Analysis of Reliability of Welded Connections Liquefied Gas and Condensate Pipelines

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Abstract. To assess the strength and reliability of welded joints, the metal of welded joints of the unstable condensate pipeline was tested for static tension and low-cycle durability. The tests were carried out on defect-free specimens, specimens with defects such as lack of fusion, undercut, single pore, single slag inclusion and specimens with defects combining lack of fusion and undercut. A comparative analysis of the effect of defects combining lack of penetration and undercut and separately located defects such as lack of penetration, undercut, single pore, single slag inclusion on tensile strength and low-cycle durability of welded joints is carried out.

1. Introduction
Welded joints of field pipelines intended for the transportation of liquefied gas and unstable condensate have many defects of various origins, and some separately located defects at operating pressures operating in the pipeline are acceptable in accordance with the requirements of regulatory documents, but at the same time a combination of two or more such defects in welded joints leads to a decrease in their strength and durability. The goal was to experimentally investigate the influence of the most dangerous combinations of permissible crack-like defects such as undercut and lack of penetration, located in the same welded joint in different cross-sections, each of which individually corresponds to the rejection rate, on the strength and durability of the welded joint.

The mutual influence of a combination of two or more defects in welded joints of pipelines is estimated by theoretical stress concentration factors [1]. According to the normative document [2], single defects are pipeline defects, the distance between which exceeds the length of the largest of them, and if the distance between them is less than the length of the largest of the defects, then they are referred to as group defects. In the normative document [2], there are no recommendations on taking into account the effect of defects in welded joints combining several single defects permissible according to the rejection rate on the stress concentration in the welded joint and on calculating the theoretical stress concentration factor for such defects. In the sources [1,3,4], the formulas of theoretical concentration and deformation coefficients take into account the relative position of defects in one cross-section, the dimensions of the defects and the pipe cross-section, but there are no recommendations on the joint effect on the concentration of their stresses with defects located in other cross-sections weld. The normative document [5] standardizes the total length of internal defects permissible in height: for any 350 mm of the welded joint, it should not exceed 50 mm, but not more than 1/6 of the perimeter of the
welded joint, and recommendations are given that the welded joint is repaired if the total the length of all detected defects is less than 1/6 of the perimeter of the welded joint, otherwise the welded joint must be cut out. In the source [6], the stress-strain state of the welded joint and the method for assessing the hazard from a combination of transverse displacement of the ends of butted pipes and slag inclusion are considered. However, the combination of crack-like defects located in different cross-sections of the weld and their combined effect on the stress concentration were not considered. Normative documents and references [7,8,9,10] refer to the criteria for rejection of circular welded joints of pipelines based on the results of non-destructive testing, taking into account, among other things, those given in Appendix A [5], but not taking into account the effect of joint action of lack of penetration of the base metal and undercuts.

2. Research
Formulas for determining the theoretical stress concentration coefficients [1] are obtained on the assumption that the defects are located in one cross section of the weld, and the maximum effect of defects on the stress concentration in the weld will be observed. In reality, the defects are often located in different cross-sections of the weld, and as the distance between the defects in the direction of the longitudinal axis changes, the joint effect of defects on the stress concentration will also change. The nature of the influence of defects on the stress concentration in welds varies depending on the shape of the defects and their origin. The object of the study was a pipeline transporting unstable condensate, with the following parameters: category II pipeline, nominal diameter $D = 200\text{mm}$; design pressure $p = 1.6\text{MPa}$; design temperature of the pumped medium $T = 20–40^\circ\text{C}$; seamless steel pipes, 09G2S, wall thickness 8.0 mm; welded joints are made by manual arc welding. As a result of research on the welded joints of the pipeline, defects with permissible dimensions were revealed, among which the most common were single pores (36.42 %) and slag inclusions (31.96 %). Combinations of permissible defects were also identified, such as lack of penetration and undercut, lack of penetration and time, lack of penetration and slag inclusion, time and undercut, undercut and slag inclusion in different cross-sections of the weld. It was assumed that the combination of lack of penetration and undercut, even of admissible dimensions, is the most dangerous, since these are crack-like defects, which are stress concentrators prone to the initiation and development of cracks in them. Therefore, for testing, welded joints with defects combining lack of penetration and undercut, located in different cross sections of the weld, as well as welded joints with defects of the single pore type and a single slag inclusion, were selected for testing, as the most common defects, which are stress concentrators that reduce the strength of the weld.

3. Experiment
Cutting of samples from welded joints of unstable condensate pipeline was carried out during repair works. As a result, nine plates with dimensions 160×200 mm with defects such as lack of penetration, undercut, single pore, single slag inclusion, combination of lack of penetration and undercut in different cross-sections of the weld and one plate without a defect. To carry out tests for static tension, samples were made from these plates with the following parameters: length 150 mm; width 10 mm; thickness 7 mm. The samples were not subjected to any additional processing, and the reinforcement of the welded seam remained unremoved. The type of samples is shown in Figure 1.
Figure 1. Sample for static tensile tests: 1 - location of lack of penetration on the inside of the seam, 2 - location of the undercut, 3 - heat-affected zone, 4 - weld joint.

Static tensile tests were carried out on an Instron Model 8801 Universal Tensile Tester at 20°C. Four samples were tested: sample № 1 without defects in the welded seam; sample № 2 with a single internal pore; sample № 3 with a single slag inclusion; sample № 4 with a defect combining lack of penetration and undercut. During the static tensile tests of specimens № 1, 2 and 3, the rupture of the specimens was revealed not along the weld, but along the base metal in the zones close to the clamps of the tensile testing machine (Figure 2), as a result of which it was concluded that a single slag inclusion and a single pore of such dimensions practically does not affect the strength of the welded joint. When testing sample № 4, the sample ruptured along the welded seam (Figure 2), from which it follows that the presence of a defect in the welded seam, combining lack of penetration and undercut, affects the decrease in its strength. As a result of the tests, the maximum force at break and the force during plastic deformation of the samples were determined, and diagrams of the dependence of the elongation of the samples on versus the tensile force were plotted. Test results are presented in Table 1.

Table 1. Results of static tensile tests.

| Sample No. | Maximum breaking force, N | Effort at plastic deformation, N |
|------------|----------------------------|---------------------------------|
| 1          | 66375                      | 47041.1                         |
| 2          | 62370                      | 42639.5                         |
| 3          | 60901                      | 41652.2                         |
| 4          | 51500                      | 36148.3                         |

Figure 2. Samples after static tensile tests.
For testing for low-cycle durability, plates were selected that have single defects - lack of penetration and undercut, and a combination of these defects. The sizes of defects are given in Table 2.

The selection was carried out taking into account the fact that in the weld specimen there were permissible individual defects such as undercut and lack of penetration and combinations of undercut and lack of penetration in different cross sections of the welded seam having permissible geometric dimensions according to [5]. The dimensions of the defects were determined during non-destructive testing of welded joints by radiographic inspection. Four samples were made from the plates with dimensions: length 80 mm; width 30 mm; thickness 5 mm. The type of samples is shown in Figure 3. The weld was machined to remove the reinforcement.

![Sample for testing for low-cycle durability.](image1)

The ultimate tensile strength of 09G2S steel according to the manufacturer’s certificate is 420 MPa. Calculated force for low-cycle life tests:

\[ N = 0.4 \cdot \sigma_u \cdot a \cdot b = 0.4 \cdot 420 \cdot 5 \cdot 30 = 25200 \cdot N = 25,2 kN. \]  

(1)

Based on the calculation results, the following parameters of cyclic loading were selected: maximum force 25.2 kN, minimum force 3.2 kN, loading amplitude 11 kN, initial force 14.2 kN. Cyclic loading of the samples was carried out on an Instron model 8801 universal tensile testing machine at a temperature of 20°C. The view of the sample after testing for low-cycle durability is shown in Figure 4.

![Sample after testing for low-cycle durability.](image2)
Table 2. Test results for low-cycle durability.

| №   | Defect name                  | Defect dimensions (h-depth, l-length along the axis of the weld) | The number of cycles until the destruction of the sample |
|-----|------------------------------|-----------------------------------------------------------------|--------------------------------------------------------|
| 1   | Lack of penetration          | $h = 0.57 \text{ mm}; l = 21.6 \text{ mm}$                    | 24603                                                 |
| 2   | Undercut                    | $h = 0.48 \text{ mm}; l = 15.5 \text{ mm}$                      | 27625                                                 |
| 3   | Undercut; Lack of penetration | $h = 0.2 \text{ mm}; l = 19 \text{ mm}$                        | 12854                                                 |
| 4   | Undercut; Lack of penetration | $h = 0.3 \text{ mm}; l = 24 \text{ mm}$                        | 9376                                                  |

4. Conclusions

- It has been established that the static tensile strength of welded joints with defects is 1.09 - 1.29 times less than the static tensile strength of defect-free welded joints.
- It was found that the combination of defects such as lack of penetration and undercut, located in different cross-sections of the welded seam, reduces the static tensile strength of the welded joint by 1.19 - 1.22 times compared to a welded joint with individual defects such as a single pore, a single slag turning on.
- It has been established that with a combination of defects such as lack of penetration and undercut, the low-cycle durability of the welded joint is reduced by 2.1 - 2.9 times in comparison with the durability of welded joints with individual defects such as lack of penetration and undercut.
- In view of the foregoing, a combination of defects such as lack of penetration and undercut in one welded joint is unacceptable even with permissible geometric dimensions of such defects, and sections of the welded seam with a combination of such defects are subject to repair.
- It is recommended to amend the departmental normative documents for quality control of welded joints of liquefied gas and condensate pipelines of oil fields, installations of head facilities for cleaning and preparing a product for long-distance transport. defects such as lack of penetration and undercut.

5. References

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