DOI: https://doi.org/10.37434/tpwj2024.09.06

REINFORCEMENT OF AN NPP PIPELINE WITH A WALL THINNING DEFECT BY APPLYING EXTERNAL WELD OVERLAY

G.V. Vorona, O.S. Kostenevych, O.S. Milenin, O.V. Makhnenko

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

Repair of NPP pipelines with erosive and corrosive wear defects is an urgent problem of the nuclear power industry of Ukraine. When repairing the pipeline, the defective section is cut out and a new pipe coil is installed by welding. However, for a large number of technological pipelines with identified isolated defects, inadmissible wall thinning, replacement of a pipe section is associated with a large volume of repair work. To extend the service life, the defective section of the pipeline can be reinforced, for example, by welding an external overlay, weld deposition, installing a bandage or a welded sleeve. In order to justify the expediency of using reinforcing structures of welded external overlay type at pipeline repair, a finite element analysis of the stress-strain state of a straight section of the pipeline with an erosion-corrosion wear defect under the action of internal pressure before and after repair was carried out. The results of the analysis showed a high efficiency of reinforcement the defective section of the pipeline in the case of using a welded external overlay at repair. The obtained results can be used at justifying the introduction of alternative pipeline repair technologies at NPPs of Ukraine.

KEYWORDS: NPP, pipeline, erosion-corrosion wear, wall thinning defect, reinforcing structure, welded external overlay, stress-strain state, ductile fracture, finite element method

INTRODUCTION

Erosion-corrosion wear (ECW) in pipelines is one of the common problems at long-term operation of NPP. At repair the defective pipeline section is cut out, and a new pipe coil is installed by welding. This process is rather labour consuming and requires draining the transported liquid. As regards pipelines of the primary and secondary circuit of NPP units, such a repair technology is the most reliable and completely restores the pipeline service life. For a large number of technological pipelines, however, replacement of a pipeline section, particularly when individual local wall thinning of inadmissible dimensions is detected, can be excessive. In other sectors, for instance in the main pipeline transportation [1] or in foreign standards [2, 3] there exist several methods of pipeline repair by reinforcement of the defective section, namely welding an external overlay, weld deposition, installing a bandage or welded sleeve. The effectiveness of the defective section reinforcement by mounting a bandage or welded sleeve was considered earlier [4]. In this work the variant of pipeline reinforcement exactly by the welded external overlay is considered. The variant of installing the overlay and its geometrical parameters are shown in Figure 1.

The **objective** of the work is calculation-based assessment from strength viewpoint of the possibility of using an alternative technology of repair of NPP technological pipelines with ECW defects by welding an external overlay.

The admissibility of further operation of a pipeline section with ECW defect was assessed from the viewpoint of ductile fracture, namely, by the results of prediction of the increment of plastic strain intensity (strain criterion) in the defect zone under the action of operational load. The finite element method was used to study the influence of the geometrical parameters, namely initial gap between the pipeline surface and welded overlay

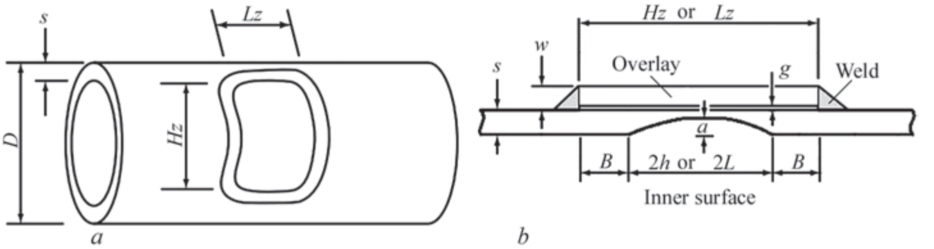

Figure 1. Scheme of reinforcement of the pipeline defective section by a welded external overlay: *a* — general view of the pipeline with the mounted overlay; *b* — section in the external overlay zone

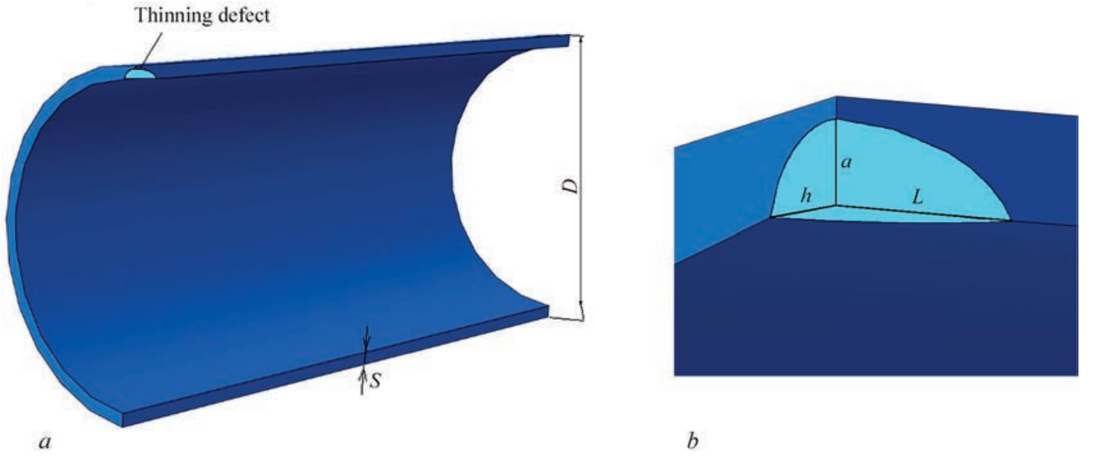

Figure 2. Geometrical model of the straight defective section of the pipeline (1/4 part) (*a*) and inner semi-elliptical defect of wall thinning (*b*)

and linear dimension of the overlay relative to the size of the wall thinning defect, as well as residual welding stresses generated by welding the external overlay on the effectiveness of reinforcement in the straight pipeline section with the wall thinning defect.

PROBLEM DEFINITION

As an example we considered the straight pipeline section having one of the standard dimensions and load parameters for NPP technological pipelines: material was steel 20, pipeline external diameter $D = 630$ mm, wall thickness $s = 25$ mm, design pressure $P = 11.8$ MPa, temperature $T = 300$ °C.

Critically dangerous geometrical parameters of pipeline wall thinning defect were determined (Figure 2, *b*) by MT-T.0.03.224–18 procedure [5] from the viewpoint of admissibility of further operation of the pipeline section. Dimensions of the critical wall thinning defect (idealized ECW defect of semi-ellipsoid shape) can be as follows: length $L = 2s = 50$ mm, width $h = s = 25$ mm, depth $a = 20$ mm.

The following dimensions of the reinforcing structure of the type of welded external overlay were selected: overlay thickness is equal to pipeline thickness $W = s = 25$ mm, distance from the thinning edge to overlay edge $B = 70$ mm, overlay length in the circumferential direction $H_z = 190$ mm, in the axial direction $L_z = 240$ mm.

FINITE ELEMENT MODEL

These parameters were used to develop the geometrical and finite element model of the straight pipeline section with ECW defect. Due to symmetry in the two planes (longitudinal and transverse) the developed model consists of 1/4 of the full model (Figure 2, *a*). Mechanical properties of the material are as follows: Young's modulus $E = 2.1 \cdot 10^5$ MPa, Poisson's ratio $\mu = 0.3$, yield limit for steel 20 at the temperature of $T = 300$ °C, $\sigma_y = 177$ MPa [2]. The finite element model with welded overlay application was developed in a similar way.

The problem of the stress-strain state of the defective pipeline section was considered in the elasto-plastic definition, as plastic strains can develop in the zone of ECW defect under the action of internal pressure. In the defect zone the working pressure $P = 11.8$ MPa is applied to the pipe inner surface. Axial tensile stresses were added to the model end face surface as a boundary condition [8]:

$$\sigma_{zz} = \frac{P\,D/2}{2s} \rightarrow \sigma_{zz} = 72.6 \text{ MPa}. \qquad (1)$$

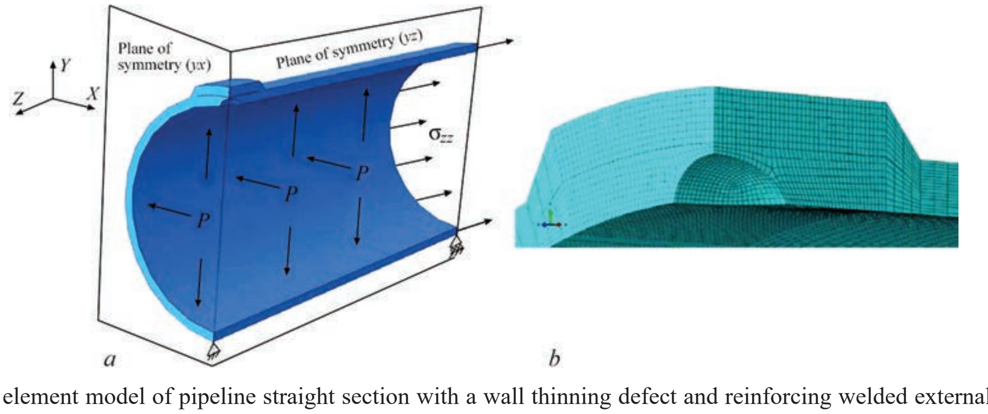

Figure 3. Finite element model of pipeline straight section with a wall thinning defect and reinforcing welded external overlay: *a* — model scheme; *b* — grid of finite elements in the defect zone

Minimal dimension of the finite elements (hexagonal volume element) of the model grid is equal to 3 mm (Figure 3, *b*). Minimal size of the plotted grid elements was selected proceeding from the condition that the value of the maximal equivalent plastic strain changes by less than 5 % at 2 times reduction of the grid minimal dimension.

In pipelines with detected ECW defects the mode of fracture under the impact of internal pressure, is, usually due to the ductile mechanism. The deformation criterion was used to predict the critical condition at ductile fracture under the action of internal pressure in pipeline material with erosion-corrosion wear defect [7]:

$$\int \frac{d\varepsilon_i^p}{\varepsilon_c} \succ 1, \quad (2)$$

where $d\varepsilon_i^p$ is the increment of plastic strain intensity; ε_c is the critical value of plastic strain, which depends on the rigidity of the stressed state, temperature, material inhomogeneity, etc.

RESULTS OF FINITE ELEMENT ANALYSIS OF SSS

Results of the conducted analysis of SSS of pipeline section without the reinforcing structure showed that under the impact of internal pressure P = 11.78 MPa maximal circumferential stresses of up to 227 MPa (Figure 4) arise in the defective zone, which exceed the material yield limit (177 MPa).

The nominal admissible stress of static strength is determined according to PNAE G 7-002–86 [6], under the condition that

$$[\sigma] = \min\left\{\frac{\sigma_u}{2.6}; \frac{\sigma_y}{1.5}\right\}. \quad (3)$$

At temperature T = 300 °C the yield limit and ultimate strength are equal to σ_y = 177 and σ_u = 363 MPa, respectively. In keeping with (3), the admissible stress is equal to [σ] = 118 MPa. Such an approach, based on comparison of acting stresses of pipeline wall, developing under internal pressure with admissible stresses for pipeline material in practice is used to establish the nominal dimensions during design. Evaluating the boundary state, determined by development of ductile fracture of pipeline material with a thinning defect, this approach is too conservative. More rational is the above-described approach (2), based on analysis of the results of increment of ductile strain intensity in the defective zone.

By the results of finite element analysis in the case of the defective pipeline section without the reinforcing structure, the maximal circumferential stresses (227 MPa) exceed the admissible stresses and reach the material yield limit (Figure 4, *a*), and the maximal intensity of plastic strains (Figure 5, *a*) in ECW defect zone is equal to $d\varepsilon_i^p$ = 0.011 (1.1 %). Such an increment of the intensity of plastic strains exceeds the established "conditional" limit value ε_c = 0.01 (1%) [7]. Therefore, it can be assumed that conditions are in place for the start of development of ductile fracture of the material.

In the case of a defective section of the pipeline with the mounted external overlay, even though the maximal circumferential stresses (225 MPa) still exceed the admissible stresses and reach the materi-

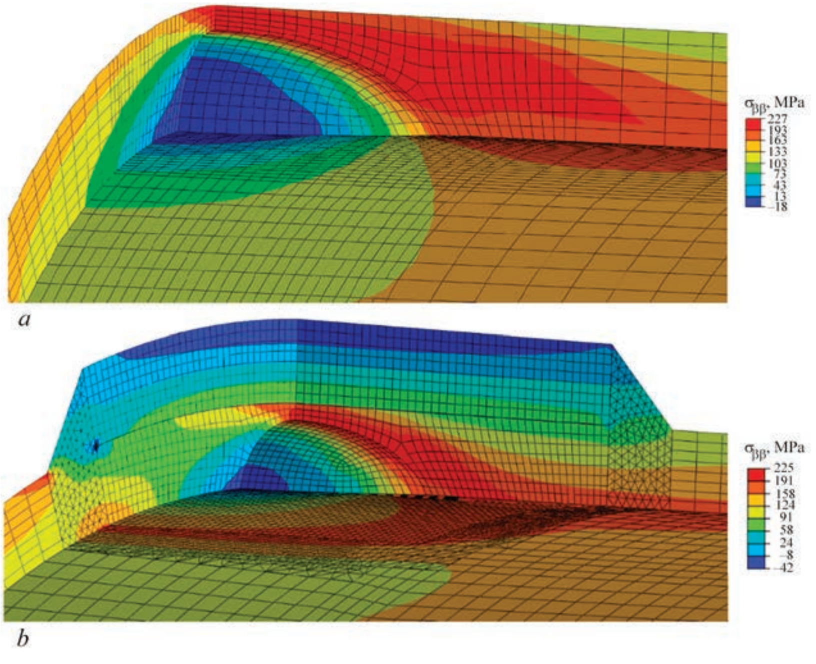

Figure 4. Distribution of circumferential stresses $\sigma_{\beta\beta}$ in the pipeline defective section: *a* — without the reinforcing structure; *b* — with external overlay

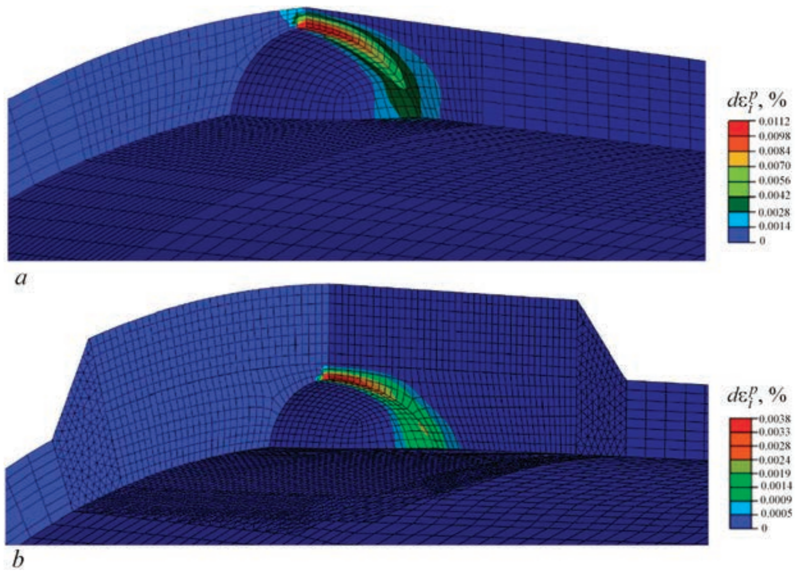

Figure 5. Distribution of the increment of plastic strain intensity in the defective zone of pipeline section: *a* — without the reinforcing structure $d\varepsilon_i^p$ = 0.011; *b* — with external overlay $d\varepsilon_i^p$ = 0.004

al yield limit (Figure 4, *b*), the maximal intensity of plastic strain (Figure 5, *b*) decreased to $d\varepsilon_i^p$ = 0.004 (0.4 %) and is no longer higher than the limit strain of 1 %. Thus, mounting a reinforcing structure of the type of welded external overlay effectively contributes to the prevention of development of plastic strains and pipeline failure in the zone of wall thinning defect under the action of internal pressure.

INFLUENCE OF THE INITIAL GAP

Derived results of numerical prediction of the stress-strain state of the pipeline defective section at its reinforcement by mounting an external overlay showed that the value of gap *g* between the surfaces of the pipeline and the overlap during its mounting does not influence the effectiveness of the defective section unloading (Figure 6, *a*), i.e. unloading occurs not due to contact interaction between the surfaces of the pipeline and the overlay, but as a result of reinforcement of the defective section through the welded joint of the external overlay. This is an important advantage of such a repair technology, as no thorough work on overlay surface preparation and its pressing to the pipeline surface are required before mounting the welded external overlay.

INFLUENCE OF EXTERNAL OVERLAY DIMENSIONS

Another important parameter of the technology of reinforcement of the pipeline defective section by the welded external overlay are the geometrical dimensions of the overlay. The overlay thickness is usually taken equal to the wall thickness of the pipeline being reinforced, as in the case of ECW defect development through the entire wall thickness, the welded external overlay will have the load-carrying capacity, close to that of the pipeline wall. The linear dimension of the external overlay should be greater than that of wall thinning defect. In Figure 1 this increase of the dimensions from each side of the external overlay is marked

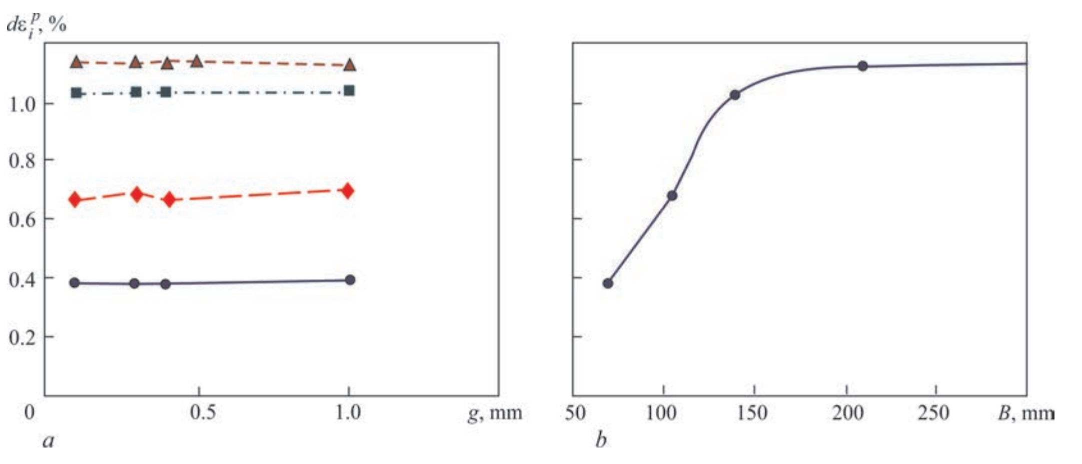

Figure 6. Dependence of maximal values of the increment of intensity of plastic strains $d\varepsilon_i^p$ in the pipeline defect zone on the size of the gap *g* (*a*) and for external overlays of different dimensions (*b*): ● — *B* = 70 mm; ♦ — 105; ■ — 140; ▲ — 210

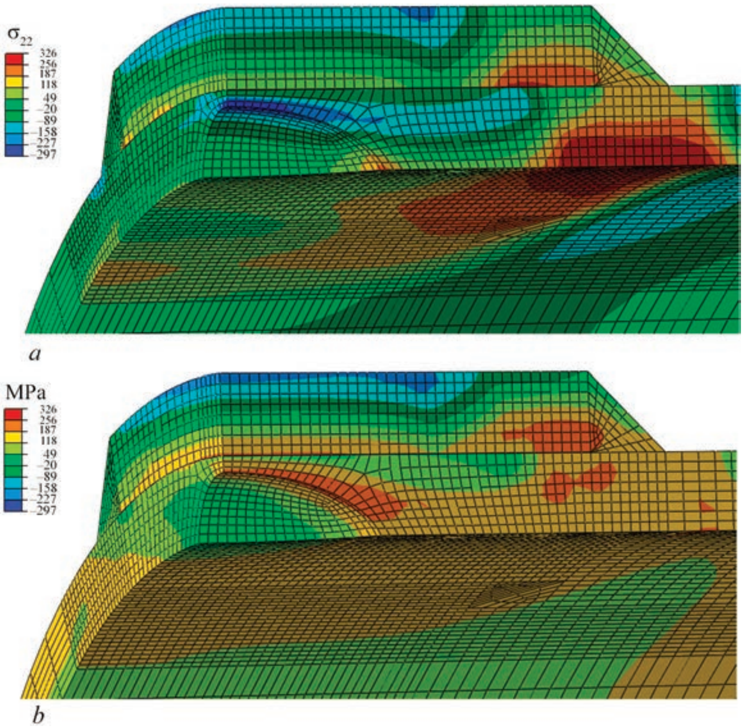

Figure 7. Distribution of circumferential stresses in the zone of pipeline defective section with an external overlay: *a* — residual welding stresses; *b* — from operational load allowing for residual welding stresses

as size *B* — the distance from the defect edge to that of the overlay. Minimal size *B* should be [3]:

$$B = \frac{3}{4}\sqrt{\frac{D \cdot s}{2}} = \frac{3}{4}\sqrt{\frac{630 \cdot 25}{2}} \approx 70\ \text{mm}. \quad (4)$$

Results of prediction of the influence of dimension *B* on unloading of the pipeline defective section (Figure 6) showed that at increase of the linear dimension of the overlay the intensity of increment of ductile strains from operational load in the wall thinning zone becomes much greater, i.e. the effectiveness of the reinforcing structure becomes smaller. This is also explained by the fact that reinforcement of the defective section occurs through the welded joint of the external overlay, and the farther is the welded joint from the wall thinning zone, the lower is the effectiveness of unloading in the thinning zone. Therefore, at repair it is more rational to use minimal admissible linear dimensions of external overlays, which will ensure greater effectiveness of the defective section reinforcement, and will reduce the material cost and welding time.

INFLUENCE OF RESIDUAL WELDING STRESSES

Considering that the welded joints of the external overlay can influence the SSS in the zone of pipelines defect, numerical determination of the residual state of the defective section after welding the external overlay was performed. Welding was conducted by a three-pass fillet weld. Welding speed was 2 mm/s, energy input in the first pass was 23.2 kJ/cm that in the second and third passes was 28.5 kJ/cm.

Residual stresses and strains were determined using thermoplastic analysis by finite element method as a result of following the kinetics of stresses and strains in time under the impact of the thermal cycles of heating and cooling during performance of each welding pass along the external overlay edge.

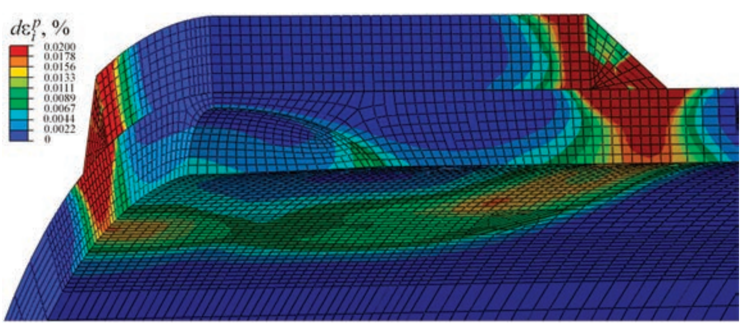

Figure 8. Distribution of the intensity of plastic strains $d\varepsilon_i^p$ in a pipeline section with a wall thinning defect with an external overlay after welding and loading by internal pressure and temperature (in the thinning zone $d\varepsilon_i^p$ = 0.001–0.002)

In keeping with the results of the numerical study (Figure 7), high (up to the yield limit and higher) tensile residual stresses form in the zone of external overlay welded joints, which in the zone of the wall thinning defect cause generate the balancing high compressive stresses of up to 200 MPa. At operational load under the impact of internal pressure $P = 11.8$ MPa and temperature $T = 300$ °C the residual stresses are redistributed, and a stressed state forms in the zone of wall thinning defect (Figure 7), which is characterized by a zone of high tensile stresses (up to the material yield limit) of smaller dimensions, compared with the data without allowing for the residual welding stresses (Figure 4, *b*). Accordingly, the increment of the intensity of plastic strains $d\varepsilon_i^p$ in the zone of wall thinning in the pipeline defective section, from operational load, decreased from 0.004 to 0.001–0.002 (Figure 8). We can come to the conclusion that the compressive residual stresses, developing in the wall thinning zone as a result of welding the external overlay, can contribute to increase of the effectiveness of reinforcement of the pipeline defective section.

CONCLUSIONS

Results of the conducted package of computational studies of the effectiveness of unloading the defective section of a pipeline with ECW defect showed that mounting the welded external overlay can be an effective technology of repair of the technological pipelines with ECW defects for the needs of nuclear power engineering. It was determined that:

1. It is rational to use minimal admissible dimensions of external overlays, that ensures the highest efficiency of reinforcement the pipeline defective section and reduces the material costs and repair time.

2. A significant advantage of welded external overlays over bandages and welded sleeves is the fact that the initial gap between the reinforcing structure and the wall in the case of welded external overlay does not influence the effectiveness of unloading the pipeline defective section. This factor allows greatly reducing the labour consumption of the process of the overlay preparation and mounting (welding) at pipeline repair.

3. Compressive residual stresses, forming in the wall thinning zone as a result of external overlay welding, can contribute to increase of the effectiveness of reinforcement of the pipeline defective section.

REFERENCES

1. (2011) GBN V.3.1-00013741-12:2011. *Main gas pipelines. Repair by arc welding in service conditions.* Ministry of Energy and Coal of Ukraine [in Ukrainian].
2. Jaske, Carl E., Hart, Brian O., Bruce, William A. (2006) *Updated pipeline repair manual.* R2269-01R, United States.
3. *Repair of pressure equipment and piping*. An American national standard. ASME PCC-2-2018 (Revision of ASME PCC-2-2015).
4. Vorona, G.V., Makhnenko, O.V., Milenin, O.S. (2023) Effectiveness of unloading a section of NPS pipeline with a pipe wall thinning defect by mounting a band or welded sleeve. *Tekh. Diahnost. ta Neruiniv. Kontrol*, **4**, 11–19 [in Ukrainian]. DOI: https://doi.org/10.37434/tdnk2023.04.02
5. (2019) MT-T.0.03.224–18: *Procedure for determination of acceptable thicknesses of NPP pipeline elements from carbon steels subjected to erosion-corrosion wear*. NAEK Energoatom [in Russian].
6. (1989) PNAE G-7-002–86: *Norms of strength analysis of equipment and pipelines of nuclear power plants*. Moscow, Energoatomizdat [in Russian].
7. Milenin, A., Velikoivanenko, E., Rozynka, G., Pivtorak, N. (2019) Probabilistic procedure for numerical assessment of corroded pipeline strength and operability. *Int. J. of Pressure Vessels and Piping*, **171**, 60–68. DOI: https://doi.org/10.1016/j.ijpvp.2019.02.003
8. Timoshenko, S.P., Voinovsky-Krieger, S. (1966) *Plates and shells*. Moscow, Nauka [in Russian].

ORCID

G.V. Vorona: 0000-0002-9724-3759,
O.S. Kostenevych: 0000-0002-7427-2805,
O.S. Milenin: 0000-0002-9465-7710,
O.V. Makhnenko: 0000-0002-8583-0163

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

O.V. Makhnenko
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: makhnenko@paton.kiev.ua

SUGGESTED CITATION

G.V. Vorona, O.S. Kostenevych, O.S. Milenin, O.V. Makhnenko (2024) Reinforcement of an NPP pipeline with a wall thinning defect by applying external weld overlay. *The Paton Welding J*., **9**, 44–49.
DOI: https://doi.org/10.37434/tpwj2024.09.06

JOURNAL HOME PAGE

https://patonpublishinghouse.com/eng/journals/tpwj

Received: 23.04.2024
Received in revised form: 10.06.2024
Accepted: 03.09.2024