3. The experimental procedure was developed, on the basis of which the hardware-measuring complex was assembled to investigate the effect of charge voltage at EDT on such parameters as amplitude values of pulsed current I and dynamic loading P.

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RISK OF FAILURE IN THINNING OF MAIN PIPELINE WALL AT THE AREA OF CIRCUMFERENTIAL WELDS IN THE PRESENCE OF BENDING MOMENTS ALONG THE PIPELINE AXIS

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The effect of longitudinal bending moment in pipeline with a wall thinning defect of large overall size in circumferential direction on the risk of failure is considered. It is shown that the critical sizes of thinning in circumferential direction can be determined with a certain conservatism on the basis of total nominal stresses induced by bending and internal pressure in pipeline.

Keywords: *main pipelines, critical sizes of defects of wall thinning, effect of bending moment, risk of failure, Weibull distribution*

Allowable overall size c of defects of thinning along the pipe circumference is much larger than that of s along the generatrix in pipeline loading with internal pressure P that is due to a large extent to higher circumferential normal stresses $\sigma_{\beta\beta}$, as compared with axial ones σ_{zz}, at other things being equal, that is demonstrated visually by the typical diagrams of limiting overall sizes c and s, given in work [1].

However, the thinning with high c values can be rather often observed under loading conditions when alongside with internal pressure P in the zone of thinning the bending moment $M_{\rm bend}$ is acting, caused by soil settling down (for underground pipeline) or wind load at certain air transitions, etc. The nominal stresses at such loading can noticeably change in the zone of a defective area of the pipeline wall.

There is a relationship for points in section $\beta \le 0$ for nominal longitudinal stresses σ_{zz} in pipeline with internal pressure P and bending moment $M_{\rm bend}$, acting in longitudinal plane $\beta = 0$, assuming the presence of pure elastic deforming and preserving the shape of pipe transverse sections:

$$\sigma_{zz} = \frac{PR}{2\delta} + \frac{M_{\rm bend}\cos\beta}{\pi R^2\delta}\left(1 + \frac{\xi}{R}\right), \qquad (1)$$

where R is the internal radius of pipeline; δ is the wall thickness ($-\delta/2 < \xi < \delta/2$).

Relationship (1) can be presented in the form of

$$\sigma_{zz} = \frac{PR}{2\delta}\,[1 + \kappa(\beta)],$$

where $\kappa(\beta) = \dfrac{2M_{\rm bend}\cos\beta}{\pi R^3 P}(1 + \xi/R)$ determines the addition, due to $M_{\rm bend}$, to nominal stresses σ_{zz}, caused only by pressure in pipeline. If the defect of thinning is located so that $\beta = 0$ is in the middle of the defect length c and $c/2R < 0.1\pi$, then the membrane stresses in this zone prevail for all the β inside the interval

$-0.1\pi < \beta < 0.1\pi$ $\cos\beta \approx 1.0$ and at $\delta/R < 0.1$. Consequently, when determining the critical sizes c_{cr} of defects for these cases it is possible to come from total nominal stresses σ_{zz}, acting in the zone $(-c/2 < \beta < c/2)$ or from the given pressure

$$P_{giv} = P(1 + \kappa)...$$

Thus, on the basis of relationships indicated in work [1], as applied to critical overall sizes of defects of thinning (c_{cr} — along the circumference, s_{cr} — along the generatrix, and $a_{cr} = \delta - \delta_{min}$ in wall depth)

$$c_{cr} = 2R\sqrt{\frac{0.7358 + K_c}{10.511 - 13.838K_c}}, \qquad (2)$$

where $K_c = \delta_{min}/[\delta]$; $[\delta] = P_{giv}R/[\sigma]$; δ_{min} is the minimum thickness of wall in defect zone; $[\sigma]$ are the allowable stresses for pipe material at the given area. Relationship (2) is valid for K_c within $0.2 < K_c < 0.7596$.

At $K_c < 0.7596$, $c_{cr} \to \infty$, at $K_c < 0.2$, $c_{cr} = 0.694R$. Value of s_{cr} (overall size of defect along the generatrix, negligibly reacting to a bending moment) is determined traditionally by an operating pressure P_{op}, i.e. at $\kappa = 0$

$$s_{cr} = \lambda_{cr}\sqrt{2R[\delta]}\,\frac{1}{1.285},$$
$$\lambda_{cr} = 1.299\sqrt{\left(\frac{1.0 - K_s}{0.9 - K_s}\right)^2 - 1.234},\ K_s = \frac{\delta_{min}}{P_{op}R}[\sigma]. \qquad (3)$$

Acceptability of effect of approximation approach of account for bending moment on critical sizes c_{cr} of defect of thinning was studied in this work on the basis of analysis of three-dimensional stressed state in the zone of defect of thinning for pipe steel with yield strength $\sigma_y = 480$ MPa, tensile strength $\sigma_t = 564$ MPa, modulus of elasticity $E = 2 \cdot 10^5$ MPa, Poisson's factor $\nu = 0.3$.

Figure 1 shows a pipeline element, cut out by coordinate planes $\beta = 0$, $z = 0$, $\beta = \beta_*$ and $z = z_*$, with external defect of wall thinning of an ellipsoid type, whose planes of symmetry coincide with planes $z = 0$ and $\beta = 0$. In plane $\beta = \beta_*$ the stresses $\sigma_{\beta\beta} = PR/\delta$ and $\sigma_{\beta z} = \sigma_{\beta r} = 0$ are acting, in plane $z = z_* - \sigma_{zz} = P_{giv}\dfrac{R\cos\beta}{2\delta}$ and $\sigma_{rz} = \sigma_{\beta z} = 0$, while in planes $\beta = 0$ and $z = 0$ the symmetry conditions are valid: the conditions of free surface are on internal surface $r = R$, $\sigma_{rr} = -P$ and $\sigma_{r\beta} = \sigma_{rz} = 0$, on the external surface $- r = R + \delta(z, \beta)$.

All the examined area was divided into separate finite elements (Figure 2), formed by orthogonal surfaces of a cylindrical system of coordinates, i.e. $r = \text{const}$, $\beta = \text{const}$, $z = \text{const}$. Eight node points, obtained by crossing these surfaces, determine the calculation volume $\Delta V_{m,n,k}$ of each of finite elements,

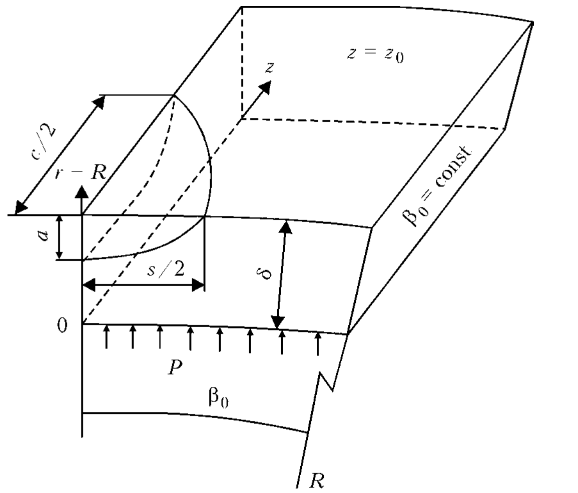

Figure 1. Region of pipeline $2R \times \delta$ in the zone of defect of thinning $c \times s \times a$, confined by surfaces $z = 0$, $z = z_*$, $\beta = 0$, $\beta = \beta_*$, $r = R$ and $r = R + \delta(z, \beta)$

for which the appropriate components of tensor of increment of deformations $\Delta\varepsilon_{ij}$ in the system of coordinate $i, j = r, z, \beta$ are expressed through components of vector of increments of displacements in the following way for the model of a finite element:

$$\Delta\varepsilon_{rr} = \frac{\Delta U_{m,n,k} - \Delta U_{m-1,n,k}}{r_{m,n,k} - r_{m-1,n,k}},$$
$$\Delta\varepsilon_{\beta\beta} = \frac{\Delta U_{m,n,k}}{r_{m,n,k}} + \frac{\Delta V_{m,n,k} - \Delta V_{m,n-1,k}}{(r\beta)_{m,n,k} - (r\beta)_{m,n-1,k}},$$
$$\Delta\varepsilon_{zz} = \frac{\Delta W_{m,n,k} - \Delta W_{m,n,k-1}}{z_{m,n,k} - z_{m,n,k-1}},$$
$$\Delta\varepsilon_{r\beta} = \frac{1}{2}\left[r_{m,n,k}\frac{(\Delta V/r)_{m,n,k} - (\Delta V/r)_{m-1,n,k}}{r_{m,n,k} - r_{m-1,n,k}} + \frac{\Delta U_{m,n,k} - \Delta U_{m,n-1,k}}{(r\beta)_{m,n,k} - (r\beta)_{m,n-1,k}}\right], \qquad (4)$$
$$\Delta\varepsilon_{z\beta} = \frac{1}{2}\left[\frac{\Delta V_{m,n,k} - \Delta V_{m,n,k-1}}{z_{m,n,k} - z_{m,n,k-1}} + \frac{\Delta W_{m,n,k} - \Delta W_{m,n-1,k}}{(r\beta)_{m,n,k} - (r\beta)_{m,n-1,k}}\right],$$
$$\Delta\varepsilon_{rz} = \frac{1}{2}\left[\frac{\Delta U_{m,n,k} - \Delta U_{m,n,k-1}}{z_{m,n,k} - z_{m,n,k-1}} + \frac{\Delta W_{m,n,k} - \Delta W_{m-1,n,k}}{r_{m,n,k} - r_{m-1,n,k}}\right].$$

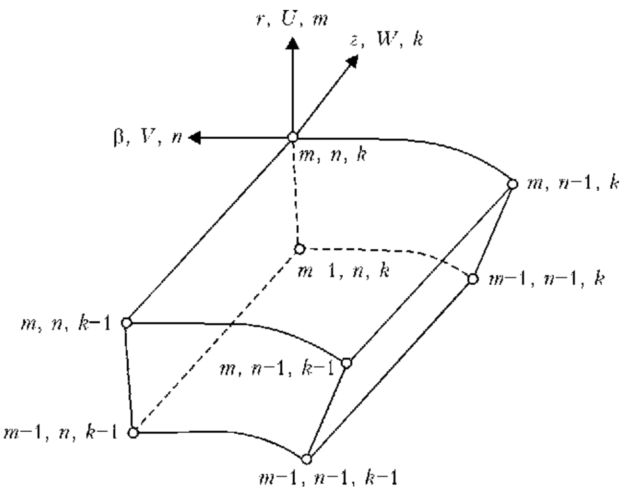

Figure 2. Scheme of finite element in system of coordinates β, z, r with appropriate displacements U, V, W and numeration of nodes m, n, k

The link of components of tensor $\Delta\varepsilon_{ij}$ with components of stress tensor σ_{ij} is realized on the basis of theory of elastic-plastic yielding of Prandtl–Reiss, associated with a yielding condition of Mises, i.e. the following relations given in work [2] are valid:

$$\Delta\varepsilon_{ij} = [\psi(\sigma_{ij} - \delta_{ij}\sigma) + \delta_{ij}K\sigma] - b_{ij} \quad (i, j = z, r\beta),$$

where ψ is the function of material state in finite element m, n, k; δ_{ij} is the unit tensor (Kronecker symbol); $\sigma = \frac{1}{3}(\sigma_{rr} + \sigma_{zz} + \sigma_{\beta\beta})$; $K = \frac{1 - 2\nu}{E}$; b_{ij} is the known function of stresses obtained at the previous step of observing the elastic-plastic deformations (denoted by index*):

$$b_{ij} = \left[\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G} + \delta_{ij}K\sigma\right]^*.$$

Function of state ψ is determined at each step of observation coming from the condition of yielding, i.e.

$$\psi = \frac{1}{2G}, \text{ if } f = \sigma_{eq}^2 - \sigma_y^2 < 0, \qquad \psi > \frac{1}{2G}, \text{ if } f = 0 \text{ and } \Delta f > 0, \tag{5}$$

where $\sigma_{eq} = -\sqrt{\frac{1}{2}(\sigma_{ij} - \delta_{ij}\sigma)(\sigma_{ij} - \delta_{ij}\sigma)}$; σ_y is the yield strength of material with account for work hardening, obtained at the previous step of observation; condition $f > 0$ is inadmissible.

Increments of components of tensor of plastic deformations at each step of observation are determined by the following relationships:

$$\Delta\varepsilon_{ij}^p = \left(\psi - \frac{1}{2G}\right)(\sigma_{ij} - \delta_{ij}\sigma) \quad (i, j = r, z, \beta).$$

Significant non-linearity, contained in conditions (5), is realized by iteration. An appropriate algorithm of iteration process is offered in work [2] and tested well enough in practice [3].

Components of stress tensor for each finite element (m, n, k) are connected with appropriate components in neighboring volumes or at the boundary surfaces by equilibrium equations.

Resolving system of algebraic equations relative to three components of vector of increments of displacements in each node (m, n, k) is formed at each step of observation and iteration by ψ as a result of minimizing of functional

$$E = -\frac{1}{2}\iiint_Q (\sigma_{ij} + Y_{ij})\Delta\varepsilon_{ij} r dr d\beta dz + \int_\Gamma q_i \Delta U_i$$

by unknown increments of displacements

$$\Delta U_i = \begin{vmatrix} \Delta U \\ \Delta V \\ \Delta W \end{vmatrix},$$

where Q is the volume of examining area with boundary Γ, in which the components of power load q_i ($i = r, \beta, z$) are preset:

$$Y_{ij} = \frac{1}{\psi}\left(\frac{\sigma_{ij} - \delta_{ij}\sigma}{2G}\right)^* + \delta_{ij}\frac{(K\sigma)^*}{K} \quad (i, j = r, \beta, z).$$

At a very small step of observation, when the linear relations are valid (4), the given algorithm allows accounting for the large deformations by means of displacement of nodes U, V, W (by specifying coordinates of nodes r, β, z in expression (4)). Here, the change in volumes of finite elements, indicated in coefficients of resolving equations, occurs only due to elastic deformations, i.e. it is negligible up to failure of integrity and can be neglected.

After receiving the data on kinetics of stress-strain state in the zone of thinning with the growth of P and M_{bend}, it is important to solve the problem concerning the model of integrity failure, as the traditional approach, based on maximum stresses in one separate point (element), is much conservative, in particular with account for a real shape of surface in the zone of a corrosion thinning.

The Weibull probabilistic approach, based on fault probability α at least in one point of «hot section» S_j in the zone of thinning, is worthy of attention, i.e.

$$\alpha = 1 - \exp\left\{-\int_{S_j}\left[\left(\frac{\sigma_{jj} - A}{B_j}\right)^\eta\right]\right\}\frac{dS_j}{h_0^2} \quad (\sigma_{jj} > A).$$

Here, σ_{jj} (normal stresses in section with a normal j) and A, B, η (parameters of Weibull distribution) are determined on the basis of processing the appropriate experimental data.

It is possible to assume $\eta = 4.0$, $A = \frac{\sigma_t + \sigma_y}{2}$. The h_0 value is the geometric characteristic of a finite element in the zone of defect of thinning, at which the further decrease in sizes of the finite element does not influence the σ_{jj} value, B is determined on the basis of experimental critical sizes s_{cr} at $j = \beta$ or c_{cr} at $j = z$ (relationships (2), (3) at assumption that $\alpha =$

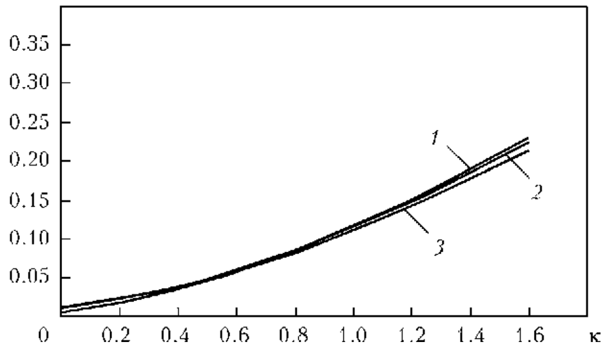

Figure 3. Results of calculation of failure probability depending on κ values at B_z from the Table at different a of 10 (*1*), 12 (*2*) and 14 (*3*) mm at $D = 1420$ mm, $\delta = 18$ mm, $P = 7.5$ MPa and $A = 522$ MPa)

Results of calculation of parameter B_j and appropriate α_j at P_{op} = 7.5 MPa

a, mm	B_z, MPa	c_{cr}, mm (α = 0.05)	α	B_β, MPa	s_{cr}, mm (α = 0.05)	α_β
10	4980	840	0.00514	970	126	0.0099
12	5270	650	0.011	840	90	0.0066
14	4995	530	0.0112	525	66	0.0029

= 0.05, and the test pressure in pipe $P_{test} = 1.2P_{op}$ for $j = \beta$ and $P_{test} = 1.47P_{op}$ for $j = z$ and $w = 0$.

In accordance with these recommendations the values of B_j are determined for the examining pipe at h_0 = 2 mm, A = 522 MPa and different depths a of the defect.

It is seen from these data that increase in depth of the defect in the ranges of $10 \le a \le 14$ mm decreases the critical values of c_{cr} from 840 to 530 mm. However, in this case the B_z value is changed in relatively narrow ranges, such as 4980–5270 MPa, but not monotonously.

It is seen from Figure 3 that the curves of effect κ are arranged well enough on one curve at $P_{op}(1 + \kappa)$ = 1.47 MPa; α = 0.05, i.e. the bending here adds mainly the membrane stresses in section $z = 0$. The use of average B_z value for different a, as shown in Figure 4. without changing the quality pattern, gives quantitatively somewhat other results. It is characteristic that the presence of bending moment has a low influence on the risk of failure due to longitudinal size s of wall thinning.

The risk of failure α_β for a = 14 mm, $s = s_{cr}$ = = 66 mm, P_{op} = 7.5 MPa at different κ values is the following:

κ	0	0.2	0.4	0.6	0.8	1.0
α_β	0.0029	0.0033	0.0040	0.0034	0.0026	0.0018

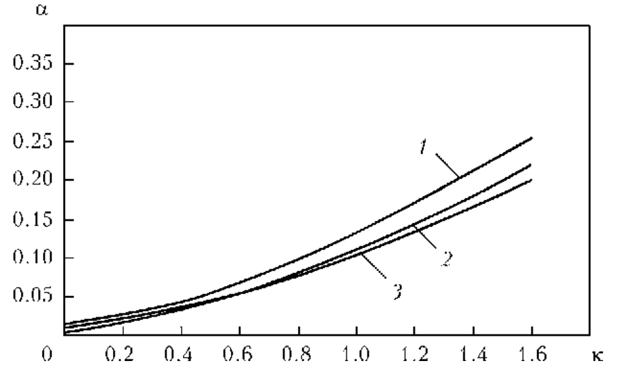

Figure 4. Results of calculation of effect of bending moment at c_{cr} from the Table for different a of 10 (*1*), 12 (*2*) and 14 (*3*) mm at D = 1420 mm, δ = 18 mm, P = 7.5 MPa, A = 522 MPa and B_z = = 5080 MPa

CONCLUSIONS

1. It is shown that in evaluation of critical sizes s_{cr} and c_{cr} of defects of thinning of main pipeline wall in the presence of longitudinal bending moments, caused by soil settling, wind load, etc., it is possible to apply the recommendations of work [1] for s_{cr}, i.e. relationship (3), as the longitudinal bending moment has a low effect on s_{cr}.

2. For the circumferential overall size c_{cr} of defects of thinning, rather typical of the zone of site circumferential welds, the presence of bending moment can increase greatly the risk of failure. In this case the values of c_{cr} at known values of bending moment M_{bend} and internal pressure P can be evaluated by the relationships given in work [1], i.e. by expression (2) using the given pressure P_{giv}.

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