Oliynyk O. I.[1], *Perepichay A. O.*[2], *Torop V. M.*[1], *Prokhorenko O. V.*[2], *Perepichay I. I.*[1]

[1] **E. O. Paton Electric Welding Institute of NAS of Ukraine. Ukraine, Kiev**
[2] **National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute». Ukraine, Kiev**

RESIDUAL STRESS-STRAIN STATE IN ZONE OF WELDED-UP PIPE WALL THINNING DEFECT OF MAIN PIPELINES

The results of modelling of residual stress-strain state in a defect welding zone were presented for a pipe wall thinning defect of 1420×16 mm thickness from steel 17Г1С of main pipelines. It has an oval shape with 100×60 mm size and 6 mm depth. Calculation finite-element model of pipe area with defect was developed and parameters of residual stress-strain state were determined. Mechanized CO_2 solid wire welding-up of the defect was carried out on a pipe specimen and residual welding stresses, which verified reliability of numerical results of the modelling, were determined using experimental mechanical method. [dx.doi.org/10.29010/083.5]

Key words: *pipe wall thinning; finite-element model; stress-strain state; main pipeline.*

Introduction

The important factors for efficiency and reliable operation of linear part of main pipelines is periodic control of state of the pipeline linear part, visual examination and inspection using technical internal and external diagnostic means as well as timely maintenance and repair works.

The statistical data from external diagnostic of the state of main pipeline linear part, accumulated during two last decades, indicate that corrosion type damages, i.e. pipe wall thinning, pits and metal wear-out, are the most widespread by number of found defects. Quantity of such defects makes not less than 50–60% of total volume [1].

The main methods of repair are installation of the bands or unions of various designs on the damaged pipe surface or restoration of wall thickness by welding.

The latter method is rational in terms of minimizing time and materials and efficiency work execution. For example, it allows making repairs in places where installation of reinforcing structures is complicated or impossible.

In general case repair welding of the defect takes place in four stages.

- deposition of the first layer with parallel "stringer" beads along the pipe axis;
- deposition of the second layer with parallel "stringer" beads in circumferential pipe direction;
- contour weld of 10–14 mm width with electrode oscillation for overlapping of the base and deposited metal of the second layer;
- deposition of thermal-annealing layer by "stringer" beads in pipe longitudinal direction.

The effect of residual welding stresses on welded jointperformance is thoroughly studied in many papers [2, 3, 4], but as for welding of corrosion defects, the information on nature of the stressed state is limited. In this connection, there is necessary to carry out research works on calculation and experimental determination of distribution of residual stresses, distortions and deformations in the place of repair of pipe wall thinning. In order to solve a determined calculation problem it is reasonable to use mathematical modelling of stress-strain state (SSS) parameters by finite-element method [5] during repair welding of the pipe wall corrosion defect.

The aim of the work is calculation of the stress-strain state (SSS)parameters in a welding repair zone of the defect and comparison with the experimentally obtained results as well as determination of the dependencies of residual stress distribution for this method of defect welding-up.

Investigation problems

- Solution of coupled thermo-elasto-plasticity problem during welding of volumetric wall thinning defect of set parameters on main pipeline specimen.
- Verification of adequacy of developed finite-element model of calculation of stress-strain state parameters by means of comparison of calculation results with experimental data.
- Determination of distribution nature and value of residual stresses, effective plastic strains and distortion after welding-up of wall thinning defect on main pipeline specimen.

Main part

Determination of SSS in a defect repair zone was performed by calculation using developed finite-element model of pipe specimen with defect, which takes into account geometry of specimen and defect, dependence on temperature of mechanical (modulus of elasticity, yield point) and thermophysical (temperature coefficient of linear expansion, thermal conductivity, volumetric heat capacity) characteristics of base and weld metal, composition of consumables, parameters of welding modes, number and sequence of passes for multi-pass welds.

Reliability of finite-element modelling of defect welding-up process is based on comparison of geometry of simulated weld pool with actual data determined on experimental specimens for given modes of layers deposition.

The object of investigation is the pipe wall thinning of oval shape and the following size, i.e. length – 100 mm, width – 60 mm, depth – 6 mm. The defect on length matches with a pipe longitudinal direction, defect width with the circular direction. The defect is made mechanically on outer surface of a pipe section of 1420 mm diameter and 16 mm wall thickness from 17Г1С steel.

The experimental part of the work lied in welding-up of the corrosion defect on pipe outer surface by successive deposition of “stringer” beads by mechanized CO_2 arc welding with Св-08Г2С wire of 1.2 mm diameter and determination of residual welding stresses by a mechanical method in pre-selected places.

Physical and chemical properties of steel 17Г1С and welding wire are shown in Tables 1, 2. The parameters of modes of beads deposition depending on the type of deposited layer are given in Table 3.

Repair technology according to [8] was used for defect welding-up. It supposes deposition of each layer normal to previous one and boxing of defect along the contour. A scheme of repair performance is shown in Figure 1.

Taking into account locality of distribution of welding stresses around the defect and in order to reduce the time consumption for solving the thermo-elasto-plasticity problem for real size pipe section, it is reasonable to perform calculations of SSS parameters around the corrosion defect for finite-element model of pipe sector. This model is a plate of rectangular shape of 250×300 mm size, oriented by smaller size along the pipe generatrix. The larger defect is also oriented along the cavity tube. The finite element mesh has the dimensions from 0.3 mm in the place of repair

Table 1

Composition of base metal and consumables, % [6, 7]

Material	C	Si	Mn	S	P
17Г1С	0,17	0,4–0,6	1,15–1,6	<0,04	<0,008
Св-08Г2С	0,085	0,72	1,65	0,020	0,015

Table 2

Mechanical characteristics of base metal and consumables [6, 7]

Material	σ_u, MPa	σ_y, MPa	δ, %
17Г1С	510	345	23
Св-08Г2С	550	430	31

Table 3

Parameters of modes of bead deposition

Layer No.	Welding current, A	Arc voltage, V	Deposition rate, m/h	Arc efficiency of deposition process
First, second filling	135	20–21	16,2	0,8
Contourweld, thermal-annealing	135	20–21	13,6	0,8

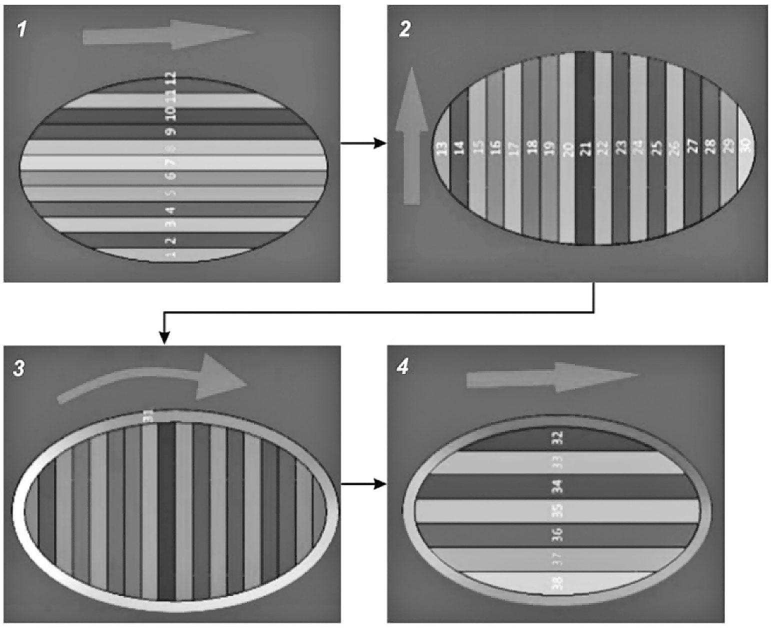

Fig. 1. Scheme of deposition of beads on defective area for each layer:
1 – filling (1–12 beads);
2 – filling (13–30 beads);
3 – contour (31 bead);
4 – thermal-annealing (32–38 beads)

and around the corrosion defect, at a distance from the repair place the dimensions of the elements are 10 mm.

The finite-element model of the plate with defect has fixation in only in one node to ensure the correspondence of simulated process of defect welding to the conditions of defect welding on a free plate-specimen made experimentally.

Modelling of the process of defect welding-up is carried out taking into account modern methods of mathematical modelling of thermal processes in welding. A model of volumetric heat source is used in this paper. It was proposed by J. Goldak in a form of double ellipsoid, which takes into account the dimensions of frontal and end parts of weld pool as well as metal penetration depth [9].

Geometry parameters of the weld pool were determined experimentally for different layers during defect welding-up (Figure 2). The results of full-scale measurements of dimensions are given in Table 4.

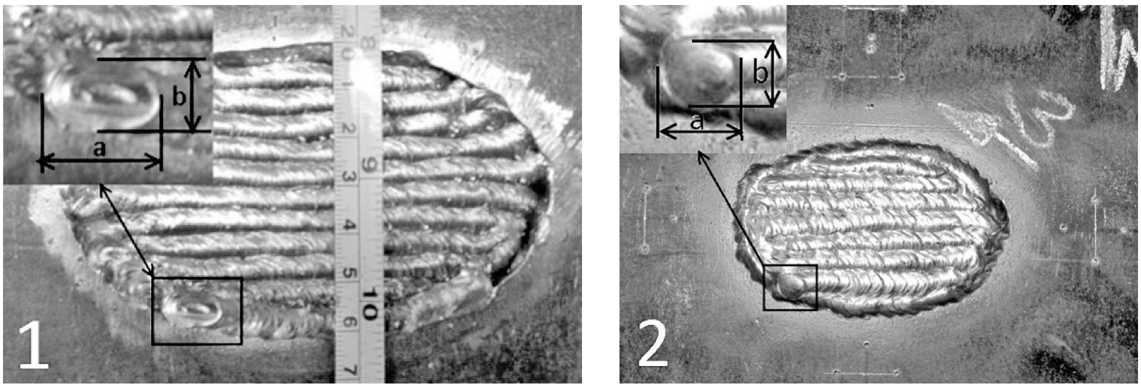

Fig. 2. Experimental determination of geometry parameters of pool for: filling – (1) and thermal-annealing – (2) deposited layers

Table 4

Geometry parameters of weld pool for calculation model

Layer	Width b, mm	Length a, mm	Depth h, mm
First, second, filling	8	11	4
Contour, thermal-annealing weld	10	12	4

Experimental determination of longitudinal and transverse stresses was carried out mechanically. For this purpose, the gauge lengths, i.e. holes of 1 mm diameter drilled to 3–4 mm depth were made before welding in two mutually perpendicular directions (longitudinal and circumferential) with 25 mm spacing on external and internal surfaces of pipes. Measurements of gauge length distortions were performed before and after welding using mechanical strainmeter in accordance with the procedure described in [3]. Further, the calculated values of residual relative elastic strains converted in residual stress according to Hooke's law for biaxial stress-strain state were calculated. The diagrams of experimentally obtained stresses are presented in Figures 4 and 8.

Results of finite-element modelling of residual stress-strain state of pipe specimen with thinning defect

Thermo-elasto-plasticity problem was solved for outer and inner surfaces of pipe specimen with defect. As a results the parameters of residual SSS in form of fields of distribution of residual stresses (σ_z, σ_x), plastic strains and distortions were obtained as well as distributions of these parameters in mid longitudinal and cross sections of the pipe specimen with corrosion defect were plotted.

Figure 3 shows the fields of longitudinal normal stresses σ_z in area of defective section deposition on pipe outer and inner surfaces.

At the outer surface, the maximum tensile stresses σ_z reach the values of ~340 MPa and are concentrated in the contour weld zone and in the place of deposition welding completion. The compression stresses zones are formed in transverse direction on both sides of the defect.

It is obvious increase of tension stresses σ_z to values close to base metal yield point on the inner side of specimen pipe under defective zone, outside the defective zone there are compression stresses at the level of ≈ -70 MPa.

As can be seen fromFigure 3 the stresses in the area of completion of surfacing of thermal-annealing layer are higher on outer as well as inner pipe surfaces. This is explained by high level of plastic strains that arise in the place of deposition of last weld layer and cause increase of level of tensile stresses in this area [10].

Welding of contour weld (third layer) results in σ_z stresses increase on the outer side due to longitudinal shrinkage metal and insignificant relaxation on the inner side.

Distribution of residual longitudinal stresses in midcross and longitudinal sections of pipe in the place of corrosion defect is shown in Figure 4 and Figure 5, respectively.

As can be seen from Figure 4 the stresses on outer side in the defect zone are lower (~110...282 MPa) in contrast to the inner side (~237...347 MPa). Such a magnitude of stresses in the defect area indicates formation of a deflection in the direction ofpipe radius. The inner surface of pipe is more stretched by longitudinal stresses than outer one. In addition, the outer side of pipe specimen has transfer of tensile stresses into compression stresses up to ~ -241...-274 MPa. The magnitude of stresses on the inner side under the defect approaches the yield limit for this steel and reaches ~340...350 MPa, and in places outside the defect stresses decrease to ~50...70 MPa values.

Residual stresses do not exceed 280 MPa and have a uniform distribution nature according to distribution of longitudinal stresses σ_z (Figure 5) on the pipe inner surface in the central zone under the defect.

Stresses in the defect zone on pipe outer side are slightly lower than ~180 MPa, with the exception of individual peaks of ~550...600 MPa in the contour weld zone due to longitudinal shrinkage of the latter.

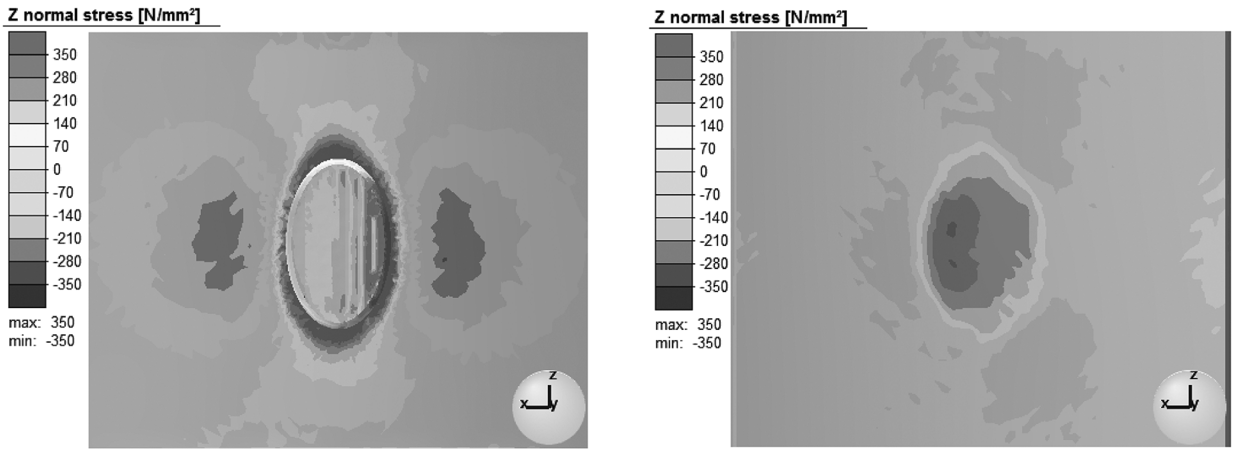

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Fig. 3. Fields of longitudinal residual stresses σ_z on outer – (a) and inner – (b) surfaces of pipe specimen

In general, nature of stress distribution in the defect zone on pipe outer and inner sides is similar.

Fields of circumferential residual stresses σ_x, which are presented in Figure 6 are similar to the fields of longitudinal stress σ_z and slightly vary in value.

Zones of compression circumferential stresses are concentrated at the ends of defect in longitudinal direction of the pipe specimen. The biggest values of tensile stresses are concentrated in the area of contour weld, namely on outer surface under the defect, circumferential stresses σ_x make 210...280 MPa, and on inner surface it is 140–210 MPa, and in general they are lower by ~30–34% in comparison with the longitudinal stresses σ_z, value of which reaches 115...185 MPa on the outer and 340...350 MPa on inner surfaces of the investigated pipe specimen.

Figure 7 shows the chartsof distribution of residual circumferential stresses in the middle cross section for outer and inner surfaces of the pipe specimen. On free side and end surfaces, transverse stresses equal zero that correlates well with stress-strain theory [3]. Tensile stresses on pipe specimen outer surafce in a zone over the defect reache ~280 MPa.

As can be seen from distribution of circumferential stresses σ_x (Figure 7), a zone near the contour weld on pipe outer surface was subjected to significant plastic strains due to longitudinal shrinkage of the latter. Circumferential stresses σ_x in this section are ≈ 15...25% greater than yield limit of the material of pipe specimen σ_y = 345 MPa and reach 410–460 MPa level. At the same time, on the back side, under defect zone, there are sifficintly uniform stresses of $\sigma_x \approx 200 \pm$ ± 20 MPa value. Also, there is a small area with compression stresses $\sigma_x \approx$ -100 MPa to the left of defect welding-up place.

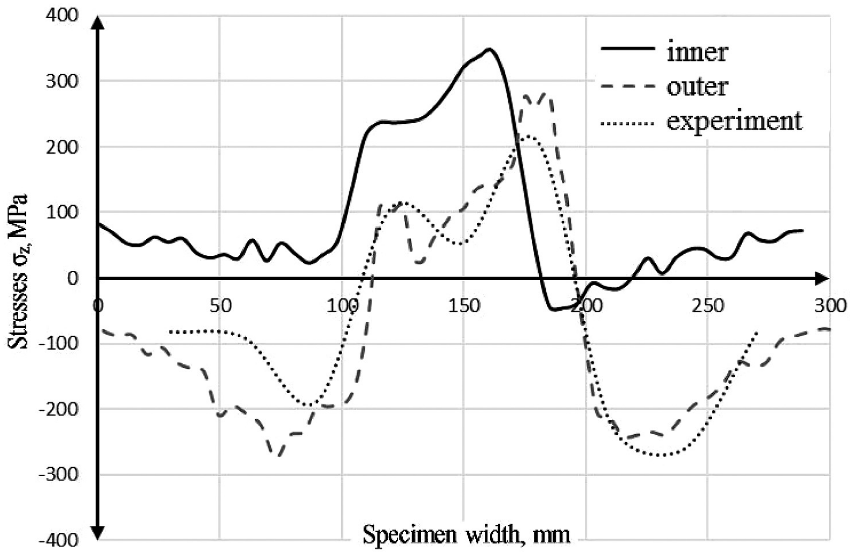

Fig. 4. Distribution of residual longitudinal stresses σ_z in cross section of pipe specimen in the place of corrosion defect

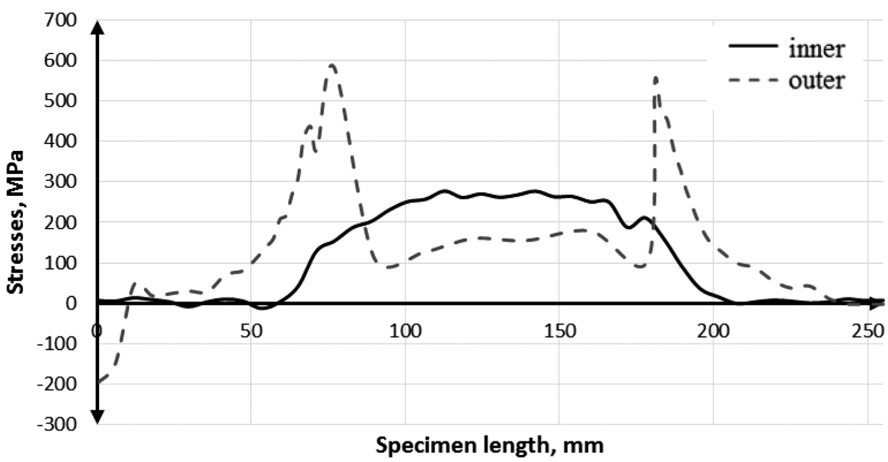

Fig. 5. Distributon of residual longitudinal stresses σ_z in longitudinal section of pipe specimen in the place of corrosion defect

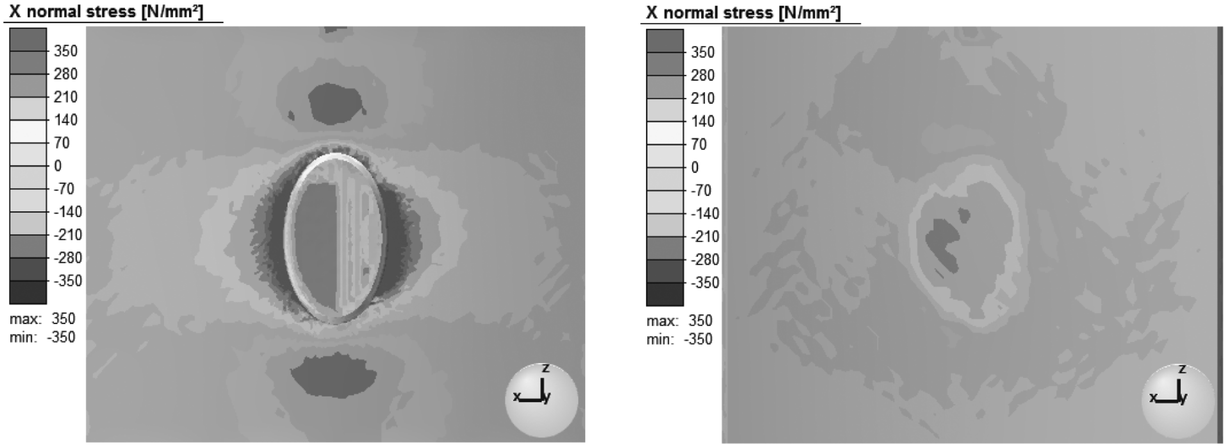

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Fig. 6. Fields of residual circumferential stresses σ_x on outer – (a) and inner – (b) surfaces of pipe specimen

Stresses σ_x on the pipe outer surface in the contour weld make ~410–460 MPa and this is 60% higher than that in filling welds (~256...278 MPa).

Circumferential stresses σ_x by the length of welded joint are distributed as shown in Figure 8. It is clear from the diagram that zones of compression stresses were formed on the pipe outer surface out of defect boundaries, their maximum values reach ~265... -269 MPa. In the defect zone on the outer surface tensile stresses σ_x (~ +260 MPa) are ~22% higher than that on the inner (~203 MPa). The nature of circumferential stresses σ_x distribution in the pipe cross section is similar to the distribution of longitudinal stresses σ_z in the pipe longitudinal section, except for that the longitudinal stresses (Fig. 5) in the defect zone are higher than the same on the pipe inner surface, and circumferential stresses (Fig. 7) are higher than that on the outer surface.

The characteristic for process of deposition welding or filling by several layers of local areas on platework shell structures is a highly concentrated local heat input.

This results in development of complex thermodeformation processes in a product, which cause distortion ofsurface points in different directions, and during cooling, provoke shrinkage of deposited metal in transverse and longitudinal directions, which causes development and non-uniform distribution of residual plastic strains.

Uncompensated residual effectiveplastic strains, which have non-unoform distribution in specimen cross section as well as in a zone of deposited defect, are the main reason of formation of residual welding stresses, therefore it is reasonable to analyze their nature of distribution.

Figure 9 shows the fields of residual effective plastic strains for outer and inner surfaces of the pipe,

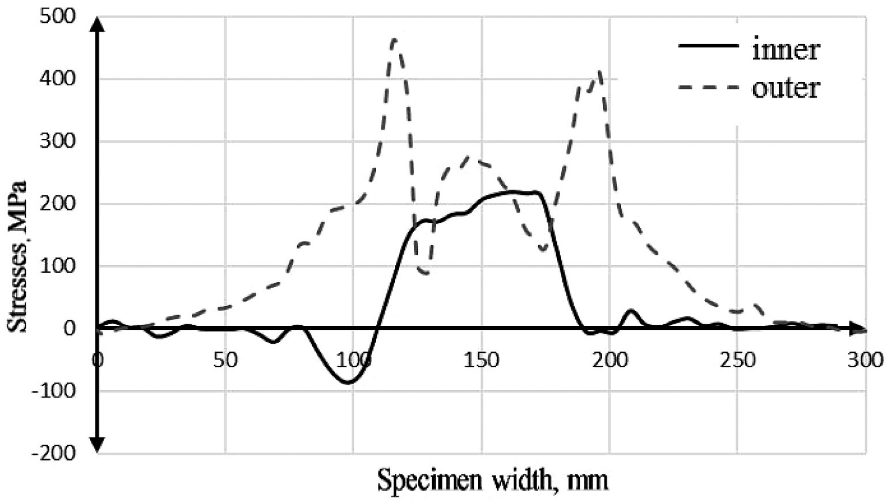

Fig. 7. Distribution of residual circumferential stresses σ_x in pipe specimen cross section in place of corrosion defect

which following the expectations are localized in the area of welded-up defect.

The maximum values of effective plastic strain appear on pipe specimen outer surface in the contour weld bead of the defect and in the last welded-up bead of thermal-annealing layer and makes ~0.1. On pipe inner surface, the plastic strain is concentrated in the defect center and does not exceed ~0,005, and it is

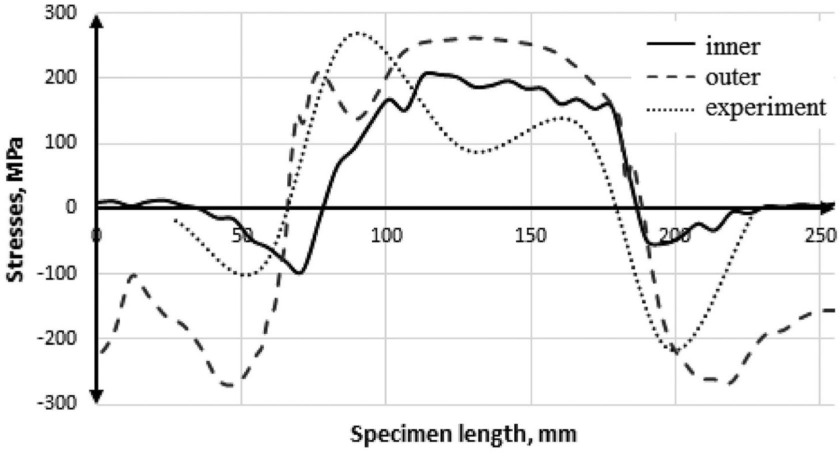

Fig. 8. Distribtuion of residual circumferential stresses σ_x in longitudinal section of pipe specimen in palce of corrosion defect

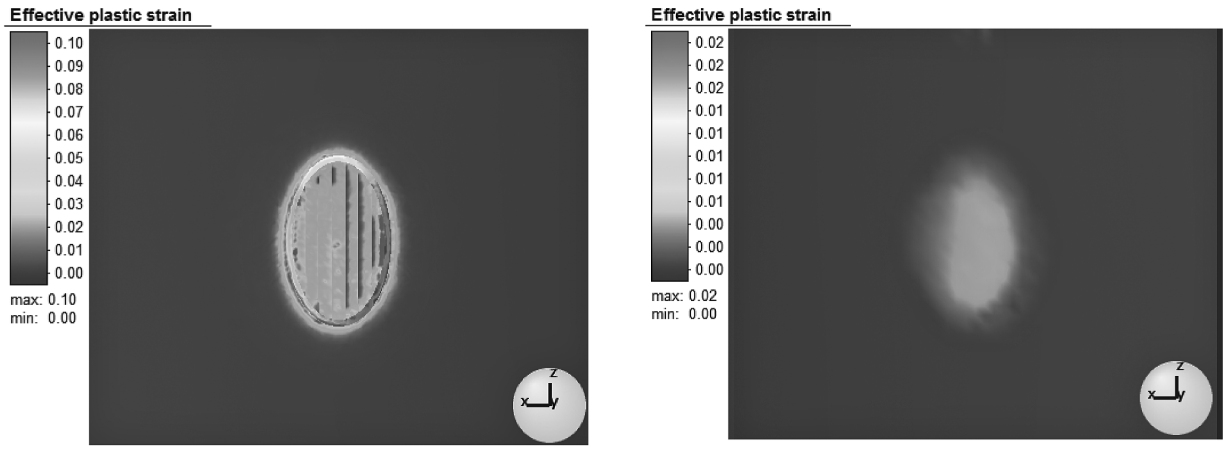

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Fig. 9. Fields of residual effectiveplastic strains on outer (a) and inner (b) surfaces of pipe

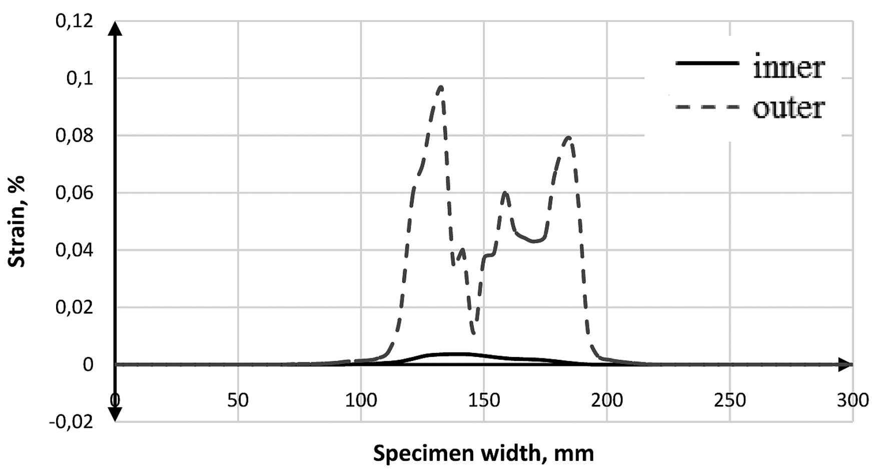

Fig. 10. Distribution of residual effectiveplastic strains in middle cross section of pipe specimen

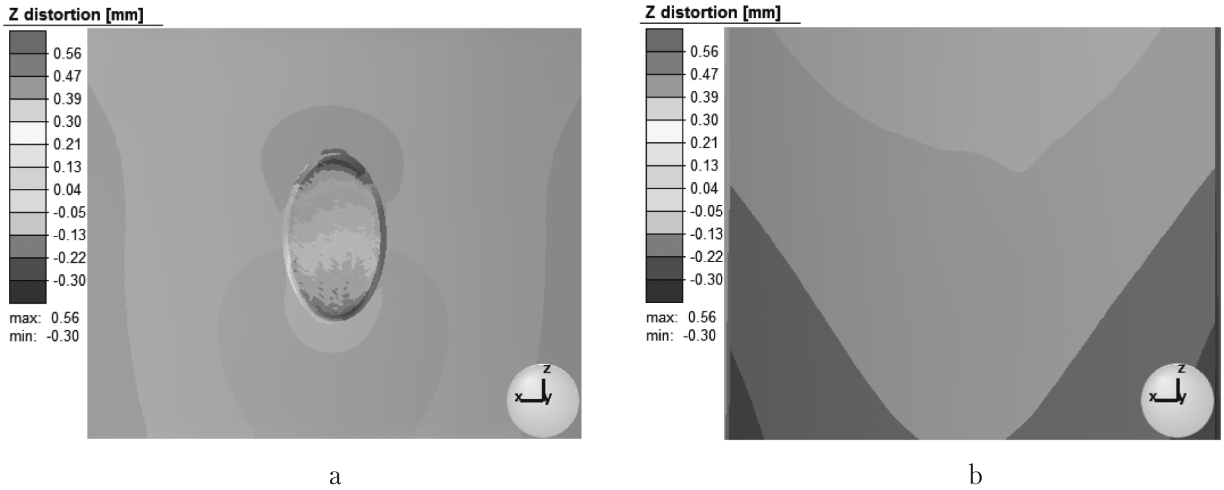

Fig. 11. Field of longitudinal distortions on outer (a) and inner (b) surafces of pipe

~0,02...0,05 on the outer surface in the center. This feature can be explained by joint effect of shrinkage of deposited metal in the longitudinal and circumferential directions during welding-up of pipe wall defect.

According to Figure 10 residual effective plastic strain on the outer side has non-uniform distribution, namely residual plastic strain is ~50...60% less in the center of defective zone than at the edges (~0.079...0.096) and on average makes ~0.04. Peak values of deformation are formed in welding-up of contour weld and make ~0,079...0,1.

Following existing classification of residual distortions in welded structures for large diameter pipelines, it is expected that distortion of pipe walls will have form of concavity (lobing) or convexity caused by action of shrinkage forces [3].

Figure 11 shows the fields of distribution of residual distortions in longitudinal direction for the case of defect welding-up in 300×250 mm pipe section in free condition without fixing according to the experiment.

Distortions along the generatrix of pipe wall outer surface are distributed non-uniformly. Upper part of the defect (Figure 11, a) in the contour weld zone was displaced with "-" sign, i.e. -0.22...-0.30 mm, and the lower part of much larger distortions with "+" sign, namely 0.47...0.56 mm. Thus, longitudinal shrinkage of weld metal in the defect region took place in the given coordinate system, origin of which is combined with the defect center and the axes directed in accordance with Figure 11.

The inner side of pipe wall (Figure 11, b) was also subjected to longitudinal reduction in -0.05...-0.10 mm range. Such non-uniform distribution of distortions can be explained by rigid fixing of pipe specimen assemblies from one side only and longitudinal plastic reduction of welded-up area.

Figure 12 shows the distribution of longitudinal displacements along the weld, from which it is seen that the peak values of distortion points on outer surface are in the range from -0,1 mm to ~ +0,5 mm. The inner side of pipe wall wall specimen in this cross section displaces no more than by -0.1 mm.

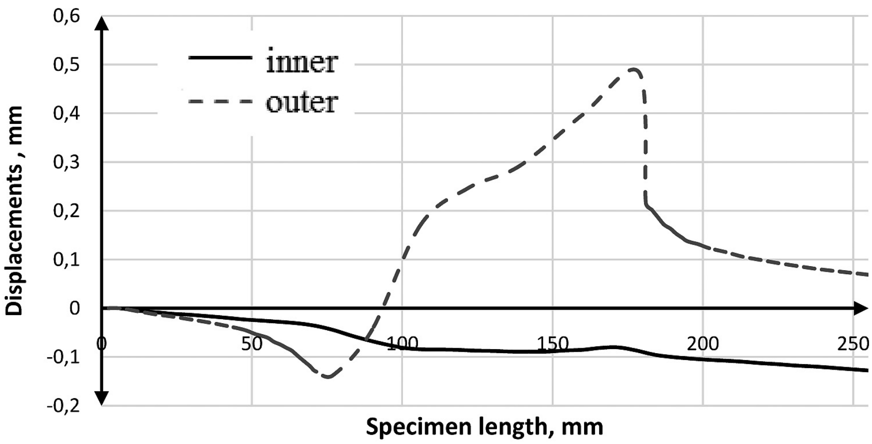

Fig. 12. Distribution of longitudinal displacements in middle longitidinal section of pipe specimen

The fields of transverse distortion (Fig. 13) are similar in nature to distribution of longitudinal distortion. However, there is also a difference, i.e. virtually complete symmetry of the distortion fields on the both sides of defect on the outer surface, which is absent in Figure 12. This can be explained by symmetry of boundary conditions for pipe specimen in transverse direction, no fixation of nodes along the model lateral edges. The total transverse shrinkage of deposited metal was about 0.68 mm.

Distortions at the edges of pipe specimen on outer surface decrease and make ~0.05 mm with the sign "+" on the left and "-" on the right. On the inner side the distortions increase at pipe specimen edges.

Such non-uniform distribution of distortions in the pipe specimen width is caused by non-uniformity of temperature distribution along the defect width. Transverse displacemtnts by nature of distribution are similar to the front and back sides, but vary in value.

Fig. 15 shows the fields of residual distortions from the plane of welded-updefect. It can be seen that the zone of welded-up defect contains bending deflection to the reverse side of whole defective area by ~ -0,5 mm value on outer surface and ~ -0,2 mm – on inner one. Not fixed part of pipe specimen located below the defective zone has been bent upward by ~1.3...1.5 mm in front surface direction.

Figure 16 shows the charts of distortions along Y axis in longitudinal section of pipe specimen. It can be seen from the diagram that a local concavity is formed on the tests plate in the zone of defect welding-up.

The area with deposited metal on the outer side of pipe specimen deflects down to -0.57 mm, at that the free end of pipe specimen is displaced by a value up to +1.5 mm in opposite direction.

The nature of distribution of these distortions on the inner side of pipe specimenis preserved, only values of curve deflection reaches -0,2 mm, and the edges rise to +1,3 mm.

Since the distortions from the plane are the largest by value in comparison with the longitudinal and transverse reductions, they shall be taken into account during repair at operating pipeline.

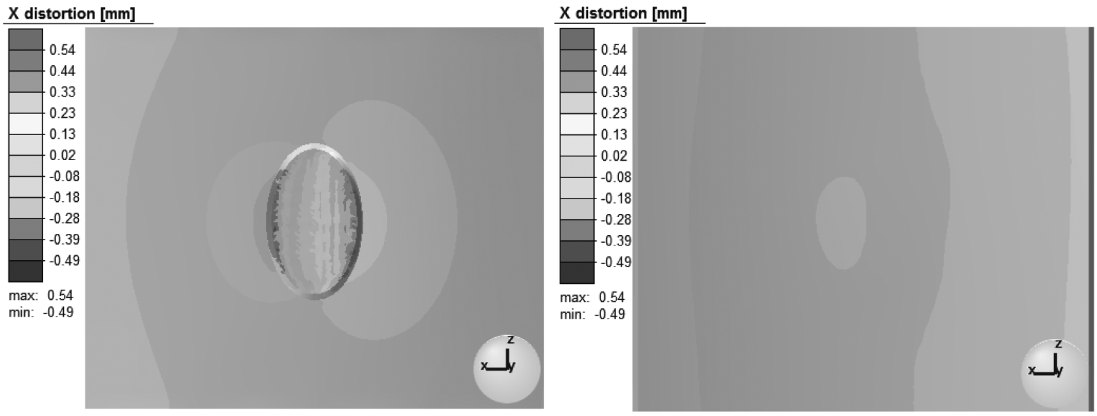

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Fig. 13. Field of residual transvese distortions on outer (a) and inner (b) surafecs of pipe speicimen

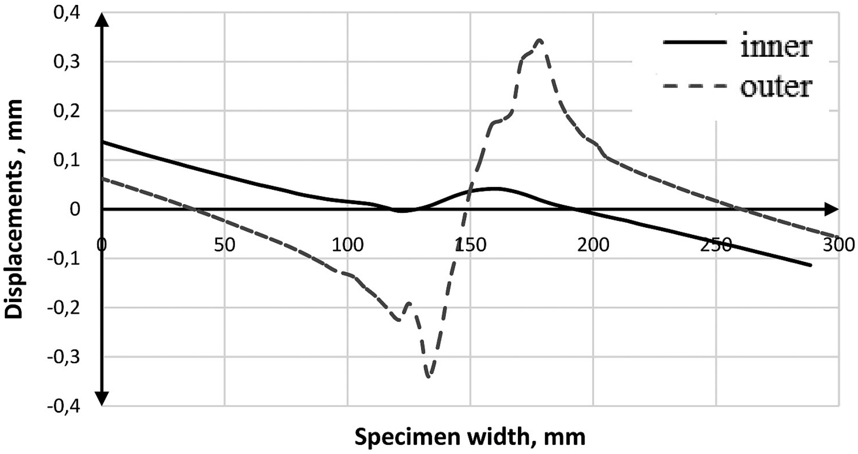

Fig. 14. Distribution of transverse displacements on pipe specimen width

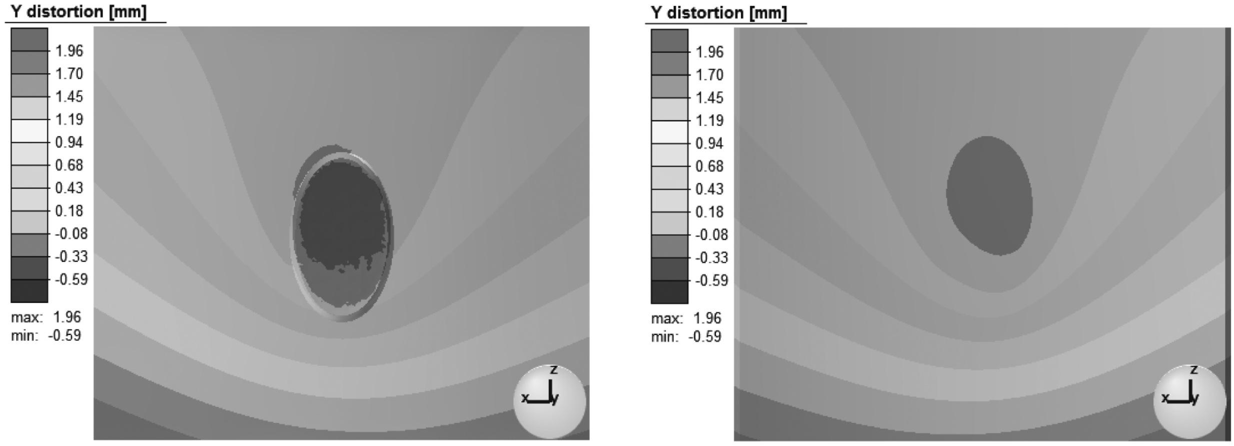

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Fig. 15. Fields of residual Y displacements form plane on outer (a) and inner (b) surfaces of pipe speicimen

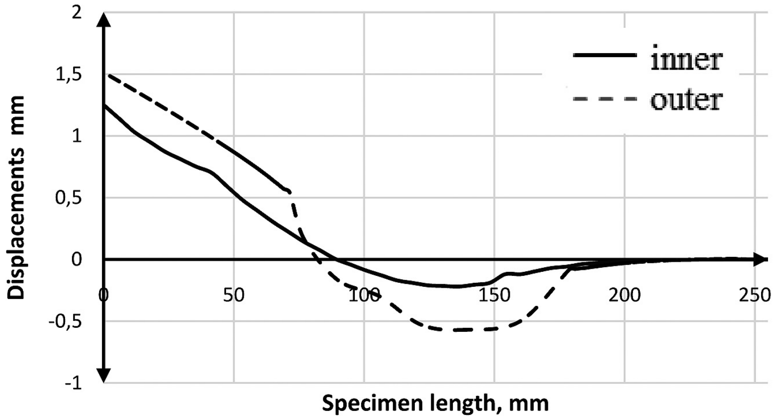

Fig. 16. Distribution of distortions from plane along pipe specimen length

Conclusions

1. The finite-element method was used to solve the coupled thermo-elasto-plasticity problem in sequentail multi-pass welding-up of pipe wall thinning defect by four layers using semi-automatic CO_2 consumable electrode welding and correspondance of the calculated values of residual welding longitudinal and circumferential stresses in the pipe section with a defect toexperiment results was established.

2. It is shown that longitudinal welding stresses in zone of welding of contour weld of defect on outer side of the pipe specimen make ~110...282 MPa, that is ~20...54% less than tension stresses on outer side ~237...347 MPa, that promote formation of deflection of defective area in pipe radius direction.

3. It is determined that distribution of longitudinal stresses in zone under the defect is uniform and the values of residual stresses do not exceed ~280 MPa on inner side of the pipe and ~160 MPa on pipe outer surface.

4. It is shown that circumferential stresses in contour weld on outer pipe surface make ~410...460 MPa and this is ~60% less than in filling welds (~256...278 MPa).

5. It is found that the maximum values of circumferential stresses σ_x were formed in defect area and make 210...280 MPa on outer surface and -140...210 MPa on inner surface, and in total they are ~30...34% lower in comparison with longitudinal stresses σ_z, value of which reach 115...185 MPa on outer and 340–350 MPa on inner surfaces of investigated pipe specimen.

6. It is determined that distortions from the plane are the largest on value in comparison with longitudinal transverse reductions and they shall be taken into account during repair at operating pipeline.

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Олійник О. І. ***[1], Перепічай А. О.[2], Тороп В. М.[1], Прохоренко О. В.[2], Перепічай І. І.[1]***

[1] Інститут електрозварювання ім. Є. О. Патона НАН України. Україна, м. Київ
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ЗАЛИШКОВИЙ НАПРУЖЕНО-ДЕФОРМОВАНИЙ СТАН В ЗОНІ ЗАВАРЕНОГО ДЕФЕКТУ СТОНШЕННЯ СТІНКИ ТРУБИ МАГІСТРАЛЬНИХ ТРУБОПРОВОДІВ

Для дефекту стоншення стінки труби діаметром 1420×16 мм зі сталі 17Г1С магістральних трубопроводів, який має форму овалу з розмірами 100×60 мм і глибиною 6 мм представлені результати моделювання залишкового напружено-деформованого стану в околі заварювання дефекту. Створена розрахункова скінченно-елементна модель ділянки труби з дефектом та визначені параметри залишкового напружено-деформований стану. На зразку труби виконано заварювання дефекту механізованим способом в CO_2 дротом суцільного перерізу та визначені експериментальним механічним методом залишкові зварювальні напруження, які підтвердили достовірність числових результатів моделювання. [dx.doi.org/10.29010/083.5]

Ключові слова: *стоншення стінки труби; скінченно-елементна модель; напружено-деформований стан; магістральний трубопровід.*

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