RISK OF FRACTURE OF PRESSURISED MAIN PIPELINE WITH DEFECTS OF THE TYPE OF WALL THINNING DURING REPAIR

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

It is shown that welding repair of defects of the type of pipeline wall thinning by compensating the metal lost in the thinning zone by the deposited metal using low-current (~90 A) manual arc weld deposition is a sufficiently efficient technology. Wide application of this technology for repair of pressurised main pipelines is limited by the safety problem. Also, it is shown that the minimum admissible wall thickness in the defect zone under operating pressures depends upon the size of a defect along the generating line and, to a much lesser degree, upon its size on the circumference, as well as upon the thermal parameters of welding and accepted sequence of welding-up (deposition) of the defect.

Keywords: *main pipelines, pressure, thinning defects, minimal thickness, welding repair, welding sequence*

Repair of a linear part of main pipelines without their putting out of operation is a problem of current importance. The most common defects in such structures are caused by corrosion damages on the external surface of a pipe, which are accompanied by decrease in thickness of the wall metal. Normally, such defects are schematised by a certain spatial figure with dimensions S, c and a (Figure 1). In approximate description of this volume in a system of coordinates x, y, z (Figure 2) by the second-order surface in a form of

$$\left(\frac{2x}{S}\right)^2 + \left(\frac{2y}{c}\right)^2 + \left(\frac{z}{a}\right)^2 = 1, \qquad (1)$$

volume V of the filler metal required to weld up such a defect with no allowance for spattering is determined as follows:

$$V = \pi \frac{Sca}{6}. \qquad (2)$$

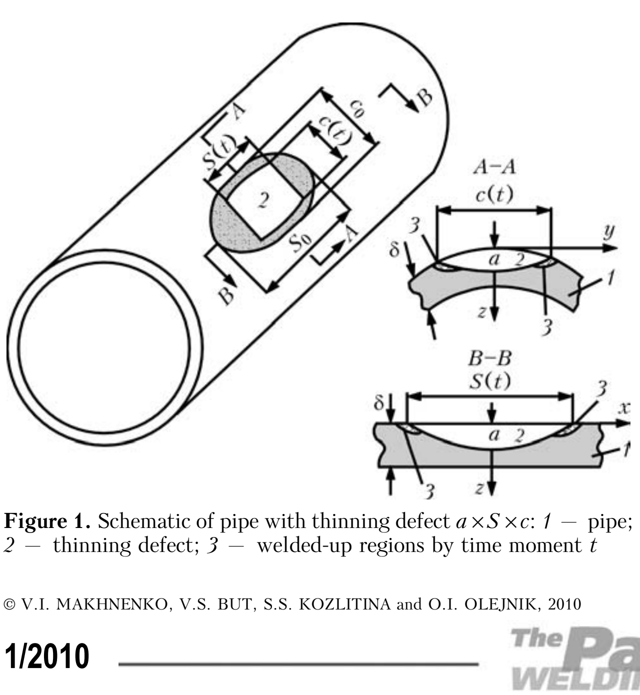

Figure 1. Schematic of pipe with thinning defect $a \times S \times c$: *1* — pipe; *2* — thinning defect; *3* — welded-up regions by time moment t

Time t_r necessary to compensate for the lost volume of metal, V, is equal to

$$t_r = \frac{V\gamma}{\alpha_d I_w}\,\xi, \qquad (3)$$

where γ is the specific weight of the deposited metal (7.8 g/cm^3 for steel pipes); α_d is the deposition efficiency equal to about 7.8 g/(A·h) for manual arc welding at low currents I_w; and $\xi > 1.0$ is the coefficient allowing for the losses of time for performing auxiliary operations.

At $\xi = 1.5$ and $I_w = 90$ A, one welder per shift (6 h) can fill up the volume of the deposited metal characterised by sizes S, c and a, and by the surface described by expression (1), this volume corresponding to product $Sca = 688 \cdot 10^3$ mm^3. Under the above conditions, sizes of the defects, which can be repaired by one welder per 6 h of operation at rather low operating parameters of manual fusion welding, are given in Table 1. It can be seen from the Table that welding repair of corrosion defects is a very efficient technology. However, its wide application for pressurised pipelines is limited by difficulties associated with ensuring safety in implementing this technology.

The matter of safety can be conditionally subdivided into two groups. The first group includes problems associated with the thermal effect of the welding

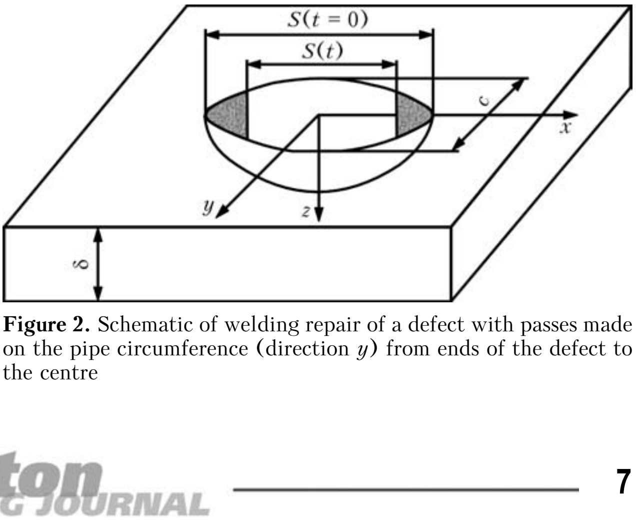

Figure 2. Schematic of welding repair of a defect with passes made on the pipe circumference (direction y) from ends of the defect to the centre

Sizes of thinning defects (mm) which can be repaired by one welder per shift at I_w = 90 A and ξ = 1.5

a = 2		a = 3		a = 4		a = 5		a = 6		a = 7		a = 8	
S	c	S	c	S	c	S	c	S	c	S	c	S	c
100	3440	100	2300	100	1470	100	1380	100	1150	100	980	100	860
200	1720	200	1150	200	735	200	690	200	575	200	490	200	430
400	860	300	575	400	375	400	345	400	290	400	245	400	115
800	430	400	290	800	185	800	172	800	145	800	122	800	60

arc and corresponding risk of burn-through or fracture of the pipeline wall as a result of decrease in its resistance to force loads (internal pressure, bending moments in repair). The second group relates to the problems of weldability of pipe steels under sufficiently rigid welding conditions and force loading, namely with prevention of cold (hydrogen-induced) cracking, as well as unfavourable microstructural changes capable of deteriorating performance of a pipeline region repaired by welding.

Available are publications on both first and second groups of safety issues. However, because of their complex and critical nature they require further investigation, as well as development of methods for prediction of consequences of application of these or those technological solutions.

This study considers the issues of maintaining integrity of a pipeline, which are directly associated with heating of a pipe wall by the welding arc in welding repair of thinning defects on the external surface, i.e. the first group of the safety issues. As applied to welding repair of isolated pit-like defects, these issues are considered in detail in study [1]. As to welding repair of defects of the thinning type, which are extensive both on the circumference and along the pipeline axis, these issues were experimentally investigated in studies [2, 3].

The results obtained provide important references to ultimate bounds of applicability of manual arc welding for repair of the above thinning defects. However, the absence of theoretical generalisation of the results limits their application for the cases outside the considered initial data.

This study suggests a mathematical model for estimation of the risk of violation of integrity of wall of a pressurised pipe under conditions of heating of the thinning zone in welding (see Figure 1). The model is based on tracing the temperature field during welding (weld deposition) of a defect by fixing changes in its dimensions $S(t)$ and $c(t)$ with time. With this calculation, the depth of the defect, $a_r(t)$, is determined at different time moments t from the maximal depth of penetration of temperature, $T_r^{\max}$, at which resistance of a material to deformation is insignificant. For pipe steels, the value of $T_r^{\max}$ ranges from 720 to 1000 °C, according to different recommendations. The last value is in a rather good agreement with the experimental data [3], and the first one is more conservative.

According to the data of study [4], the condition of admissibility of a corrosion thinning defect with dimensions $S(t)$, $c(t)$ and $a_r(t)$ in a pipeline at time moment t can be written down as follows:

$$Y(t) = \delta - a_r^m(t) - [\delta]R_j > 0 \quad (j = S,\ c), \tag{4}$$

where

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

$$R_c = \begin{cases} 0.2, \text{ if} \dfrac{c}{D} \le 0.348, \\ \dfrac{-0.7358 + 10.511(c/D)^2}{1.0 + 13.838(c/D)^2}, \text{ if } \dfrac{c}{D} > 0.348; \end{cases} \tag{5}$$

D is the internal diameter of the pipeline; and $[\delta]$ is the admissible calculated thickness of the pipeline wall at the absence of defects, which depends upon the material of the pipe and its force loading, and is known for a given pipeline region.

As noted above, in welding repair of a given defect the $S(t)$, $c(t)$ and $a_r(t)$ values required for the calculation are determined depending upon the welding conditions, initial heating and sequence of deposition of separate passes. In the majority of cases it is enough to determine conditions for maintaining the integrity in deposition of the first layer to weld up the defect for $S(t) = S(0)$, or after deposition of end zones of the defect to substantially decrease the $S(t)$ value, compared with $S(0)$ (Figure 2).

For these purposes, it is possible to use modern methods of mathematical modelling of temperature fields in welding by an appropriate method. Below we will consider such a possibility for the case of arc welding-up of a thinning defect on the surface of a pipe of steel 17G1S with diameter D = 1420 mm, wall thickness δ = 20 mm and $[\delta]$ = 16 mm. Welding parameters were as follows: I_w = 120 A, U_a = 22 V, and v_w = 2 mm/s. The initial heating temperature within the defect zone, T_0, varied from 20 to 150 °C (for walls with thickness δ = 15 and 10 mm, using welding parameters with I_w = 90 A).

Welding repair was performed by depositing beads on the circumference of the pipe (direction y in Figure 2) from the ends of the defect along the generating line (direction x in Figure 2).

While modelling each pass, it was taken into account that the effective power of the welding arc, $q_e = \eta_U I_w U_a$, is introduced partially with the deposited metal, q_1, while the rest of the power, $q_2 = q_e - q_1$, is introduced by the normal law from a heat source moving at speed v_w = 2 mm/s.

The value of q_1 is determined from the following dependence:

$$q_1 = \frac{\alpha_d I_w}{3600\gamma} (T_f c\gamma + \kappa), \qquad (6)$$

where T_f is the temperature of the filler metal; $c\gamma$ is the volumetric heat capacity of metal, and κ is the latent melting heat.

At T_f = 2100 °C, α_d = 8 g/(A·h), γ = 7.8 g/cm^3, κ = 2080 J/cm^3, I_w = 120 A and $c\gamma$ = 5.2 J/(cm^3·°C), it yields that q_1 = 445 W.

Accordingly, at η = 0.8 and U_a = 22 V, q_2 is equal to

$$q_2 = 2112 - 445 = 1667 \text{ W}.$$

Parameter q_2 has a distribution following the normal-circular law, when

$$g(r) = g_0 e^{-kr^2}, \qquad (7)$$

where $g_0 = q_2 k/\pi$; $r^2 = (x - x_s)^2 + (y - y_s)^2$; $x_s = x_s(t)$ and $y_s = y_s(t)$ are the coordinates of the heat source at time moment t, and k is the concentration coefficient equal to 0.05 1/mm^2.

The data on temperature field $T(x, y, z, t)$ were obtained by using the software developed by the E.O. Paton Electric Welding Institute, which realises a corresponding numerical solution of the thermal conductivity problem for a volume limited by surface (1) allowing for the deposited metal, as well as by surfaces $z = \delta$ and $z = 0$, for which the conditions of heat exchange with the environment were set according to the Newton law with heat exchange coefficients α_1 for surface $z = 0$ and α_2 for $z = \delta$. Coefficient α_2 = 0.05 W/(cm^2·°C) allows for heat exchange on the internal surface with a gas having a temperature of 40 °C and moving at a speed of 6 m/s, while α_1 = 0.005 W/(cm^2·°C) allows for heat exchange on the external surface.

Thermal-physical properties of steel 17G1S were taken from the reference data depending upon the temperature, like in study [1].

Results of the calculations by using the described procedure in the form of minimum admissible thicknesses within the thinning zone

$$\delta_{\min} = \begin{cases} \delta - a^{\max}(t), \\ \delta - a_0, \end{cases}$$

where $a^{\max}$ is the maximal depth of T_f isotherm, starting from surface $z = 0$; and a_0 is the maximal depth according to (4) at c_0 and S_0 (5) with initial dimensions $a_0 \times c_0 \times S_0$ (is shown in Figure 3 depending upon the value of S_0). These data show the effect of wall thickness δ at δ = 20, 15 and 10 mm and diameter D = 1420 mm, where admissible thicknesses [δ] at the absence of a defect were assumed to be 16, 12 and 8 mm, respectively.

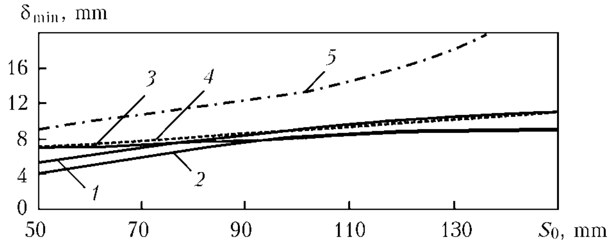

Figure 3. Results of calculation of minimal pipe thickness within the defect zone depending upon defect size S_0 at c_0 = 70 mm (see Figure 2), D = 1420 mm and welding parameters I_w = 90–120 A, U_a = 22 V and v_w = 2 mm/s: *1, 4, 5* — δ = 20 mm, [δ] = 16 mm; *2* — δ = 15 mm, [δ] = 12 mm; *3* — δ = 10 mm, [δ] = 8 mm; *1–3* — T_0 = 150 °C, T_{cr} = 1000 °C; *4* — T_0 = 20 °C, T_{cr} = 750 °C; *5* — T_0 = 150 °C, T_{cr} = 750 °C; *1, 4, 5* — I_w = 120 A; *2, 3* — I_w = 90 A

The initial temperature of heating of the defect zone, T_0, was varied from 20 to 150 °C, and critical temperature T_{cr} — from 750 to 1000 °C.

It follows from the data shown in Figure 3 that the minimal wall thickness within the zone of the defect under conditions of its welding repair corresponding to manual fusion arc welding at a current not higher than 120 A for δ = 20 mm, and 90 A for δ = 15 and 10 mm, at the initial heating temperature equal to 150 °C (corresponding to a considerable heating within the welding zone) depends upon defect dimensions S_0 along the pipe axis. However, at low δ and [δ] (Figure 3, curve *3*), this dependence grows from 6 mm at S_0 = 50 mm to about 9 mm at S_0 = 150 mm, whereas at δ = 20 mm and [δ] = 16 mm (Figure 3, curve *1*) this dependence grows from approximately 5 mm at S_0 = 50 mm to 11 mm at S_0 = 150 mm. Curve *2* in Figure 3, corresponding to δ = 15 mm and [δ] = 12 mm, lies between curves *3* and *1*, it being closer to curve *1* in a zone of low S_0 and closer to curve *3* at high S_0.

Curves *4* and *5* in Figure 3 show that critical temperature T_{cr} = 720–750 °C postulated in a number of suggestions leads to substantial overestimation of minimal wall thicknesses within the defect zone in terms of application of welding, compared with experimentally verified $T_{cr} \approx$ 1000 °C [3], for modern pipe steels used for transportation of hydrocarbons.

It should be noted that in welding repair of the considered defect along the generating line, where length of the defect, $S(t)$, insignificantly varies with time, the minimal thickness within the given defect

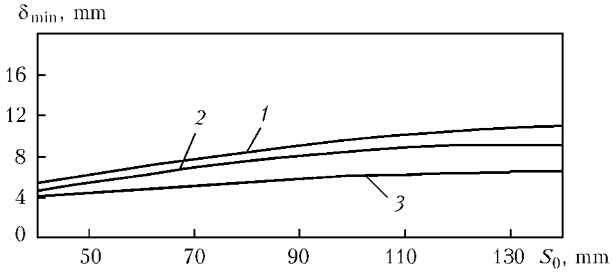

Figure 4. Effect of decrease in operating pressure on minimal thickness within the defect zone at I_w = 120 A, T_0 = 150 °C, δ = 20 mm, c_0 = 70 mm for welding on the circumference: *1* — p = 7.5; *2* — 5.6; *3* — 3.75 MPa

zone for the welding parameters under consideration is determined by the depth of penetration of temperature T_{cr} in the zone of a maximal initial depth of the defect, a_0, i.e. approximately 5 mm above the curves in Figure 3, respectively: for curve *1* ($\delta = 20$ mm) the minimal values of thickness within the defect zone will be $\delta_{min} = 9$ mm at $S_0 = 50$ mm and $\delta_{min} = 16$ mm at $S_0 = 150$ mm; for curve *2* ($\delta = 15$ mm) it will be $\delta_{min} = 9.5$ mm at $S_0 = 50$ mm and $\delta_{min} = 14$ mm at $S_0 = 150$ mm. For $\delta = 10$ mm, this welding sequence is inadmissible in terms of the accepted safety requirements.

Note the possibility of decreasing pressure in the pipeline as a method of improving safety of welding repair of defects of the type of thinning. Figure 4 shows the curves demonstrating the efficiency of this method for a case of large sizes of thinning.

CONCLUSIONS

1. In repair of thinning defects in main pipelines by arc welding, the minimum admissible thickness within the defect zone according to the safety requirements under operating pressures depends upon size S of the defect along the generating line, to a much lesser degree upon size c on the circumference, as well as upon the thermal parameters of welding and accepted sequence of welding-up of the defect.

2. In terms of the safety requirements, the best way of welding repair of defects is to deposit beads on the circumference, starting from the end regions located along the generating line, which allows decreasing the length of a defect in the indicated direction.

3. Worthy of notice from the practical standpoint is development of nomograms to evaluate the possibility of using welding with specific process parameters to repair the considered thinning defects, depending upon the geometric dimensions of the defect, such as S_0, c_0 and a_0, wall thickness δ, pipe diameter D and internal pressure in a pipeline.

1. Makhnenko, V.I., But, V.S., Velikoivanenko, E.A. et al. (2001) Mathematical modelling of pitting defects in active oil and gas pipelines and development of a numerical method for estimation of permissible parameters of arc welding repair of defects. *The Paton Welding J.*, **11**, 2–9.
2. Bruce, W.A., Mishier, H.D., Kiefner, J.F. (1993) *Repair of pipelines by direct deposition of weld metal*: A.G.A. Pipeline Research Committee Project PR-186-9110. Edison Welding Institute.
3. Bruce, W.A., Swatzel, J.F., Dorling, D.V. (2000) Repair of pipeline defects using weld deposition. In: *Proc. of 3rd Int. Pipeline Technology Conf.* (Brugge, Belgium, May 21–24, 2000).
4. *Fitness-for-service*: American Petroleum Institute Recommended Practice 579.

POSSIBILITIES FOR LOWERING DYNAMIC STRESS IN STRUCTURAL ELEMENTS OF MACHINES USING NANOSTRUCTURED COATINGS*

A.I. USTINOV[1], **A.P. ZINKOVSKY**[2], **I.G. TOKAR**[2] and **V.S. SKORODZIEVSKY**[3]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]G.S. Pisarenko Institute for Problems of Strength, NASU, Kiev, Ukraine
[3]G.V. Kurdyumov Institute for Metal Physics, NASU, Kiev, Ukraine

The paper gives the results of experimental studies of the influence of structural characteristics on physico-mechanical properties of coating materials and damping capacity of coated structural elements allowing for such factors as temperature, frequency and amplitude of stress.

Keywords: *coating, material nanostructure, temperature, structural element, vibration frequency, logarithmic damping decrement, dynamic stress*

Progress of modern mechanical engineering leads to high requirements made of the reliability and fatigue life of both individual structural elements and machines as a whole. As most of them are operating under the conditions of a broad spectrum of dynamic loads, which may lead to failure and breaking up of structural elements, and can have catastrophic consequences, ensuring their dynamic strength is one of the key problems in achievement of reliable functioning during the required service life. This is particularly urgent for aviation gas turbine engines (AGTE), most of the defects in which (more than 60 %) detected during design, development and operation, are due to insufficient strength of the components and structural elements, and, primarily, blades. About 70 % of the defects are of vibration-related origin.

One of the most important technico-economic quality indices of mechanical engineering products is ensuring their vibration reliability. In most of the cases, however, it is impossible to eliminate hazardous resonance modes as a result of a considerable density of

---

[*] The article was prepared on the basis of results of accomplishment of the NASU targeted integrated program «Problems of Remaining Life and Safe Operation of Structures, Constructions and Machines» (2007–2009).