CALCULATION OF PARAMETERS OF EXPLOSION TREATMENT FOR REDUCTION OF RESIDUAL STRESSES IN CIRCUMFERENTIAL WELDS OF PIPELINES

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Reduction of residual stresses in circumferential welds of pipelines is laborious and expensive process. Explosion treatment as an alternative to heat-treatment provides for significant time and expenses reduction. Experiment-calculation method is developed for determination of modes of explosion treatment of circumferential pipe welds of different dimension-type. The method is based on application of general form dependence of deformation of cylindrical shell wall on external static load, obtained in scope of elasticity theory, applicable to solution of problem on determination of value of dynamic load necessary for development of plastic strains, providing reduction of residual stresses in circumferential pipe welds. Dependences for calculation of main parameters of explosion treatment are derived based on this method. Experimental investigations verifying suitability of obtained dependencies for practical application without participation of technology developers were carried out. 13 Ref., 2 Tables, 3 Figures.

Keywords: *explosion treatment, heat treatment, residual stresses, deformations, circumferential weld, pipelines*

Residual welding stresses (RS) from circumferential welds can significantly reduce working capacity of the pipelines operating under low temperature conditions, influence of corrosive medium and other unfavourable factors [1, 2]. Reduction of RS is performed with the help of heat treatment being expensive and laborious technology [3]. Explosion treatment (ET) providing lower prime cost and high efficiency can be an alternative to heat treatment.

ET technology has found wide application in providing of safety and service life of technological pipelines of aluminous production and gas fields with increased content of hydrogen sulphide, providing transportation of corrosive media which promotes cracking of circumferential welds. Unique experience of ET application for prevention of avalanche-like cracking was obtained during laying of Taas-Tumus-Yakutsk gas pipeline, on which 295 erection joints made by manual arc welding under field conditions were treated. Absence of damages on treated joints of the gas pipeline, including under extremely severe winter conditions, shows efficiency of application of ET structures operating under low temperatures. Obvious advantage of ET compared to heat treatment is an absence of necessity of application of special equipment and power sources. The technology can be used not only in pipeline assembly, but in performance of on-line tasks on repair and replacement of damaged sections.

On-line selection of modes of ET of circumferential pipe welds has important practical value, in particular, when its accuracy provides selection of modes close to optimum ones allowing eliminating expensive experimental investigations.

Considered are the peculiarities of ET process using charges representing them self specific quantity of winds of explosive cord (EC) located on outer surface of the pipe close to weld. Figure 1, *a* shows generalized diagram of elastic tangential strains of pipe wall from circumferential weld. Loading from explosion effect in accepted scheme is considered equal to distributed one and should be applied to zone of compression RS effect [4] (area AB, Figure 1, *b*). Cross section of the charge from EC is shown in Figure 1, *c* in form of circles.

Unique determination of ET mode of circumferential weld of pipe of known dimension-type requires searching of charge mass m, charge width a and distance from axis of treated circumferential weld to end of charge b nearest to it [b]. Value of pipe wall deformation created by explosion is determined by mass of charge, therefore, selection of latter should depend on pipe deformation resistance, i.e. on cylindrical rigidity (geometric parameters) and material yield strength. Location of created deformations is determined by charge parameters a and b.

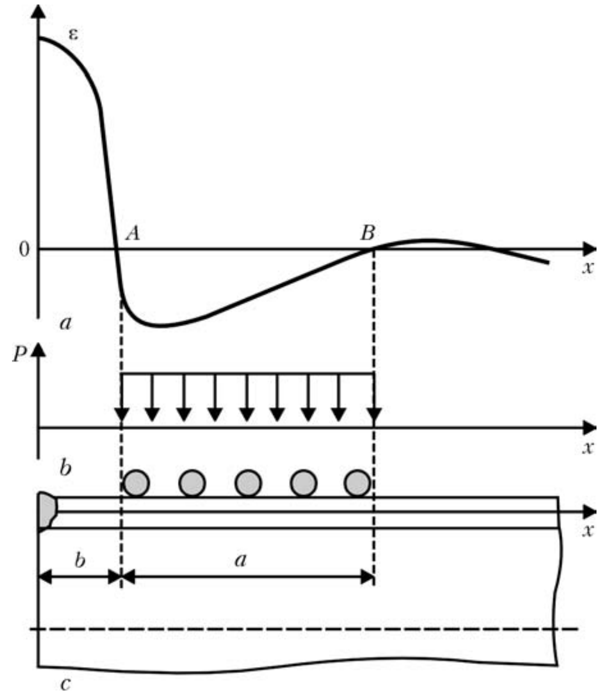

Figure 1. Scheme of charge positioning during ET: *a* — general diagram of tangential residual elastic strains; *b* — distribution of loading from explosion; *c* — positioning of charge from EC

There are analytical as well as numerical methods of solving of dynamic problems [6, 7]. These methods and form of representation of solutions obtained with their help are, as a rule, very bulky and difficult, and require application of precising experiments in each specific case. It is reasonable to develop sufficiently easy method allowine for on-line calculation of optimum values of ET parameters for circumferential welds of pipes of different dimension-types using existing results of calculation investigations and accumulated experience of practical methods of selection of charge parameters.

Considering that circumferential stresses (operational and welding) in pipelines are, as a rule, significantly higher of axis ones, and that ET obviously results in reduction of axial welding residual stresses [7], present paper studies distribution of only circumferential RS in welds.

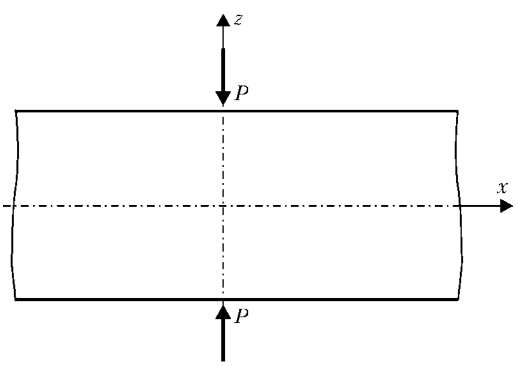

Figure 2. Scheme of calculation of charge width for ET of circumferential pipe weld: *P* — distribution of load on circle; *x* — distance along the generatrix of pipe from place of load application

Calculation of charge width. The reason of appearance of residual deformations and stresses in welded joint is formation of plastic shortening strain in the process of welding heating, width of which is indicated as b_p. The charge width a should be so as to provide deformation of pipe wall in zone of formation of elastic welding contraction strains, i.e. equal the width of $[AB]$ area (Figure 1). Therefore, ET parameter b should equal b_p, position of point A corresponds to $x = b_p$ coordinate, position of point B is determined by coordinate of transfer into zero of diagram of elastic welding contraction strains. Further, increase of charge width will not result to significant increase of ET efficiency, although provide no negative consequences, except for over-expenditure of EC and time for charge assembly.

Practice of RS measurement in pipes shows that width of this zone even for pipes of one dimension-type can be different since it depends on conditions of welding of circumferential weld, conditions of pipe manufacture, measurement error and other factors. At the same time, multiple experiment investigations and industrial application of ET indicate that applied ET scheme provides for high efficiency even at some deviations of selected charge width from that accepted in considered scheme. This testifies that accuracy of calculation data can be leveled by random factors which couldn't be considered in the calculation model even with the most well-set problem.

In this connection the simplest scheme for calculation of width of zone of compression strain is taken.

Influence of weld on the rest of pipe will be modeled based on external contraction load P (Figure 2) uniformly distributed on circumference of pipe cross section and concentrated in direction of longitudinal axis x. Symbolically $b_p = 0$ is taken at such statement of problem.

Equation of defected axis of shell for present case takes on the following form [8]:

$$w = 0.125Pe^{-\beta x}(\sin\beta x + \cos\beta x)/D_\beta\beta^3, \qquad (1)$$

where $\beta = [3(1 - \nu^2)/R^2h^2)]^{0.25}$ is an auxiliary geometric parameter of the pipe; ν is a Poisson's ratio; R is a radius; h is a thickness; $D_\beta = Eh^3/12(1 - \nu^2)$ is a cylindrical rigidity of the shell; E is a modulus of elasticity of steel of pipe being treated.

Width of ET charge is determined on coordinate x, at which $w = 0$:

$$\sin\beta x + \cos\beta x = 0.$$

Since only first positive root of equation (1) is interesting for us, it is finally found:

$$a = x\,|_{w = 0} = 0.75\pi/\beta, \qquad (2)$$

or in more simple form

$$a = 1.8\,\sqrt{Rh}\,. \qquad (3)$$

Determination of charge mass. Mass of the charge equal the mass of explosive material (EM) in EC and can be expressed in the following way:

$$m = 2\pi Rnj, \qquad (4)$$

where n is the quantuty of EC winds; j is the portion of EM per unit of length in EC.

Considering that charges for ET of circumferential pipe welds are manufactured from EC which is characterized by sufficiently stable detonating specifics, it can be assumed that dynamic yield strength σ_y^d is proportional to static yield strength σ_y:

$$\sigma_y^d = K\sigma_y. \qquad (5)$$

It is also supposed that data of pipe calculation as elastic static shell will be sufficiently valid in moment of appearance of first plastic strains under the charge regardless the dynamic character of problem being solved.

Let's consider the following problem (Figure 3). Some part of infinitely long pipe with width a is loaded along the circle by uniformly distributed load p (Figure 1, b). Divide this pipe on three parts in $x = 0.5a$ and $x = -0.5a$ sections, and balance their effect on each other by distribution of bending moments M and intersecting forces Q acting in these sections.

Functions of shell bending are found by means of solving of differential equation of symmetric deformation of circular cylindrical shell with constant thickness [8]:

$$\frac{d^4w}{dx^4} + 4\beta^4 w = \frac{p}{D_\beta} \qquad (6)$$

and have form

$$w_1 = e^{-\beta x}(C_1\cos\beta x + C_2\sin\beta x) + e^{\beta x}(C_3\cos\beta x + C_4\sin\beta x) + 0.25p/\beta^4 D_\beta \qquad (7)$$

for the first (central, final length) part of the pipe and

$$w_2 = e^{-\beta(x - 0.5a)}[C_5\cos\beta(x - 0.5a) + C_6\sin\beta(x - 0.5a)] \qquad (8)$$

for the second (right, semiinfinite length) of its part; $C_1 - C_6$ are the unknown coefficients;

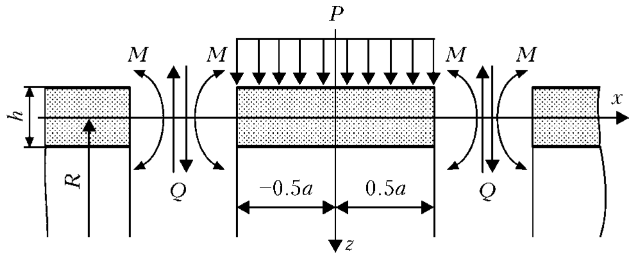

Figure 3. Calculation model for determination of charge value

$0.25p/\beta^4 D_\beta$ is the partial solution of equation (3).

It is determined that $C_3 = C_1$, $C_4 = -C_2$ considering that $w_1(x) = w_2(-x)$.

C_1 and C_2 are determined from condition of equality of bendings, angles of wall turning, moments and intersecting forces of the shells *1* and *2* in point $x = 0.5a$:

$$C_1 = -p\,\frac{1}{8\beta^4 D_\beta k}; \quad C_2 = p\,\frac{tg(0.5\beta a)}{8\beta^4 D_\beta k},$$

where $k = (\cos 0.5\beta a + \mathrm{tg}\,0.5\beta a \sin 0.5\beta a)e^{0.5\beta a}$.

Then

$$w_1 = \frac{p}{8\beta^4 D_\beta k}\,[e^{-\beta x}(-\cos\beta x + \mathrm{tg}\,0.5\beta a\sin\beta x) + e^{\beta x}(-\cos\beta x - \mathrm{tg}\,0.5\beta a\sin\beta x) + 2k]. \qquad (9)$$

Maximum circumferential stresses (at $x = 0$) $\sigma_{\beta\max}$ in the shell can be found on formulae [9]:

$$\sigma_{\beta\max} = N/h + 6vM/h^2;\ N = -Ehw/R;\ M = -D_\beta d^2w/dx^2,$$
$$\sigma_{\beta\max} = \frac{pR}{hk}\,[1 - k - \frac{3v\,\mathrm{tg}\,0.5\beta a}{\sqrt{3(1 - v^2)}}] = pf(R, h, a), \qquad (10)$$

where $f(R, h, a)$ is a function determined only by geometry parameters of the pipe and loading scheme.

The next reasons are given in order to evaluate possibility of application of solution of static problem for selection of parameters of corresponding dynamic loading of the pipe.

1. Based on that an expression for static maximum stress consists of two multipliers, namely force p and geometry $f(R, h, a)$, it is assumed that structure of expression for maximum dynamic stress will be similar in dynamic formulation (10):

$$\sigma^d_{\beta\max} = A_d I f(R, h, a), \qquad (11)$$

where I is an uniformly distributed pressure pulse at ET; A_d is a some function considering dynamic of the process and determined only by EM properties;

2. Achievement of high efficiency of ET requires development of dynamic stresses equal the dynamic yield strength.

The following is obtained from (5) and (11) considering made assumptions:

$$K\sigma_y = A_d I f(R, h, a).$$

K and A_d are unknown as a rule, therefore, the expression can be written in the form:

$$\sigma_y = AIf(R, h, a). \quad (12)$$

Considering possible errors of above assumptions, experimentally received information about already well elaborated mode with I_0 and a_0 parameters is used for determination of function A for some pipe, which is called reference, with R_0, h_0 and σ_{y0} characteristics:

$$\sigma_{y0} = AI_0 f(R_0, h_0, a_0).$$

Write for reference pipe considering (10):

$$\sigma_{y_0} = \frac{AI_0R_0}{h_0k_0}\left[1 - k_0 - \frac{3v \text{ tg } 0.5\beta_0 a_0}{\sqrt{3(1-v^2)}}\right],$$

for studied pipe:

$$\sigma_{y_i} = \frac{AI_iR_i}{h_ik_i}\left[1 - k_i - \frac{3v \text{ tg} 0.5\ \beta_i a_i}{\sqrt{3(1-v^2)}}\right]$$

and after corresponding transformations the next is obtained:

$$I_i = I_0 \frac{\sigma_{y_i}R_0h_i}{\sigma_{y_0}R_ih_0}\left(\frac{k_i}{k_0}\frac{1 - k_0 - 3v \text{ tg } 0.5\beta_0 a_0/\sqrt{3(1-v^2)}}{1 - k_i - 3v \text{ tg } 0.5\beta_i a_i/\sqrt{3(1-v^2)}}\right).$$

It should be noted that pressure pulse I is inversely proportional to charge width and directly proportional to mass of EM charge falling on unit of pipe area and mass of charge is determined by equation (4), i.e. $I \sim jn/a$, considering what will get:

$$n_i = n_0 \frac{j_0 a_i \sigma_{y_i} R_0 h_i}{j_i a_0 \sigma_{y_0} R_i h_0} \times \left(\frac{k_i}{k_0}\frac{1 - k_0 - 3v \text{ tg } 0.5\beta_0 a_0/\sqrt{3(1-v^2)}}{1 - k_i - 3v \text{ tg } 0.5\beta_i a_i/\sqrt{3(1-v^2)}}\right). \quad (13)$$

Expression (13) allows calculating direct quantity of EC winds which is necessary for efficient ET of circumferential welds of pipes of set dimension-type as well as determining optimum EC for specific case on portion per unit of length which can be 6, 12, 14, 18, 33 g/m for industrially manufactured cords [10].

It is shown that obtained condition of determination of charge width (2) allows simplifying expression (13). Part of this expression, in brackets, is presented through φ:

$$\varphi = \left(\frac{k_i}{k_0}\frac{1 - k_0 - 3v \text{ tg } 0.5\beta_0 a_0/\sqrt{3(1-v^2)}}{1 - k_i - 3v \text{ tg } 05\beta_i a_i/\sqrt{3(1-v^2)}}\right).$$

Inserting here value of charge width, determined by equation (2), namely $a_0 = 0.75\pi/\beta_0$, $a_i = 0.75\pi/\beta_i$ then $\beta_0 a_0 = \beta i_a i = 0.75\pi$, $k_0 = k_i$ for all dimension-types of pipes, including for reference one, means that $\varphi = 1$ and expression 13 takes the form:

$$n_i = n_0 \frac{j_0 a_i \sigma_{y_i} R_0 h_i}{j_i a_0 \sigma_{y_0} R_i h_0}. \quad (14)$$

Calculation of distance from weld axis to near end of the charge. Examine Figure 1 for determination of this parameter. Distance from weld axis to near end of the charge should equal the width of zone of plastic shortening strains appearing in welding. Well-known calculation method determining the width of plastic strain zone, proposed by G.A. Nikolaev [11], is used:

$$b_p = \frac{B\rho}{\rho - \varepsilon_y}, \quad \rho = \frac{0.484\alpha q_0}{c^*(x_1 + x_2 - 2B)}, \quad (15)$$

where B is a width of plates being welded; ε_y is a deformation, corresponding to stresses equal the yield strength of steel; α is a coefficient of linear expansion in heating; $q_0 = q/2vh$ is a welding heat input; $q = \eta IU$ is an effective capacity of power source; η is an efficiency of power source; I is a welding current; U is an arc voltage; v is a welding speed; c^* is a heat capacity of steel under specific welding conditions which can be taken equal the heat capacity at constant volume; x_1, x_2 is the position of spots of welded joint on axis x at which temperature T during welding achieves 600 and 500 °C, respectively, and is calculated on N.N. Rykalin formula [6] ($x = 0.484q_0/c^*T$). Arc voltage in manual arc welding (MAW) according to GOST 35–75 is determined on formula $U = 20 + 0.04I$, welding current is set by welder; welding current in semi-automatic arc welding is determined on amperemeter of semiautomatic device or on formula given for MAW depending on arc voltage registered by voltmeter of semiautomatic device; welding parameters in automatic welding are determined on measurers of automatic device or power source.

Model of welded joint considered by G.A. Nikolaev assumes that effect of thermal-deformation processes in welding propagates along the whole width of plates being welded. In real joint the value of elastic strains (residual one and forming in welding) quickly reduces with increase of distance from weld axis, and only part of metal, adjacent to zone of shortening strains, gives reaction to deformations and stresses. In our case width of this reaction zone (zone of residual elastic contraction strains) is determined by point B in Figure 1. The width of this zone is described above by expression (2). Insert of (2) in (15) gives expression for calculation of width of zone of plastic shortening strains in welding of circumferential pipe joints:

$$b_p = \frac{1.8\sqrt{Rh}}{1 - \dfrac{\sigma_y}{\alpha E}\left(\dfrac{1}{600} + \dfrac{1}{500} - 3.6\,\dfrac{c^*\sqrt{Rh}}{0.484\,q_0}\right)}. \quad (16)$$

Coefficients, showing properties of pipe material for low-carbon steels, have the following average values in SI dimension system [11]:

$$c^* = 5.2\cdot10^6\ \mathrm{J/m^3{\cdot}{}^\circ C},\ \alpha = 15\cdot10^{-6}\ 1/{}^\circ\mathrm{C},$$
$$E = 2\cdot10^{11}\ \mathrm{Pa}.$$

Efficiency of power source η is determined experimentally and being the reference value [7].

Taking into account given values of coefficients as well as that the welding power source has physical width and heating of base metal is virtually carried out from fusion line, the final expression for determination of distance from weld axis to near end of EM charge in MAW takes the form:

$$b = \frac{1.8\sqrt{Rh}}{1 - 1.53\cdot10^{-9}\sigma_y\left(1 - 11.3\cdot10^{9}\,\dfrac{\sqrt{Rh}}{q_0}\right)} + S_w, \quad (17)$$

where S_w is a half of width of circumferential weld.

Width of zone of plastic strains in the case of multipass welding is determined by pass with the largest q_0, welding parameters of which should be taken for calculation. As a rule, this is the last pass.

Checking of proposed method for calculation of ET modes of circumferential pipe welds was made using reference pipe of Kh46 strength class of Japan origin with the following parameters, namely radius R = 0.36 m, wall thickness h = = 0,0172 m, $\sigma_y = 440\cdot10^6$ Pa, S_w = 0.009 m, quantity of winds of EC with portion of unit of length $12\cdot10^{-3}$ kg/m is 8, total width of winding of charge being 0.14 m. Indicated mode of treatment of this pipe was elaborated in development of ET technology for Orenburg Gas Condensate Field. Considering this expression (14) takes the form:

$$n_i = 0.033\cdot10^{-6}\sigma_{y_i}a_ih_i/j_iR_i.$$

Taking into account that RS in reference pipe after ET were not equal zero and made 80 MPa (results are given below) as well as considering existing experience of ET of circumferential welds, the numerical coefficient is taken equal $0.04\cdot10^{-6}$ and final expression for determination of quantity of EC winds is written in the next way:

$$n_i = 0.04\cdot10^{-6}\sigma_{y_i}a_ih_i/j_iR_i. \quad (18)$$

Control experiments on calculation modes, given in Table 1, were carried out for validation of efficiency of proposed procedure. Table 2 shows the results of stress measurements. Measurement of stresses was carried out with the help of well-known method of fracture tensometry using strainmeter with scale interval 2 μm. Line 7 of Table 1 shows in the numerator the modes of ET of reference pipe, calculated on developed method, and in denominator that ones on which real ET (before method development) were carried out.

Obtained experimental data indicate that ET improved stressed state not only of some sepa-

Table 1. ET modes for circumferential pipe welds

No.	Dimension-size of pipe ($2R\times h$), mm	σ_y, MPa	n, winds of EC-A (j = = 12 g/m)	a, mm	b, mm
1	115×4	240	2	28	19
2	115×8	240	4	39	29
3	150×8	280	4	44	28
4	160×5	280	2	36	21
5	530×7	350	2	78	20
6	530×9	350	3	88	22
7	720×17.2	440	9.8/8	142/140	19/40
8	168×14	280	10	62	25

Table 2. Results of experimental check of calculation method

No.	Dimension-size of pipe ($D\times h$), mm	Residual stresses, MPa		
		σ_i, MPa	σ_f, MPa	$\Delta\sigma$, MPa
1	115×4	150	−30	180
2	160×5	200	−50	250
3	115×8	200	−20	220
4	150×8	250	0	250
5	530×7	300	50	250
6	530×9	300	50	250
7	168×14	250	0	250
8	720×17.2	440	80	360

Note. σ_i — initial (after welding) RS; σ_f — resulting after ET of RS; $\Delta\sigma$ — value of reduction of RS (all given values of stresses relate to external pipe surface).

rately taken specimens, but on average all specimens used in given series of experiments. Besides, results of RS reduction are sufficiently close for all tested specimens, on average the RS were reduced to zero level for this group of pipes. Any of test experiments showed unallowable deviations of results, in particular, no cases of ineffective treatment from point of view of RS reduction as well as cases of excessive deformation of treated pipes were registered. Residual bending of pipes does not exceed allowable one [12, 13]. This confirms applicability of developed procedure in selection of ET modes for practical application.

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