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ANALYSIS OF CAUSES OF FAILURE OF FIELD WELDED BUTT JOINTS OF MAIN PIPELINES AFTER LONG-TERM OPERATION

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ABSTRACT

In the work on the examples of failure of four pipelines, the authors considered and analyzed the causes of failure of circumferential welded butt joints of main gas and oil pipelines with a long-term service life of 530–1420 mm diameter from low-alloy ferritic-perlitic steels of grades 17G1S, 17GS and 15GSTYu, constructed back at the end of the twentieth century. Technical experts assume that, as a rule, accidents are associated with the failure of circumferential butt welded joints produced in field conditions. Literature sources give quite limited reliable information about the causes of defect formation that lead to the failure of field welded joints. The authors show that even having provided satisfactory mechanical properties of steels and at the absence of deviations in the chemical composition of welded joints, depressurization of pipelines occurred due to weakening of the weld as a result of defect formation during operation or during construction and assembly works. The defects include pores, lacks of fusion, lacks of penetration, edge displacement, use of embedded elements, etc. that were not detected by non-destructive testing methods. The obtained results made it possible to adjust a set of technological recommendations on the requirements and rules for performing assembly and welding works during the construction and repair of main pipelines in Ukraine over the last 20 years.

KEYWORDS: main gas and oil pipelines, circumferential butt welds, welded joints, failure, technological defects, assembly and welding works, violations

INTRODUCTION

More than 40 thou km of functioning gas and oil pipelines, the life of which is 30–50 years, are operated on the territory of Ukraine. The statistic data presented in the scientific and technical literature, as well as own experience indicate that accidents occurring on the main pipelines are often associated with the failure of circumferential welds of butt joints. As a rule, based on statistics, the cases of their failure are attributed to the rejection in construction and assembly works.

The key factors that contribute to the failure of circumferential welds are the sizes of defects, inappropriate properties of pipe steels and welded joints. In particular, the presence of loads [1] should be noted, that arise for different causes: through sources of active external effect, for example, because of the soil shift, or loads that occur in the pipeline in the process of construction and operation, etc.

For example, in many cases, as a cause of arising critical defects in producing a circumferential weld, slag inclusions are considered that were not timely detected and removed [2, 3]. The failure was also facilitated by the detected crack of 10 mm length in the weld root. But these authors did not consider the causes of defect formation. In literary sources [4], the share of failures of the main pipelines associated with the mentioned factor is estimated in 22–25 %. Moreover, welding defects are approximately 13–19 %. In [5], the results of fatigue studies have shown that in the presence of typical defects of welding in the circumferential weld, the pipeline service life may be more than 30 years. This approach may be the basis for analyzing the life and assessment of the reliability of the pipeline. The set of defects revealed by the method of non-destructive testing does not always allow finding the cause of their formation [6]. Therefore, it is important to determine the origin and causes of defect propagation in the welds to prevent their formation.

The aim of the work is to determine the probable causes for the formation of the most typical defects both at the stage of assembly as well as after a long-term operation, which led to failure during operation of gas and oil pipelines that were built at the end of the twentieth century.

PROCEDURE OF EXPERIMENTS

The studies were conducted on the samples of field butt welded joints. The fragments of circumferential joints of gas and oil pipelines were cut out from the failured parts of gas and oil pipelines with a diameter of 530–1420 mm during their repair. In most cases, by that time there were the pipes made of typical low-carbon low-alloy and microalloy steels of grades 17GS, 17G1S and 15GSTYu. The quality of welded joint metal was determined by the method of visual-optic inspection and by the study of the macro- and microsections of welded joints. The sections were prepared by the standard procedure using pastes of different

Table 1. Mechanical properties of base metal of investigated pipes

Code	Steel grade	Pipe sizes, mm, features of steel production technology	σ_y, MPa	σ_t, MPa	δ_5, %	*KCV*$^{-0}$, J/cm^2
1	17G1S	1020×14×10, normalized	460	568	30	90
2	17GS	720×7.5, hot-rolled	415	541	23	55
3	15GSTYu	1020×10.6, hot-rolled	416	592	27	109

Table 2. Chemical composition of base metal and metal of circumferential welds of investigated samples of welded joints

Steel grade	Zone of welded joint	Mass fraction of elements, %									
		C	Mn	Si	S	P	Al	Ni	Mo	Ti	Cr
17G1S	BM	0.16	1.32	0.47	0.023	0.016	N/D	0.06	N/D	N/D	0.04
	W	0.11	0.95	0.29	0.036	0.025	N/D	0.08	0.34	N/D	0.06
17GS	BM	0.18	1.09	0.49	0.029	0.023	0.006	0.09	N/D	–	0.054
	W	0.105	0.83	0.43	0.023	0.017	N/D	0.04	N/D	–	0.05
15GSTYu	BM	0.17	1.31	0.67	0.032	0.031	0.044	0.05	<0.03	0.14	0.07
	W	0.076	0.92	0.34	0.025	0.012	0.005	0.05	<0.03	0.12	0.06
17GS [8]	BM	0.14–0.20	1.0–1.4	0.4–0.6	≤0.0405	≤0.035	–	≤0.3	–	–	≤0.3
17G1S, TU 14-3-721	BM	0.15–0.20	1.15–1.60	0.4–0.6	≤0.035	≤0.030	–	≤0.3	–	–	≤0.3
15GSTYu ChMTU-156	BM	0.12–0.16	1.00–1.35	0.50–0.85	≤0.035	≤0.030	0.025–0.085	–	–	0.15–00.20-	≤0.3

granularity. The mechanical properties of steels were determined on the machine of ZDM model according to GOST 6996. The chemical composition of steels and weld metal was determined by the spectral analysis in the DFS-36 spectrometer.

RESULTS AND THEIR DISCUSSION

The authors considered and analyzed the four cases of the most characteristic failure of circumferential butt welded joints of pipelines that occurred during their operation. In the construction of such pipelines those grades of electrodes were used, which are recommended for arc welding of field joints according to VSN 006. Table 1 shows the mechanical properties of the studied pipe samples. The chemical composition of the base metal and metal of the circumferential welds is given in Table 2.

FEATURES OF MICROSTRUCTURE OF CIRCUMFERENTIAL BUTT WELDED JOINTS

Low-alloy steels in the normalized and hot-rolled state have a ferritic-perlitic structure with the grain size number 6, 7 and 8, and with a banded structure — not more than 2, Figures 1, 2, *a*.

The microstructure of metal of the studied circumferential welds on low-alloy ferritic-perlitic pipe steels 17G1S, 17GS and 15GSTYu is similar. The micro-

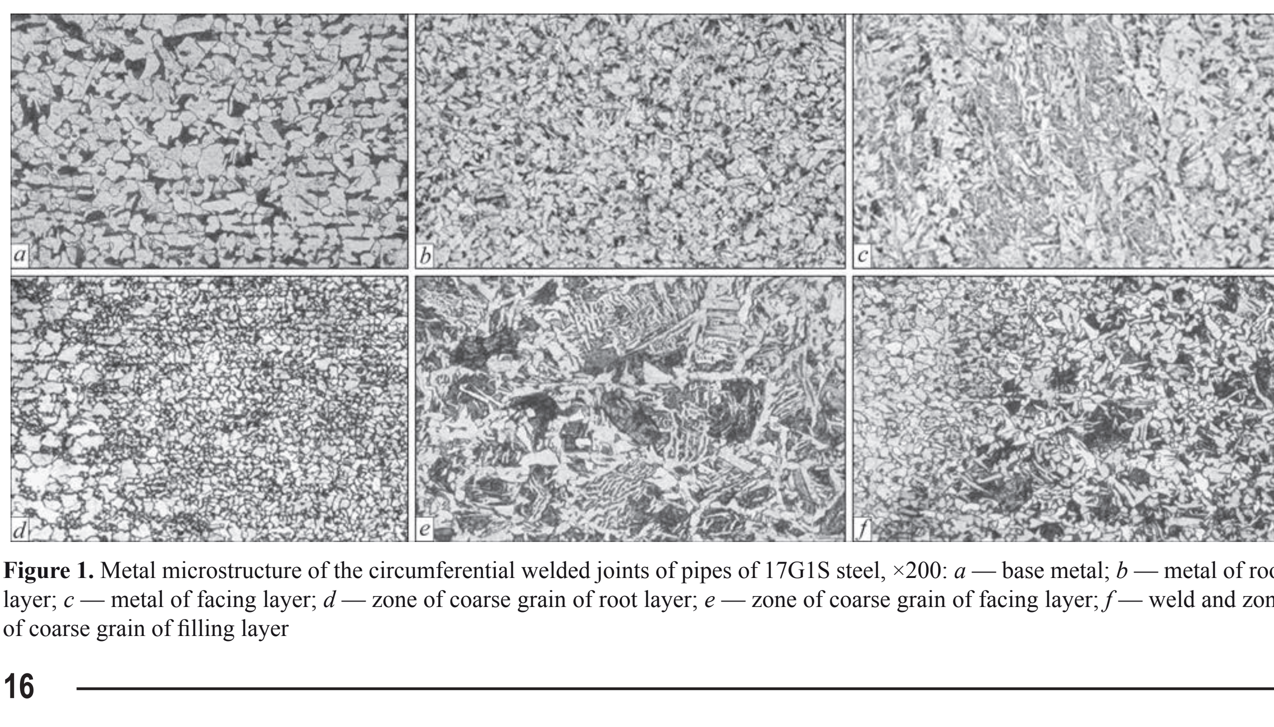

Figure 1. Metal microstructure of the circumferential welded joints of pipes of 17G1S steel, ×200: *a* — base metal; *b* — metal of root layer; *c* — metal of facing layer; *d* — zone of coarse grain of root layer; *e* — zone of coarse grain of facing layer; *f* — weld and zone of coarse grain of filling layer

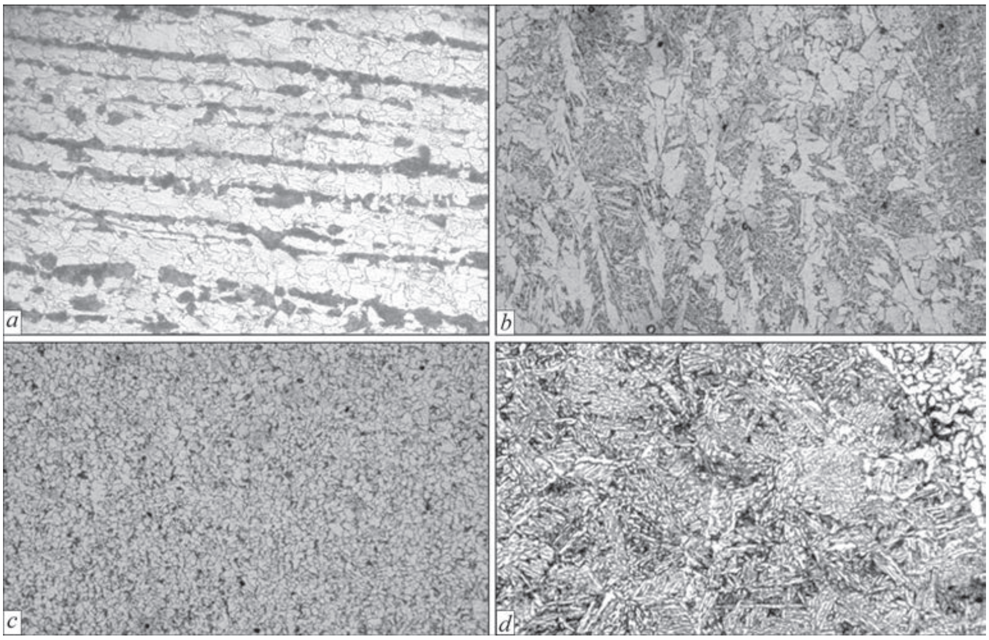

Figure 2. Metal microstructure of the circumferential weld of pipes of 15GSTYu steel: *a* — base metal; *b* — facing weld, ×200; *c* — root weld, ×200; *d* — zone of coarse grain of facing layer, ×320

structure of the metal of the root layer and filling layers, which are subjected to reheating while producing the subsequent layers, is mainly ferritic-perlitic with more equiaxial grains of ferrite (Figures 1, *b*, *d*, 2, *c*, *d*). A typical microstructure of metal of facing layers (Figures 1, 2) is a mixture of different forms of structural components of mainly polygonal ferrite, bainite, and smaller individual areas of Widmanstaetten and lamellar ferrite and pearlite. It should be noted that the change in the amount of impurities of alloy elements in steels and welds affects mainly the ratio of hypoeutectoid ferrite and intermediate decomposition structures that replace pearlite. Therefore, in the circumferential weld on the 15GSTYu steel (Figure 2), compared to the weld on the 17GS steel (Figure 1), the amount of bainite increases, and pearlite is almost absent, the amount of hypoeutectoid ferrite remains stable. The sample of the structure of the facing layer of circumferential joints of the pipe of 17GS and 15GSTYu steel is shown in Figure 1, *c* and Figure 2, *c*.

ANALYSIS OF CIRCUMFERENTIAL JOINTS OF GAS AND OIL PIPELINES WHICH FAILURED DURING OPERATION

To determine the type of defects, the specialists were guided by the acting pipeline construction and modern standard documents of SNiP II-42 and VSN 006 [9, 10], according to which, the sizes and admissibility of defects were evaluated. According to the analysis of the features of defects, the probable causes of their formation were determined. In each considered case, the focus of failure was determined, the quality (defectness) of welded joints and properties of their metal were evaluated.

In the first case, the failure of the circumferential weld of the welded joint of the main gas pipeline, constructed approximately in 1987 from spirally-welded pipes of 17G1S steel, occurred mainly over the area of fusion of the circumferential weld with the base metal (Figure 3) at the area of about 3/4 perimeter of length of this butt. The root and filling layers of the circumferential joint are produced by manual arc welding, and the facing layer — by submerged arc welding. On the surface of the fracture, at one of the areas of failure, a large number of pores with a diameter of not more than 3 mm and with a depth of not more than 7 mm (Figure 3, *a*, *b*) were found. On the transvase macrosections of the samples from this area, deep pores (Figure 3, *b*) are seen, which spread to the metal of circumferential weld from the zone of its fusion with the base metal on the outer surface of the pipe. The pores are combined with a lack of fusion zone (300 mm long, 8 mm deep) of the filling and facing layers with the base metal, which led to weakening of the weld intersection. On the opposite side of the failure, a part of the unmolten edge is seen. Also, a displacement of the axis of the outer weld relative to the root by 3 mm is observed. In the specified area, lack of fusion of the root weld with the base metal (up to 3 mm deep) is observed. The total length of this defective area is approximately 350 mm, the depth does not exceed 7 mm. In other areas of the failure around the perimeter of the circumferential weld, only separate pores with a diameter of not more than 2 mm are present. The peculiarity of this joint of pipes with a circumferential weld is reduction in the hardness of the HAZ metal by 50 HV_{49}, which is a consequence

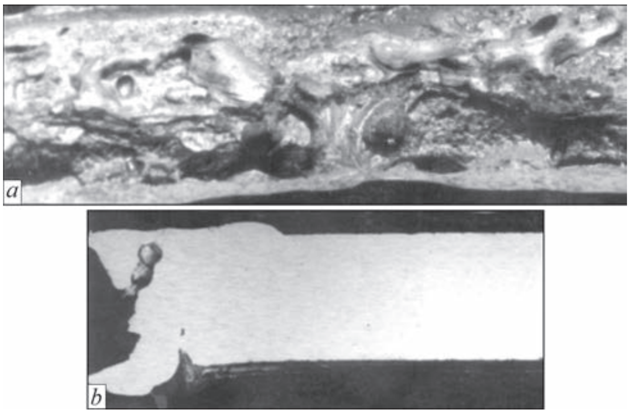

Figure 3. Appearance of fracture (*a*) and defects (*b*) in the metal of the failured weld of the gas pipeline of spirally-welded pipes with a diameter of 1020 mm of 17G1S steel: *a* — lack of fusion of 8 mm depth, pores of 7 mm; *b* — welds displacement, pores of 8 mm depth

of metal softening during welding. The width of the area of the strength decrease is 4–5 mm. The revealed metal softening in the case of welding of heat-treated pipes is a typical phenomenon and it did not cause failure of the investigated welded joint.

In view of the abovementioned, it can be assumed that the cause of the failure of the field welded joint of the gas pipeline from the spirally-welded pipes are defects of a circumferential weld formation in the form of elongated (about 300 mm) lack of fusion of the root and filling layers with one of the edges of the joint and pore clusters. These defects were formed during welding operations in the construction of the gas pipeline as a result of displacement of the mentioned layers relative to the butt of the joint edges and were not detected by non-destrutive testing.

In the second case, on the main gas pipeline of 15GSTYu steel, the construction of which dates back to 1970, while performing diagnostic works, gas leakage was detected. The working pressure in this gas pipeline was 4.7 MPa. The gas pipeline is covered with bitumen-rubber insulation. At the upper part of the circumferential joint in the weld, a through crack-like defect was revealed (Figure 4). The circumferential weld, produced by one-sided manual welding, joined a spirally-welded pipe with a size of 1020×10.6 mm of 15GSTYu steel with a 1020×9.5 mm pipe of the Kh60 steel. The detected defect is located along the weld at some displacement relative to its center. The length of the defect is approximately 250 mm. The edge preparation is insignificant (does not exceed 1 mm). The welded joint at a length of approximately 170 mm was produced with a significant edge displacement in the radial direction and with a wide gap of the edges (Figure 4, *c*). The edge displacement in this area is 6 mm, which is much higher than the allowable rate (not more than 3 mm). On the outer surface of the pipes in the defect area near the fusion line of the circumferential weld, traces of plastic deformation of the metal formed during the assembly of edges of the pipes with the purpose of their alignment for welding are observed.

At the fracture it is seen that the initial crack passes along the edge of the root layer and begins from the lack of fusion with one of the edges of the butt joint (Figure 4, *d*). The depth of the lack of fusion is approximately 3 mm. The back formation of the root layer of the weld is completely absent. The location of the crack coincides with the area of the metal flow in the zone of significant edge displacement (Figure 4, *c*). In the defect zone adjacent to the inner surface of the butt joint, there are pores and their clusters. The size of individual pores reaches 4 mm.

Taken into account the abovementioned, it can be stated that the cause of the failure of the circumferential weld of the specified main gas pipeline was a poor quality of assembly of edges of the circumferential welded joint (inadmissible sizes of radial displacement of welding edges and a wide gap), which led to the appearance of defects of formation (lacks of fusion, pores) in the root weld in the process of its welding, and subsequently provoked the occurrence

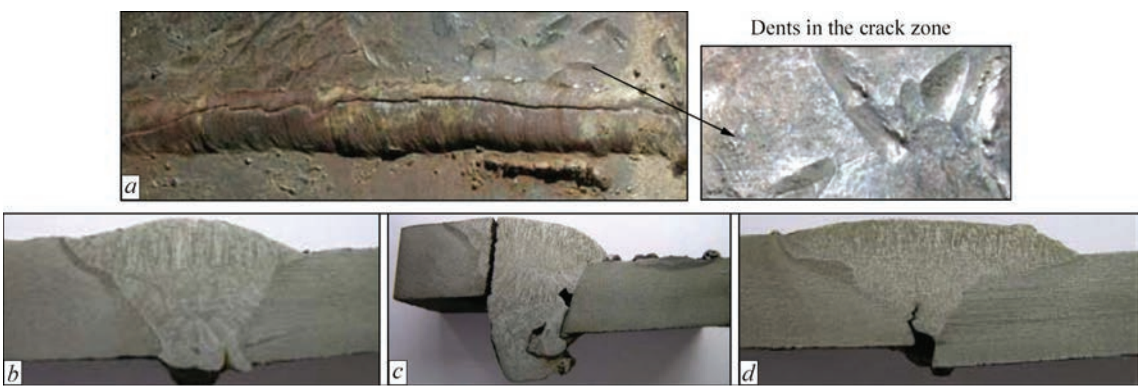

Figure 4. Defects in the circumferential weld of the pipeline with a diameter of 1020 mm from 15GSTYu steel and Kh60 steel: *a* — crack of ~ 250 mm long in the circumferential weld; *b* — macrosection of the circumferential weld outside the crack; *c* — macrosection of the circumferential weld in the crack zone, edge displacement of up to 6 mm, lack of fusion of edges; *d* — macrosection of the circumferential weld in the end part of the crack, lack of fusion and crack in the root layer, edge displacement of up to 3 mm

of a through crack. The formation and propagation of a crack was facilitated by local stresses, caused by attempts of a forced elimination of the inadmissible radial edge displacements. The crack surface is significantly damaged by corrosion indicating a long-term operation of a pipe with a defect.

Further, the failure of two circumferential welded joints of the oil pipeline with a diameter of 720 mm, built from pipes with a wall thickness of 7.4 mm of the strength class K54 was considered. In the first circumferential weld, a through crack-like defect of about 300 mm in length was revealed (Figure 5). In the crack zone, the exceeding sizes of the edges at a length of 600 mm were observed, which reached 7 mm, and a large gap between the edges of up to 10 mm at a length of 740 mm. In order to reduce the gap, contrary to standard documents, 2 rods with a diameter of 6 mm and a length of up to 150 mm were welded into the edge preparation (Figure 5, *b*). In the weld root, the formation of the inner weld is poor, here inadmissible lacks of penetration and lacks of fusion of the edges of up to 3 mm deep were found. In the second circumferential weld, in the fracture of the failured joint such defects as lacks of fusion and lacks of penetration on the side of the inner surface of the weld with a total length of about 100 mm were also detected. The minimum thickness of the deposited metal in the intersection between the outer surface and the area with defects (defect-free area) did not exceed 1 mm.

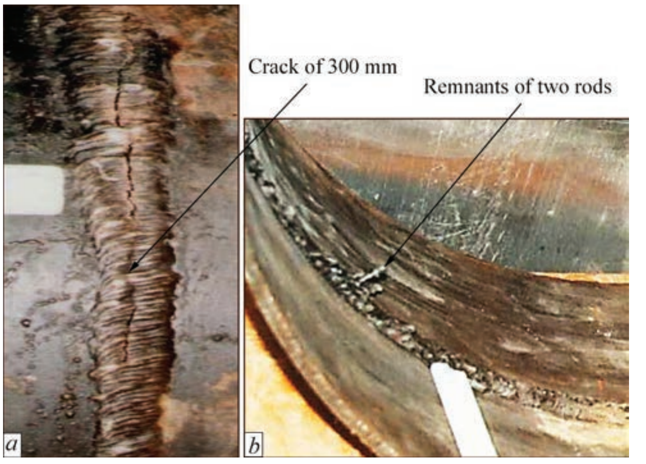

Figure 5. Circumferential joint of the oil pipeline with a diameter of 720 mm with a crack in the weld: *a* — on the side of the outer surface of the pipe; *b* — on the inner surface of the pipe

Therefore, the cause of oil leakage in the 3rd investigated case is the formation of defects in the welds of the circumferential joints as a result of improper performance of the welding process with a clear violation of rules of butt joint assembly, in particular, in the presence of a significant (up to 7 mm) excess of the edges and the gap (up to 10 mm) between them, as well as the use of additional embedded elements to fill the edge preparation. The occurrence of cracks in the circumferential welds was facilitated by the presence of inadmissible lacks of penetration in the weld root and lacks of fusion in them, caused by a low quality of assembly of the butt joint. The propagation of cracks and the formation of a through defect occurred, most probably, as a result of a variable load during the operation of the oil pipeline.

As for the 4th case, there non-structural embedded elements were detected to fill the excessive gap in the welded joint of the gas pipeline with a diameter of 1020 mm, built of the pipes made of coiled hot-rolled 15GSTYu steel. The detected through defect in the circumferential weld was oriented almost in the center of the weld and had a length of about 200 mm (Figure 6, *a*). The part of the weld of 700 mm long, which included also an area with a crack, the edge displacement of the pipes in a radial direction is present (Figure 6, *b*). The largest edge displacement (up to 5 mm) was recorded in the crack zone. Namely in the part of the crack, in the zone of the root layer, lacks of fusions of edges were observed, the depth of which reached 3.5 mm. On the inner side of the circumferential joint, there are areas of significant metal leakage (up to 7 mm in height).

The analysis of the chemical composition of the root layer metal in the crack zone revealed an excessively high content of vanadium, up to 1.7 % (usually, the content of vanadium in the welds in a low-alloy or a microalloy pipe steel does not exceed 0.1 %). This indicates that while producing the circumferential weld with a large edge displacement, metal billets were used to prevent metal leakage in this area, which led to a significant increase in the content of vanadium in the root layer and the occurrence of a hot crack in its center (Figure 6, *c*).

Taking into account the abovementioned, the cause of the failure of the circumferential butt weld-

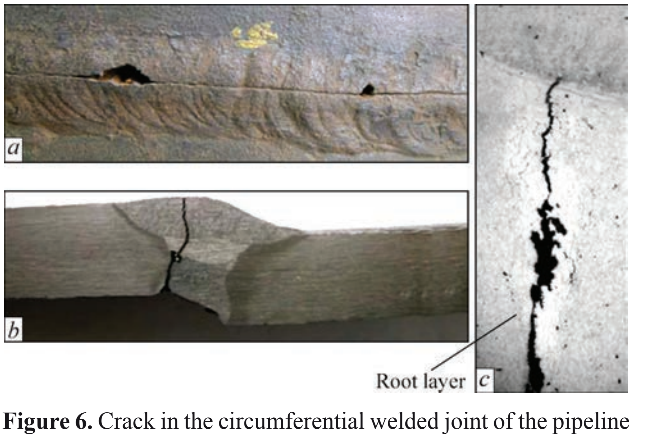

Figure 6. Crack in the circumferential welded joint of the pipeline with a diameter of 1020 mm from 15GSTYu steel: *a* — general appearance of the circumferential joint with a crack; *b* — crack in the weld, edge displacement in the area with a crack (up to 5 mm); *c* — anomalous structure of the metal of root and filling layers of the field joint (vanadium content is ~ 1.7 %), produced by manual welding in the crack zone

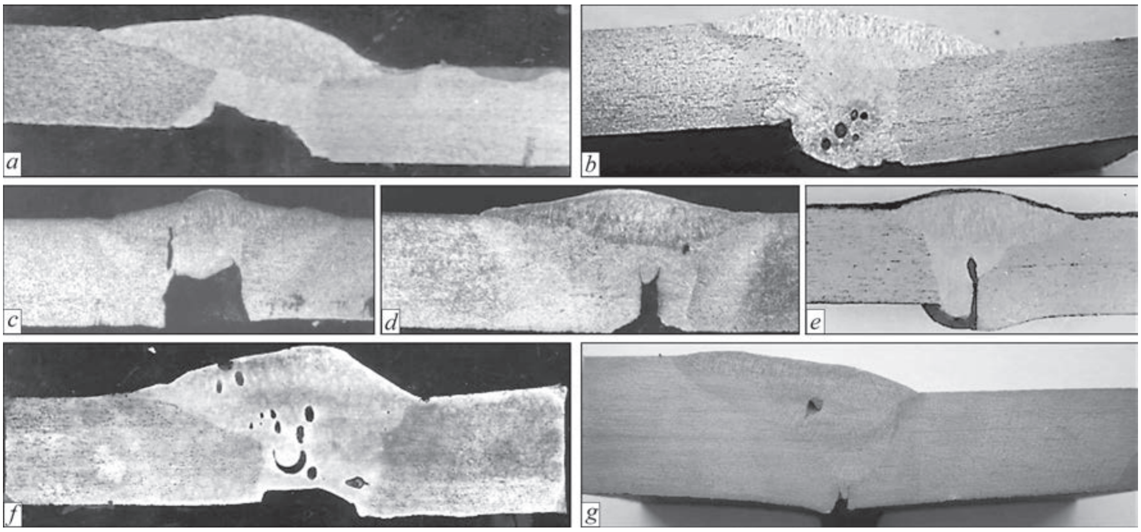

Figure 7. Defects in the circumferential welded joints of gas and oil pipelines of pipes with the sizes: *a* — 720×9mm of 17GS steel, edge displacement, wide gap, lack of filling the root part of the weld; *b* — 820×9 mm of 19G steel, edge displacement, wide gap, deformed ends of pipes, accumulation of pores; *c* — wide gap, lack of root layer, lack of fusion of the weld with the base metal; *d* — 720×7.5 mm of 17GS steel, lack of penetration in the root layer with a depth of 4 mm; *e* — 720×8mm of 16GB steel, edge displacement, lack of fusion (4 mm) in the root part of the weld; *f* — 720×9 mm of 19G steel, gap exceeding the standard, accumulation of pores; *g* — different thickness joint of 17G1S steel of 1020×10 and 1020×14 mm, deformed ends of pipes, lack of penetration in the root layer

ed joint of the gas pipeline, built from the pipes with a diameter of 1020 mm of the 15GSTYu steel, is a crack formed as a result of using additional foreign elements, gaps and excesses of edges during welding of the root layer, which are unacceptable according to standard documents. This led to a local enrichment (up to 1.7 %) of the root weld metal with vanadium and occurrence of a crack of hot origin. Thus, it can be assumed that during the operation of the gas pipeline, it gradually propagated in the filling and facing layers of the circumferential weld before the formation of a through defect. The formation of a through defect was largely facilitated by defects in the circumferential weld and disadvantages of edge assembly, first of all, excessive one, up to 5 mm, their exceeding and unacceptable gaps.

Thus, as to the conditions of arising, the revealed defects that led to the failure of gas and oil pipelines can be defined as defects of technological origin (i.e. they formed in the welded joints directly during the performance of assembly and welding works), to which, in the first turn, excessive radial edge displacements and the gap between them can be attributed, which led to the emergence of lacks of penetration, lacks of fusion, pores, cracks, cavities and other defects, including in the area of the root weld.

ANALYSIS OF CIRCUMFERENTIAL WELDED JOINTS OF GAS AND OIL PIPELINES DEFECTS REVEALED DURING REPAIR

The defects formed due to violation of the technological process of producing the circumferential weld and propagated during operation. Typical defects are shown in Figure 7.

Most often, it was possible to identify the following defects: radial edge displacement (Figure 7, *a*, *b*, *e*), excessive gap between the edges (Figure 7, *a*, *b*, *f*), lack of penetration of the root layer (Figure 7, *a*, *c*, *d*, *e*, *f*), lacks of fuion of the root or intermediate layers (Figure 5, *e*), pores and slag inclusions (Figure 7, *b*, *f*), deformed ends of pipes (Figure 7, *g*). It should be noted that in most cases the revealed defects were formed as a result of poor performance of the operation of assembly of edges (their excessive displacement or gap) of adjacent pipes in the process of pipeline construction.

Above, it was stated that during the study of the failured circumferential welded joints of the pipelines, the evaluation of mechanical properties of the metal of the adjacent pipes and the joint itself, as well as its structural features was performed. We thoroughly assume that in all investigated cases the mechanical characteristics of the pipes and joints metal were in compliance with the determined standards, and the level of characteristics or structural features do not give reason to consider them the causes of the abovementioned failures.

CONCLUSIONS

1. It was found out that defects of technological origin that caused the failure of the studied circumferential joints, occurred as a result of violation of the requirements to edge assembly (excessive radial displacements and gap between them), which led to cracking, lacks of penetration, lacks of fusion, pores, etc., first

of all, in the root layer of the circumferential weld. In some cases, the propagation of failure was also facilitated by local stresses that occurred during a cold method of eliminating unacceptable edges displacements during welding of pipes, in particular, while producing overlapped welds.

2. It was determineed that in any of the investigated cases, the level of mechanical properties or structural characteristics of the metal of the circumferential welded joints produced using the welding technologies applied during the construction of gas and oil pipelines did not become the cause of their failure.

3. The obtained results made it possible to adjust a number of technological recommendations on the requirements and rules of perfoming assembly and welding works during the construction and repair of main pipelines in Ukraine over the last 20 years.

REFERENCES

1. Young, A., Andrews, R.M. (2020) Preventing girth weld failure in pipelines: Measurement of loads and application of assessment methods. In: Proc. of *13th Inter. Pipeline Conf., Virtual, Online, 28–30 September*. DOI: https://doi.org/10.1115/ipc2020-9551.
2. Cao, J., Ma, W., Pang, G. et al. (2021) Failure analysis on girth weld cracking of underground tee pipe. *Int. J. of Pressure Vessels and Piping*, **191**, 104371. DOI 10.1016/j.ijpvp.2021.104371.
3. Xu, Y., Wu, M., Nie, et al. (2022) Performance inspection and defect cause analysis of girth weld of high steel grade pipeline. *J. of Physics: Conf. Series*, 2262(**1**), 012006. DOI: 10.1088/1742-6596/2262/1/012006.
4. Chen, M.J., Dong, G., Jakobsen, R.A. et al. (2000) Assessment of pipeline girth weld defects. У: *The Tenth International Offshore and Polar Eng. Conf. OnePetro*.
5. Lihua, Q., Hui, F., Hui, Z. et al. (2018) Effect of welding defects on mechanical properties and fatigue life of girth welds of X80 steel pipe. *Pipeline Technology Conference*.
6. Ma, W.F., Ren, J.J., Zhou, H.P. et al. (2019) Effect of type B steel sleeve rehabilitate girth weld defect on the microstructure and property of X80 pipeline. *Mat. Sci. Forum*, **944**, 854–861. DOI: 10.4028/www.scientific.net/MSF.944.854.
7. GOST 5058–65: *Low-alloyed structural steel* [in Russian].
8. ChMTU-156–68: *Provisional specifications for electric-welded pipes with a diameter of 1920 mm from 15GSTYu steel grade* [in Russian].
9. SNiP III-42–80: *Construction norms and regulations. Main pipelines* [in Russian].
10. VSN 006–89: *Construction of main and field pipelines. Welding* [in Russian].

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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