

Structural Degradation of the Welded Joint of the Gas Main after a Long-Term Operation in Sub-Acid Soil

P O Maruschak¹, R T Bishchak², O V Maruschak^{2,a}, S V Panin^{3,4}

¹ Ternopil National Ivan Pul'uj Technical University, Ruska 56 str., Ternopil 46001, Ukraine

² Ivano-Frankivsk National Technical University of Oil and Gas, Karpatska 15 str., Ivano-Frankivsk, 76000, Ukraine

³ Institute of Strength Physics and Materials Sciences SB RAS, 634021, Tomsk, Russia

⁴ National Research Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, 634050, Russia

E-mail: ^a Maruschak.tu.edu@gmail.com

Abstract. The authors investigated the main regularities in the structural and mechanical degradation of steel and a welded joint of the “Soyuz” gas main in operation. It is established that the defect accumulation kinetics in welds are determined both by technological disruptions in their manufacture and by hydrogenation of the weld during a long operating time. A weakening of the mechanical properties of the weld after a prolonged operation is shown, which in some cases led to the appearance of cracks and fracture of the gas main.

1. Introduction

Gas mains of Ukraine have been in operation for a long time, which causes degradation of their material, and especially welded joints. In addition, since the time Ukraine's gas mains were commissioned, the precision of diagnostic devices has increased significantly, due to which it is now possible to detect both in-service defects of gas mains, and technological imperfections of the process of their manufacturing. The structural heterogeneity of welds makes them a “weak point” in terms of resistance to the initiation of defects and long-term fracture of the gas main [1-2].

At present, there are many approaches to assessing the degradation of the gas main material, in particular, pipes of strength class K46-K65, whose impact toughness does not exceed 125 J/cm². It is known that welded joints, especially after a prolonged exploitation, become the most vulnerable parts of welded structures [3]. An important component of the above considerations is the assessment of the actual condition of the gas main metal after a prolonged exploitation, including welded joints, which is the basis for predicting their capacity for work.

Significant differences in the degradation mechanisms of the gas main steel lead to a variety of operational defects and damage to the structure of welds [4-6]. Consequently, the existing approaches to assessing their strength and ability to work, as well as the methods for the prevention of unpredictable fracture need to be improved and concretized. In addition, investigations into the defects of the long exploited pipe steels are the basis for the creation of high strength steels with different types of microstructures. It should be noted that the systematization of operational damage is an important scientific and engineering task, and its description requires further research [7-9].

The purpose of this paper is to analyze the degradation mechanisms of the weld of “Soyuz” gas main after a long-term operation.

2. Ecological features of operation of gas mains

To ensure a reliable and safe operation of underground gas mains, it is necessary to consider the corrosion activity of soils, in which they are laid, in addition to ensuring a high-quality protective insulating coating. Therefore, we should consider carefully the environmental indicators that



characterize the corrosive activity of the soil. It is caused by the presence of hydrogen ions, whose concentration is expressed in pH. The pH of soil varies depending on the total mineralization of groundwater and the presence of carbonate and mineral acids, acid and basic salts in it. According to the pH, soils are classified into: strongly acid (3.0-4.5), acid (4.5-5.5), sub-acid (5.5-6.5), neutral (6.5-7.0), mildly alkaline (7.0-7.5), alkaline (7.5-8.5), strongly alkaline (more than 8.5).

In all regions of the Ternopil oblast, except Zalishchitsky, Zbarazhsky and Chortkivsky, the area of acid soils has increased in recent years as compared to previous studies. The average weighted pH in the region varies from 5.5 (slightly acid reaction) to 6.7 (neutral). In the last five years, the average pH dropped by 0.1 and is 6.0 (the reaction is close to neutral). However, according to some predictions, the soil solution in the region will tend to acidification in the coming years.

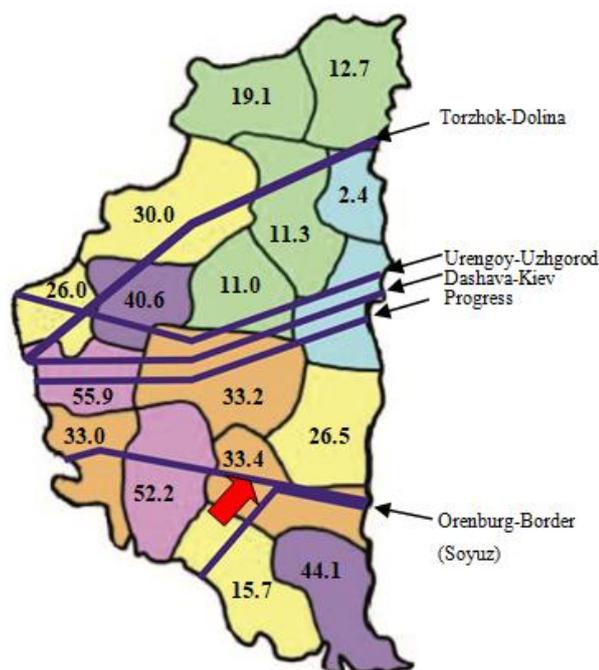


Figure 1. The map of gas mains running through the Ternopil oblast and percentage (%) of acid soils (the place of cutting the template is indicated with a red arrow)

3. Research technique

In order to analyze the reasons for the formation of a weld defect and find out a mechanism of crack propagation from it, a complex research of a fragment of the gas main was performed. In particular, we used a fragment of the “Soyuz” gas main with a diameter of 1420 mm and a wall thickness of 16 mm, which was taken near the village of Kolindiany, Chortkivsky region, Ternopil oblast, Fig. 2a.

The research included testing of the mechanical properties of the weld zone, visual inspection, and a metallographic analysis on a microscope “AXIOVERT 40- MAT”. Specimens were cut from a pipe fragment in a zone of a weld, next they were ground to attain a gradual decrease in grain size, and polished by a diamond paste on the USHPO-0 setup. After that, the prepared surface of specimens was etched in 4.0% nitric acid solution in ethyl alcohol.

Mechanical tests of the specimen cut along the weld joint of the pipeline with operational defect were performed, Fig. 2 c, d under uniaxial static stretching on a hydraulic test machine R-100. A fractographic analysis of the specimen fracture was performed on the REM-106 microscope. Measurements of microhardness were made at a load of 200 g on a microhardness tester PMT-3, based on the average result of three measurements in the selected area of the weld.

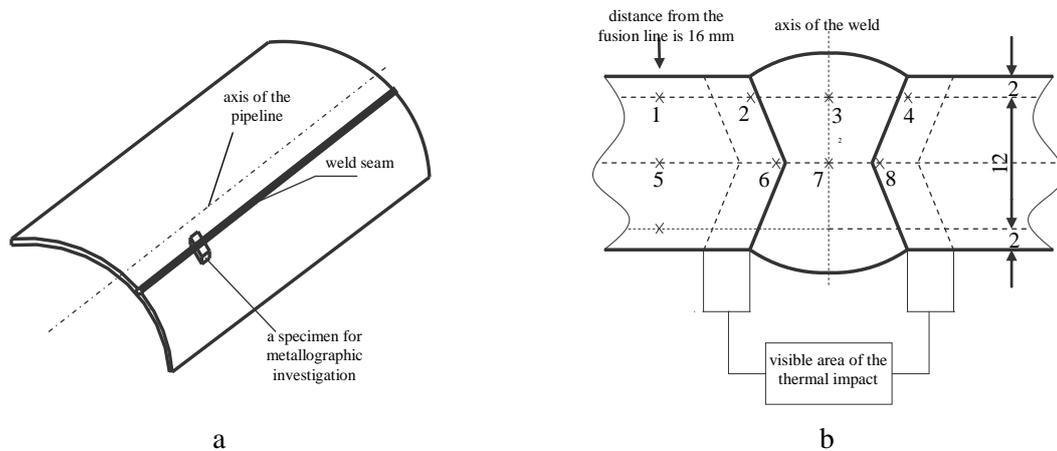


Figure 2. A general view of a pipe fragment (a) and a weld with a crack (b)

4. Analysis of the weld cross-section

The analyzed welded joint was destroyed due to the propagation of a cold crack, which was formed in the area adjacent to the outer surface of the welded joint after welding. That is, it was a technological defect that propagated during exploitation. To study the reasons, a metallographic specimen was made from the part of the welded joint that remained intact, and its hardness was measured on a hardness tester TK-2M according to the scheme of Fig. 2 b, which is related to a number of mechanical and physical properties of materials, in particular, the density of dislocations in small-angle boundaries. According to the measurement results, an increase in hardness up to 78 HRB was found around the metal of the welded joint, and its reduction to 73 HRB in the zone of thermal influence.

Table 1 Results of hardness measurement of the welded joint of “Soyuz” gas main

| Hardness | Measurement points, see Fig. 2b | | | | | | | |
|----------|---------------------------------|-----|-----|-----|-----|-----|-----|-----|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| HRB | 72 | 73 | 78 | 73 | 74 | 73 | 78 | 74 |
| HB* | 132 | 134 | 146 | 134 | 136 | 134 | 146 | 136 |

*data obtained by transferring HRB to HB [10].

According to the hardness measurements, a conventional strength limit was calculated [10]:

$$\sigma_{us} = 3.45HB \quad (1)$$

$$\sigma_{us} = 3.29HV - 47 \quad (2)$$

$$\sigma_{us} = \frac{(HV - 1.837)}{0.304} \quad (3)$$

Values of the relative strength of the weld of the gas main “Soyuz” from steel X65 (Japan, TU-1975 TECHNICAL CONDITIONS [11]) are calculated by equations (1-3).

It should be noted that the welded joint had reduced strength properties, since the main metal of this pipe was characterized by values $\sigma_{us} = 620$ MPa, $\sigma_{ys} = 590$ MPa [11]. In the analysis of the weld, an initial concentrator was discovered, from which fracture began. Degradation of the weld zone compared to the initial material was observed both in the zone of the weld and in the zone of thermal impact. This lowered the load-bearing capacity of the weld and partly its crack strength. In addition, the heterogeneity of the grain substructure is typical of the welded joint. The presence of harmful impurities, including those prone to segregation along the grain boundaries, caused the destruction of the weld. Thus, the

crack originated in the sub-surface layer of the weld, and propagated from the outer surface to the inner one.

5. Metallographic analysis of the welded joint

The microstructure of the welded joint of the gas main “Soyuz” cut out in different directions was investigated. The areas of ferrite and fine perlite were found, which, in general, gives grounds to believe that the structure belongs to the ferrite-perlite class. The grain size was 9-11 points according to GOST 5639-82. Micropores were found on the surface of metallographic specimens, which are formed at the boundary “matrix-ferrite”, Fig. 3

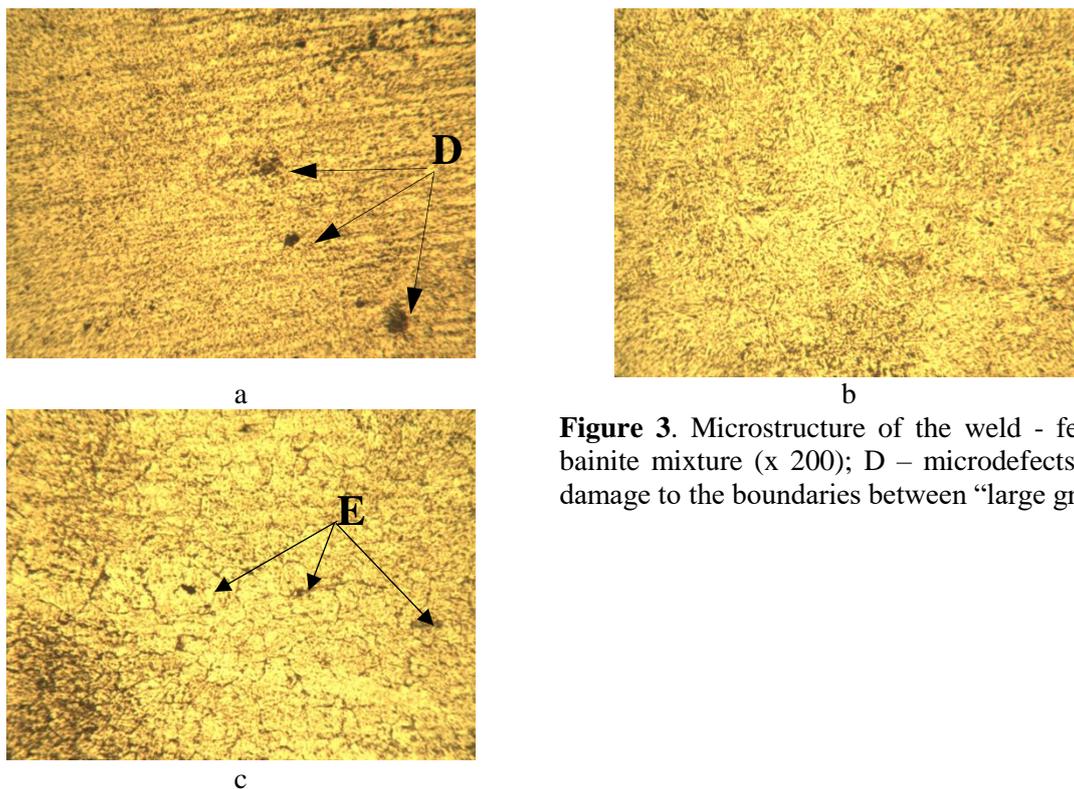


Figure 3. Microstructure of the weld - ferrite-bainite mixture (x 200); D – microdefects, E – damage to the boundaries between “large grains”

The obtained metallographic images of the metal of different zones of the weld show that small crystallites with an “ordered” structure are caused by welding technology. The structure of the metal is a ferrite-bainite mixture, Fig. 3b. Large grains are found mainly in the near-surface part of the weld. In our opinion, they result from crystallization of the metal. This structure indicates a low impact strength and generally low crack resistance [12, 13]. It is this site that served as a zone for the crack start in a weld. Also, changes in the initial structure were detected by the selection and coagulation of carbides along the grain boundaries, with a simultaneous formation of microscopic damage.

The appearance of pores and the destruction of the interstices between them, with the formation of intergranular cracks in the axial section of the weld, occurred over a long period of time, and the hydrogenation of the metal facilitated their merging with each other. Similar defects were discovered in the vicinity of a transverse cross-sectional crack in the Urengoy-Pomari-Uzhhorod gas main with a diameter of 1420 mm [14]. In our opinion, the technological reason for the defect formation is a very rapid and uneven cooling of the weld.

6. Discussion

Since the fragment of the gas main was cut in the territory of the Chortkivsky region of the Ternopil oblast, which is characterized by acid soils, one should take into account the possible complex nature of

the damage, which is due to the features of the material microstructure, the conditions of mechanical loading, and the action of the aggressive environment. It is known that in the process of a prolonged exploitation of structural steels, the resistance to brittle fracture [1-8] deteriorates most, which is dangerous due to the uncontrolled growth of cracks, especially in aggressive corrosive-hydrogen environments. Their role is twofold, because they: a) accelerate fracture particularly of the most degraded material; b) contribute to the operational degradation of the material “in volume”, which is associated with its hydrogenation. The latter factor is often neglected, as they usually consider only stresses caused by the mechanical loading of structures.

In our opinion, a crack was formed in the area of the weld due to defects accumulated on grain boundaries [12-14]. The said defects were formed in the first moments after welding, however, they were scattered and did not coalesce, because the level of welding stresses in this area was insufficient for their growth.

After mounting the pipe into the gas main, a local growth and merging of microdefects occurred under the influence of operational factors, including hydrogenation. In our opinion, such technological influence could be the “superimposition and summation” of welding stresses with technological ones, which caused the localization of microdeformation processes. Thus, according to the measurements of hardness, as well as fractographic and metallographic analysis of this defect, we can conclude that the defect was formed due to the influence of negative structural and mechanical factors: the size of austenitic grains, a significant gradient of grain structure in the weld zone, and the “coarsening of grain”.

7. Conclusions

The investigated crack of the weld has a technological and operational origin, its occurrence is a consequence of the effect of welded microdefects formed during the manufacture of the weld. An additional factor influencing the propagation of the defect is the hydrogenation of the pipe wall. Fractographic and metallographic studies have allowed revealing the zone of crack origin and micromechanisms of crack propagation. The analysis of microstructural features of the weld zone and its comparison with the morphology of the crack growth allowed determining the causes of its occurrence and stages of origin and growth of the macrodefect.

Acknowledgments

The reported study was funded by the Ministry of Education and Science of Ukraine, according to research project No. 0116U006908.

References

- [1] Semenov S E, Mandel'berg S L, Goritskii V N, Bolotov A S, Anenkov N I 1987 *Welding International* **1** 610-614.
- [2] Min Sung Joo, Kyung-Min Noh, Wan-Keun Kim, Jin-Ho Bae, Chang-Sun Lee 2015 *Metallurgical and Materials Transactions E* **2** 119-130.
- [3] Hashemi S H, Mohammadyani D 2012 *Int. J. of Pressure Vessels and Piping* **98** 8-15.
- [4] Curiel F F, García R, López V H, González-Sánchez J 2011 *Corrosion Science* **53** 2393-2399.
- [5] Zachrisson J, Börjesson J, Karlsson L 2013 *Science and Technology of Welding and Joining* **18** 603-609.
- [6] Rahman S, Ghadiali N, Wilkowski G M, Paul D 1997 *Int. J. of Pressure Vessels and Piping* **70** 209-221.
- [7] Ostsemin A A 1991 *Strength of Materials* **23** 406-410.
- [8] Gorkunov E S, Zadvorkin S M, Putilova E A, Savrai R A 2014 *The Physics of Metals and Metallography* **115** 949-956.
- [9] Khotinov V A, Arabei A B, Pyshmintsev I Yu, Farber V M 2013 *Russian Metallurgy (Metally)* **2013** 336-343.
- [10] Lee K-S, Song J-H 2006 *Int. J. of Fatigue* **28** 386-400.
- [11] X65 (Japan, TU-1975 TECHNICAL CONDITIONS).

- [12] Brahim Belkessa, Djamel Miroud, Naima Ouali, Billel Cheniti 2016 *Acta Metallurgica Sinica (English Letters)* **29** 674-682.
- [13] Erofeev V V, Aimetov F G, Shakhmatov M V, Smetanin F E, Baldin V M 1993 *Strength of Mater.* **25** 928-935.
- [14] Maruschak P O, Bishchak R T, Shlapak L S, Panin S V 2017 *IOP Conf. Series: Materials Science and Engineering* **177** 012114 doi:10.1088/1757-899X/177/1/012114