zone of the welded jont: $s_{11} = 0,\ s_{12} = 3,\ s_{21} = 20,\ s_{22} = 8,\ m_1 = 0.0625,\ m_2 = 0.10$

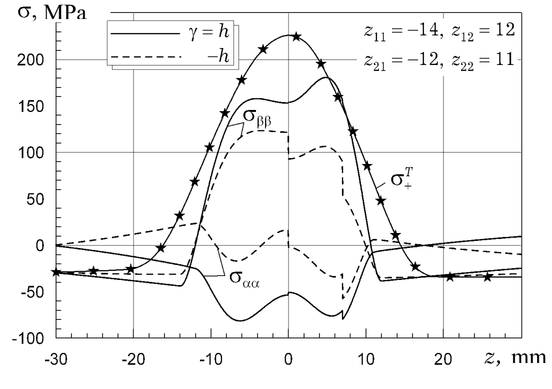

Fig. 7. Distribution of circumferential and axial residual stresses in zone of the welded jont: $s_{11} = 1,\ s_{12} = 2,\ s_{21} = 15,\ s_{22} = 10,\ m_1 = 0.0625,\ m_2 = 0.05$

The distribution of residual stresses in the welded bead zone on the outer (solid curves) and inner (dash curves) surfaces of the pipe is graphically shown in Fig. 6., Fig. 7. As it is seen from the graphs, the circumferential tensile stresses $\sigma_{\beta\beta}$ are maximal on outer surfaces of pipes near the welded bead, and with the increase in distance from its axis, they become compressive. The average difference between principal stresses σ_{+}^{T} which for $r_0 = 8$ mm is shown by the curves with asterisks (★) in Fig. 6., Fig. 7 may essentially exceed maximal circumferential stresses on outer surfaces of pipes near the bead.

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