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OPTIMAL REDUCTION OF WORKING PRESSURE IN PIPELINES FOR WELDING REPAIR OF THINNING REGIONS

V.I. MAKHNENKO, V.S. BUT, S.S. KOZLITINA, L.I. DZYUBAK and **O.I. OLEJNIK**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The possibility of using welding to repair defects of corrosion origin in walls of pressurised pipelines is considered. It is shown that the safety of welding operations is affected not only by the overall size of a defect, but also by the shape of a pipe wall thinning. Calculation algorithms are applied to substantiate the possibility of repair of defects by overlaying welding due to optimal reduction of internal pressure in the main line for a period of repair.

Keywords: *main pipeline, welding repair, overlaying welding, sizes of defects, residual thickness of pipe wall, optimal pressure*

Repair of main pipelines by welding without interruption of their operation, i.e. in a pressurised state, is finding now an increasingly wider application, as it allows an optimal reduction of downtime and pollution of the environment. A key point of this technology is safety of repair operations performed on a pressurised pipeline depending on the type of a defect, its shape and size. The most frequent defects in underground main gas pipelines are wall thinning defects of the corrosion origin, which are associated with violation of waterproof insulation. Such defects with overall sizes $s_0 \times c_0 \times a$ (Figure 1), where s is the size of a defect along the pipe axis, and c and a are the sizes of the defect on the circumference and through the wall thickness, respectively, are well studied. Different criteria are available for estimation of the risk of fracture within the zones of such defects depending on their sizes, geometric parameters of a pipeline, its mechanical properties, pressure inside a pipe [1–3], etc. For example, study [1] gives fairly simple relationships based on numerous experimental investigations, which make it possible to judge whether the wall thinning defects in pipelines are permissible or not depending on the above parameters.

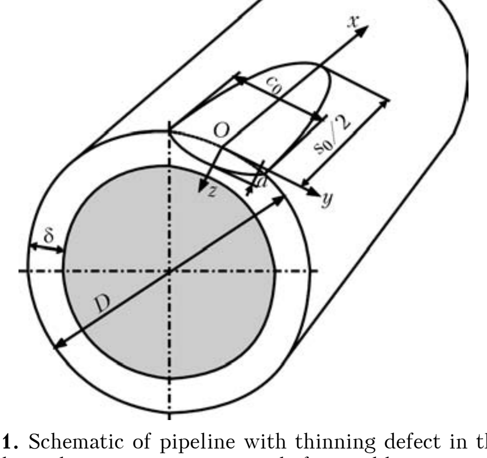

Figure 1. Schematic of pipeline with thinning defect in the form of an ellipsoid measuring $s_0 \times c_0 \times a$ before welding

The condition of permissibility of a corrosion thinning defect with sizes $s(t)$ and $c(t)$ at time moment t in a pipeline, according to [3], can be written down as

$$y(t) = \delta - a(t) - [\delta]R_j > 0, \qquad (1)$$

where

$$R_j = \delta_{min}/[\delta] \quad (j = s, c); \qquad (1a)$$

δ_{min} is the minimal measured wall thickness within the defect zone ($\delta_{min} = \delta - a$); and $[\delta]$ is the permissible calculated thickness of the pipeline wall without considering the thinning defects, i.e.

$$[\delta] = \frac{PD}{2[\sigma]}, \qquad (2)$$

where P is the working pressure in the pipe with external diameter D, made from a material with permissible stresses $[\sigma]$ for given conditions; and the following dependencies suggested in [1] for the value of R_j ($j = s, c$):

$$R_s = \begin{cases} 0.2, \text{ if } \lambda = \dfrac{1.285}{\sqrt{D[\delta]}}\, s \le 0.3475, \\ \left[0.9 - \dfrac{0.9}{\sqrt{1 + 0.48\lambda^2}}\right]\left[1.0 - \dfrac{0.9}{\sqrt{1 + 0.48\lambda^2}}\right]^{-1}, \\ \text{ if } \lambda > 0.3475; \end{cases} \qquad (3)$$

$$R_c = \begin{cases} 0.2, \text{ if } c/D \le 0.348, \\ \dfrac{10.511(c/D)^2 - 0.7358}{1.0 + 13.838(c/D)^2}, \text{ if } c/D > 0.348. \end{cases}$$

The problems of prediction of safety, allowing for the technological effects within the defect zone (cleaning, overlaying welding), which cause changes in geometric parameters $a(t)$, $s(t)$ and $c(t)$, are often encountered in practice of repair of the detected thinning defects. Of particular importance is the possibility of in-process predicting an increase in defect depth $a(t)$ as a result of cleaning the surface from corrosion (approximately to 1 mm), or as a result of welding heating using the corresponding welding technology [4] (approximately to a depth of penetration of isotherm of about 1000 °C for steel, depending on the position of a heat source in the thinning zone, allowing for variations in sizes $s(t)$ and $c(t)$ due to the regions already welded by time moment t).

It is very important at this point to take into account the extra margin for ensuring safety due to a short-time decrease of pressure in a pipeline, causing no substantial violation of the working conditions. That is, it is necessary to quite promptly obtain a compromise estimate of minimal decrease of the pressure in the pipe providing the required safety, i.e. meeting conditions (1). So, this study is dedicated to this issue.

Assume that defect sizes $a(t)$, $s(t)$ and $c(t)$ in a pipeline with geometric parameters $D \times \delta$, made from a material with permissible stresses $[\sigma]$ outside the defect, are set for time moment t.

It follows from dependencies (1) through (3) at $y = 0$ that

$$\begin{cases} \lambda(R_s) = \left[0.81\left(\dfrac{1 - R_s}{0.9 - R_s}\right)^2 - 1\right]^{0.5} 1.4434 \text{ at } R_s > 0.2, \\ \lambda(R_s) = 0.3475 \text{ at } R_s \le 0.2; \end{cases} \qquad (4)$$

$$s_{cr}(R_s) = \lambda(R_s)\, \frac{\sqrt{D[\delta]}}{1.285};$$

$$c_{cr}(R_c) = D\left[\frac{R_c + 0.73589}{10.511 - 13.838R_c}\right]^{0.5} \text{ at } R_c \ge 0.2; \qquad (5)$$

$$c_{cr}(R_c) = 0.348D \text{ at } R_c < 0.2,$$

Table 1. Results of calculation of s_{cr} and c_{cr} for P = 7.5 MPa

δ_{min}, mm	$R_s = R_c$	s_{cr}, mm	c_{cr}, mm
3.10	0.2	40.1	494.2
4.65	0.3	53.3	573.7
6.20	0.4	68.0	678.8
7.25	0.5	83.1	835.0
9.30	0.6	118.0	1104.8
10.85	0.7	151.1	1874.0
12.40	0.8	192.0	–
13.185	0.85	417.9	–

where s_{cr} and c_{cr} are the permissible critical sizes at given R_s and R_c.

By using (1a) and (2), we can write down that

$$R_j = \frac{\delta_{min}}{P}\,\frac{2[\delta]}{D} \quad (j = s, c). \qquad (6)$$

It follows from (4) through (6) that

• at $R_j \le 0.2$, permissible sizes s and c for a thinning defect do not depend on the value of δ_{min} and are equal to $s = 0.27D\sqrt{P/2[\delta]}$ and $c = 0.348D$, respectively;

• at fixed δ_{min}, the ultimate values of parameters R_s = 0.9 and R_c = 10.511/13.838, at which s_{cr} and $c_{cr} \to \infty$, according to (4) and (5), can be approached

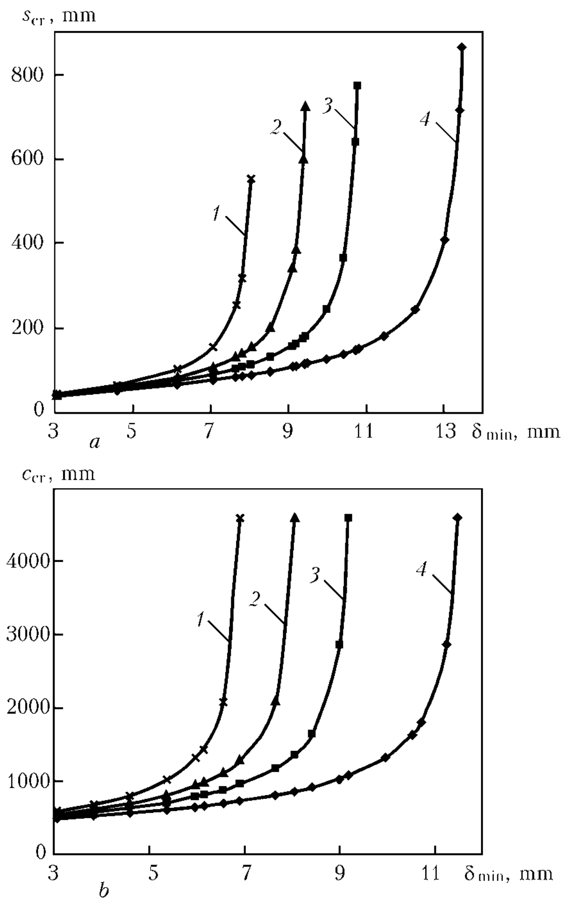

Figure 2. Dependence of s_{cr} (a) and c_{cr} (b) on minimal thickness δ_{min} of the wall of a pipe measuring ∅ 1420 × 20 mm and $[\sigma]$ = 345 MPa at P = 7.5 MPa: *1* — 0.6P; *2* — 0.7P; *3* — 0.8P; *4* — P

Table 2. Results of calculation of s_{cr} and c_{cr} for pressures of 0.8P and 0.6P

δ_{min}, mm	0.8P = 6 MPa			0.6P = 4.5 MPa		
	$R_s = R_c$	s_{cr}, mm	c_{cr}, mm	$R_s = R_c$	s_{cr}, mm	c_{cr}, mm
3.10	0.250	41.7	531	0.333	44.9	596
4.65	0.375	57.3	649	0.500	66.5	833
6.20	0.500	76.8	833	0.667	119.5	1485
7.25	0.5846	94.1	1051	0.7796	192.7	–
9.30	0.750	166.6	–	–	–	–
10.85	0.875	654.0	–	–	–	–

as closely as possible due to decrease in P, according to (6); i.e. such thinning defects become «absolutely permissible».

Consider a specific example of a steel pipe ($[\sigma]$ = = 345 MPa, P = 7.5 MPa, $[\delta]_{cal}$ = 15.5 mm) measuring ∅ 1420 × 20 mm. By setting a series of values of δ_{min} = = 20 − $a(t)$, we obtain a corresponding series of values of $R_s = R_c$ for P = 7.5 MPa (Table 1), on the basis of which we determine s_{cr} and c_{cr} from (4) and (5).

As follows from the data of Table 1 and curves P in Figure 2, a, b, the value of c_{cr} for the given example at the working pressures is by an order of magnitude higher than s_{cr} over the entire range of $\delta_{min} \geq 3.1$ mm. s_{cr} has rather low values at low δ_{min}. Here a reduction of the working pressure during repair is a relevant measure to ensure safety. This is clearly demonstrated by the data of Table 2 and curves *1* and *3* in Figure 2, a, b.

It can be seen that at low δ_{min} close to $0.2[\delta]_{cal}$ = = 3.1 mm the effect of reduction of pressure does not lead to any pronounced variation of values of s_{cr} and c_{cr}. However, at $\delta_{min} > 6$ mm, a 40 % decrease in the working pressure leads to an order of magnitude increase in s_{cr} and c_{cr}, which is very important for practical application.

As an example of using such curves, consider the safety of welding repair of a thinning defect with sizes

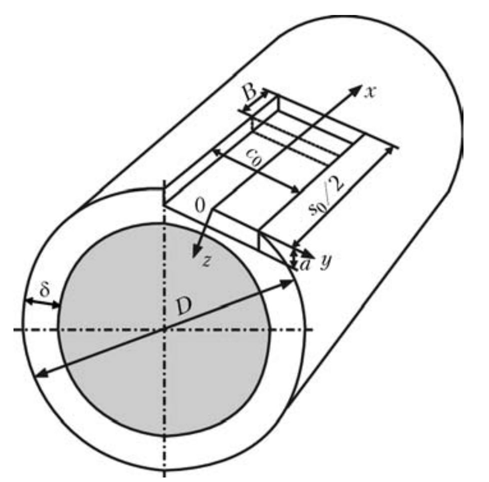

Figure 3. Schematic of pipeline with thinning defect of a rectangular shape and size $s_0 \times c_0 \times a$ before welding

$s_0 = s_{cr}$ = 100 mm and c = 40 mm at δ_{min} = 8.5 mm (Figure 3). Welding is performed from the ends of the defect around a circumference at the parameters that provide penetration of the 1000 °C isotherm to depth ξ = 3 mm (with a certain conservatism) at deposited bead width B = 10 mm. Therefore, within the deposited bead zone the residual conditional wall thickness will be $\delta_{con} = \delta - a(x) - \xi$. If $\delta_{con} > \delta_{min}$ = = $\delta - a_{max}$, ultimate critical size s_{cr} (see Figure 2, a) will remain equal to s_0, and there will be no need to reduce the pressure.

At the next step of deposition of the bead around a circumference at the other end of the defect at a working pressure, when $s = s_0 - B$ = 90 mm, and according to Figure 2, a, δ_{min} should be not lower than approximately 8 mm. If in this case δ_{con} is higher than 11 mm, there is no need to reduce the pressure.

In a general form, for welding from the ends we will obtain a change in length $s_n = s_0 - nB$, where n is the pass number. Hence, for length s of the defect, knowing its depth $a(x)$, where x is the coordinate along the axis of the defect in the n-th pass, we calculate conditional defect depth $a_{con} = a(x) + \xi$, and then compare difference $\delta - a_{con}$ with the corresponding permissible (see Figure 2, a) value of δ_{min} for s_n at pressure P. Based on this comparison, we make a decision on the necessity and degree of reduction of the pressure. For this example, Table 3 gives values of s_n, x_n, $\delta - a_{con}$ and $\delta_{min}(s_n)$ (see Figure 2, a) for n = 1, 2, ... at different pressures in the pipe.

It holds for a defect described by equation

$$a(x) = a_0 \sqrt{1 - \left(\frac{2x}{s_0}\right)^2 \left(\frac{2y}{c_0}\right)^2},$$

where $a_0 = \delta - \delta_{min}$, along the y = 0 axis, that

$$a(x) = (\delta - \delta_{min})\sqrt{1 - \left(\frac{2x}{s_0}\right)^2} \text{ at } -\frac{s_0}{2} < x < \frac{s_0}{2}.$$

The conditional depth of the defect for the n-th pass will be

$$a^n_{con} = 11.5\sqrt{1 - \left(\frac{2x_n}{s_0}\right)^2} + 3 \text{ mm}.$$

It can be seen from Table 3 that, for the defect and welding parameters (ξ = 3 mm) under consideration, the process can be quite safely performed at a working pressure of 7.5 MPa.

Consider the most conservative shape of the defect (Figure 3) in the form of

$$a(x, y) = \begin{cases} \delta - \delta_{min} \text{ at } -\frac{s_0}{2} < x < \frac{s_0}{2}, -\frac{c_0}{2} < y < \frac{c_0}{2}, \\ 0 \text{ at } |x| > \frac{s_0}{2}, |y| > \frac{c_0}{2}. \end{cases}$$

In this case, at δ = 20 mm and δ_{min} = 8.5 mm the defect is at a tolerable limit at P = 7.5 MPa. However,

Table 3. Example of calculation of the necessity of reducing the pressure in welding repair of thinning defect with s_0 = 100 mm, c_0 = = 20 mm and δ_{min} = 8.5 mm in a pipe measuring ∅ 1420 × 20 mm (see Figure 2)

n	s_n, ,mm	x_n, mm	a^n_{con}, mm	$\delta - a_{con}$, mm	$\delta_{min}(s_n)$ (P = 7.5 MPa)	$\delta_{min}(s_n)$ (P = 6.0 MPa)	$\delta_{min}(s_n)$ (P = 4.5 MPa)
0	100	50	3.0	17.0	8.5	7.3	5.6
1	90	−50	3.0	17.0	8.0	6.6	5.1
2	80	40	9.9	10.1	6.0	6.0	4.6
3	70	−40	9.9	10.1	6.0	5.5	4.3
4	60	30	12.2	7.8	5.1	4.5	3.9
5	50	−30	12.2	7.8	4.0	3.6	3.3
6	40	20	13.7	6.3	3.0	3.0	–
7	30	−20	13.7	6.3	3.1	–	–

in welding to a depth of ξ = 3 mm, the condition of permissibility from s for $\delta_{min}(s_n)$ = 8.5 − 3.0 = 5.5 mm at s_0 = 100 mm can be met only at $P \le 4.5$ MPa, i.e. this defect can be repaired by welding by reducing the pressure to the said limit (4.5 MPa).

It can be noted in conclusion that for welding repair of thinning defects in main pipelines, depending on the size and shape of thinning, and allowing for decrease in deformation resistance of a material during heating, the safety of operations can be improved by using an appropriate pressure in a pipeline.

It is shown that sizes of a thinning defect are far from always determining the safety of the welding operations. The shape of the thinning defect, in particular the presence of a region with a developed surface area in a zone of the maximal defect depth, has a strong effect on the safety of welding operations associated with removal of the thinning defect. Nevertheless, there is always a level of pressure in the pipe, below which the welding repair of the thinning defect is a safe operation in terms of preservation of integrity of the pipe. It is important that this level should satisfy, at least for a short time, the service conditions of the pipeline. For this, it is expedient to develop the diagrams of permissibility of defects of the type shown in Figure 2 for typical sizes and strength of a material of main pipelines, from which it would not be difficult to determine the optimal level of pressure in the pipeline for the case of typical defects with a developed surface area within the maximal depth zone to ensure the safety of repair under corresponding welding conditions.

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