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FATIGUE AND BRITTLE FRACTURE OF CARBON STEEL OF GAS AND OIL PIPELINES

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Abstract. The areas of low frequency and corrosion fatigue for basic metal and welding joints of oil and gas pipelines have been determined on the basis of corrosion-fatigue test results. The most dangerous diapasons of the operation loadings were also determined. The present work also proposes the methodical approaches to the survivability prediction.

Keywords: oil and gas pipelines; fatigue; failure; residual life; degradation; risk; fracture.

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Introduction

Fuel-energy complex is one of the most important sectors of the world economics. Taking into account the exceptionally important role of our country as one of the greatest transit ways of the energy supply to the European Union, it can be said that the stability and fail-safety of the Ukrainian fuel-energy complex is the guarantee of our energy safety in particular and of the European Union as the greatest transit routes.

A special attention should be paid to gas and oil pipelines, which are exploited under difficult conditions, namely, deep-sea gas and oil pipelines and those that are in mountain regions. Recent research (Wahab *et al.* 2005) shows that under these conditions the risk of initiation of the emergency complication-predicted situations is the most due to the peculiarities of loadings and influences during the exploitation process.

In mountain regions in particular, as a result of the abnormal quantities of the atmospheric precipitates, unexpected slumps are possible, as well as saline or mud landslides, and snow avalanches during winter. As a consequence of such natural cataclysms, the pipelines can be exposed to substantial impact or cyclical mechanical loads, which often lead to depressurising and even to pipeline breakage. Since there are a lot of biosphere reserves in the mountain regions of Ukraine, national parks with exclusive species of flora and fauna, even small waste of transported product can cause the difficult and sometimes irreparable outcomes for unique biogeocenoses (Poberezhnyj *et al.* 2011).

Similarly in sea abyss (deep-see) regions, as a result of the shelf relief and shape of the bottom, in particular at the transition from the shelf to an abyss, the pipeline undergoes great mechanical loads which should be taken into account during the laying stage and also at subsequent calculations of its service life under the safety exploitation and the optimisation of operation conditions.

Later research (Vianello, Maschio 2011) demonstrated that the avalanche mashing is the most dangerous situation, at which the chain loss of the pipeline stability takes place practically along the laying route, which can cause both the sizeable economic losses and also the negative results for submersible fauna, and also for vegetable and animal life of a seaboard. Besides that, during the exploitation process there are possible emergency situations conditioned by underwater mud flows, as a result of

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which the mechanical tensions into pipeline can in short time increase to 200%, which causes the depressurising and the leakage of the transported product. Such situation can be very negative and dangerous; besides the soluble in water, non-soluble or a little soluble substance (for example, oil) is washed ashore to coast dirtying and damping the seaboard. Thus, oil and gas flow causes the complex negative influence on the environment, developing the ecological danger risk. Natural gas, where the main component is the methane, is related to greenhouse effect gasses; 1.0 kg of methane causes the same negative effect as that of 35.0 kg of carbonic gas. Oil leakages are the most dangerous to fauna and flora of the seaboard and coastal shoal, and mostly to the water birds, as leaked oil damages the plumage of water birds thus causing sub-cooling and death. Oil overflows from middle to high usually cause the death of about 5,000 water birds. These water birds are the most sensitive to the oil overflows.

1. Service failure of gas and oil pipelines

The creation of scientific principles for the analysis and reliability control, safety and survivability of the pipeline systems as a whole and those which are exploited under difficult natural conditions, in particular via the framework of disaster mechanics, is an important scientific task. Recent research (Hazin *et al.* 2005) suggests that unfortunately up to the present time in Ukraine there are no clear methodologies for providing the safety of pipeline systems.

Recent investigations (Li *et al.* 2005) have found that on designing in accordance with the available normative documents, if the project corresponds to today's demands, at that time the separate safety analysis and well-grounded risk analysis with the estimation of possible failures quantity and prediction of their consequences ('failures tree') are not carried out. Such practice leads to the fact that more often we hear about the large disasters on pipeline transport. In particular, in the year 2007, a large disaster took place in the artery of gas transport system, Urengoy–Pomary–Uzhgorod, one of the Russia's main natural gas export pipelines, which is 4500 km long and the annual capacity of the pipeline is 32 milliard cubic metres of natural gas per year. As a result of the gas explosion, the crater with a diameter near 100 m remained; the territory with a radius of 1.0 km was completely burnt out. The trees were charred and the soil was changed to an orange substrate. Separate parts of the pipeline were casted away by explosion on $60.0 \div 70.0$ m, as shown in Fig. 1.

The tired and corrosive-tired tests of specimens of the basic metal and the welding joint of the sea pipelines were carried out within a total range of the amplitude tensions – from the durability limit to the limit of the corrosive endurance (Polyakov, Rybakov 2009). In our present work, the kinetics of deformation and basic supporting members' failure of oil and gas pipelines was studied on the basis of ground analysis of curves 'deformation–time (quantity of cycles)', obtained in accordance with the method developed earlier (Vianello, Maschio 2011) with the use computer registration technique under the conditions of real time with increment from 0.01 to 1.0 sec, which was selected automatically on the assumption of the change rate of measured parameter.

Fig. 1. The results of the Urengoy–Pomary–Uzhgorod pipeline disaster for the environment

For the basic metal, it was stated that the five-stage kinetics of the deformation in a field of high-amplitude tensions with the characteristic deformation peaks corresponding to the processes of speeded up cyclic undurability and following durability in the first $25 \div 150$ cycles of loading (Macdonald *et al.* 2007). The behaviour of steel for the pipeline during this stage is complication-predicted and practically non-controlled in a case of the emergency situation that can lead to practically momentary (less than 4 minutes) loss of supporting ability with depressurising and pipeline breaking-off (Fig. 2).

In seawater, similar deformation behaviour was settled, however, the undurability process is more intensive as a consequence of the Rebinder's effect influence and the apical growth of the deformation peak depending on amplitude tensions can be equal to $15 \div 35\%$ (Kishawy, Gabbar 2010).

Fig. 2. Breaking-off the Urengoy–Pomary–Uzhgorod pipeline as a result of the gas explosion

2. Experimental study

The material used in this study was Steel 20 (USSR State Standard GOST 1050-88) pipe with a diameter of 426 mm. Its chemical composition percentage (weight) is: $0.17\div0.24\%$ C, $0.17\div0.37$ Si and $0.35\div0.65$ Mn. Also, the welded joints of pipes used in this study were made manually by welding electrodes (brand SSSI-13/55). To test the base metal used in the specimen, cut from the pipe wall with a length of the working part 50 mm (Fig. 3a). To investigate the deformation behaviour of the weld length, the working part was reduced to 20 mm, allowing us to minimise the errors that hit the base metal in the studied area (Fig. 3b).

Fatigue tests were performed in an automated testing system with a computer for a comprehensive study of the kinetics of deformation and fracture and electrode potential of the pipeline material (Pokhmurskii *et al.* 1973). The staircase method was used to obtain accurate values of the fatigue limit stress for base metal and for welded metallic alloys corresponding to the fixed number of cycle.

Fatigue crack initiation, the microstructure and short cracks in the fatigue specimens were examined using both optical and scanning electron microscopes (SEM). In order to study deformation behaviour of steel pipe and tracking processes of relaxation in detail, we used stepwise loading (unloading) of specimen (Yasnii *et al.* 2009) directly. When increasing or decreasing the load on a nominal level of stress, the value of $\Delta\sigma = 20$ MPa was changed to 1 s. Exposure time at each stage of load was 19 s and total time $\Delta t = 20$ s. The frequency of loading $f = 0.8$ Hz.

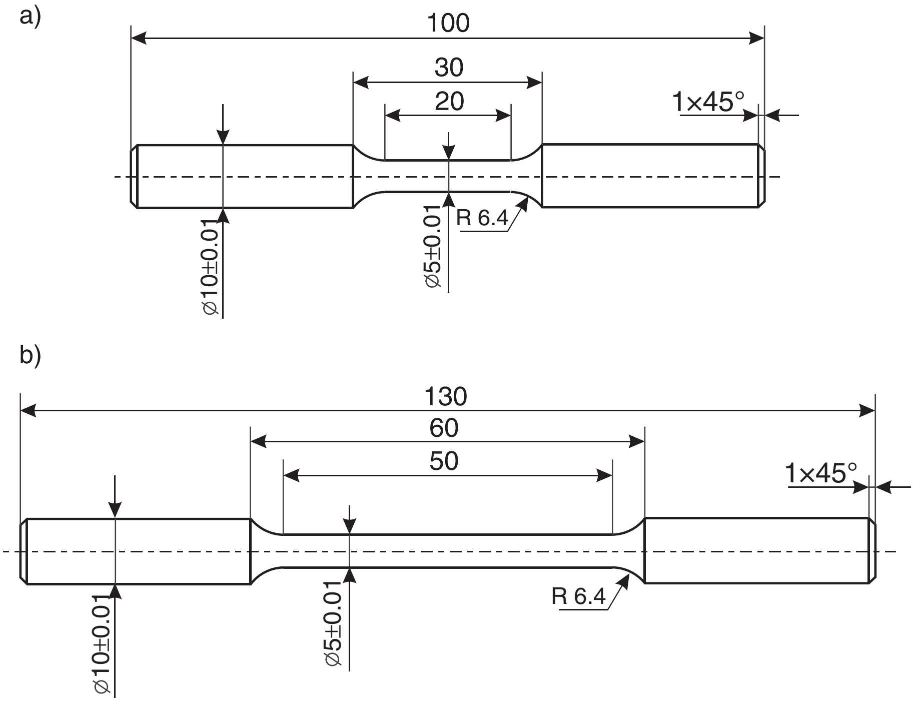

Fig. 3. Specimens for fatigue and corrosion-fatigue tests

3. Fatigue damage of welded joints

In a case of the welding joint, the deformation process which take place during the first stage are more dangerous since it is not uniformed and is under the assumption which represents by its composition 'welding seam – zone of the thermal influence' (WS–ZthI) and necessarily contains the inhomogeneities of the structure as different admixtures and defects (Gliha *et al.* 2004, 2009, 2011).

This causes the concentration of tensions in the zone of the welding joint and additional risks of the breakage or failure takes place in the stages of the building or exploitation. Results of the tests performed in seawater also showed similar deformation behaviours; however, the deformation peaks are absent and at the same time, we observed practically the monotonous rather than dangerous cyclic undurability during the first 800÷1000 cycles.

Such deformation behaviour during the first cycle of the loadings creates the risk of the severe accidents of sea oil and gas pipelines, which are exploited under difficult conditions, namely in deep-sea and landslide-prone regions. Also, it should be remembered about other dangerous condition – the avalanche mashing at pipelining by *J* method. It is necessary to carry out the additional investigations with the aim to develop the methodological approaches for the estimation and also prediction of risks caused by the anomalous deformation behaviour of pipeline steel and also measures concerning their minimisation.

Other scientific task is the estimation and prediction of the risks for depressurising and breakage of the pipelines, which are exploited during prolonged period of time (15 years and above). During the exploitation process, the accumulation of damages appears both in the basic metal and in the zone of the welding joint (compositions WS–ZthI). It is also necessary to estimate and predict the survivability stability of the external loads, and influences from the environment at the initiation and evolution of the acceptable damages. Exactly, the survivability (Palii *et al.* 2003) should be the main criterion for the estimation of the operational risks. This criterion should be well described mathematically, with the aim of prevention of superfluous complication in respective engineering calculations. This view was supported in the work of Hrabovs'kyi (2009). It is proposed to consider the duration of the last stage of tired (corrosive-tired) failure as a measure of the survivability. Data for the basic metal and for the welding joint are represented in Tables 1 and 2, respectively.

Scheme of testing device MB-1K is presented in Fig. 4.

We see from Table 1 that the survivability of the basic metal in seawater is 1.5÷3.5 times less. This is unambiguously caused by the corrosion-active medium. For an uncomplicated and correct mathematical interpretation, it was proposed to represent jointly the graphic dependencies of the material survivability both under air and under corrosive media conditions, and to call them as 'survival diagrams'. Fig. 5 shows a result of the prolonged scientific search, using the semi-logarithmic systems of the coordinates that were chosen as the optimal variant, an application of which gives the possibility of maximal simple for engineering calculations linear approximation with the acceptable trustworthiness (the deviation not exceeds 1.0÷3.0%). An analysis of the obtained dependencies for basic metal showed (Fig. 5) that in a zone of the operation loads the survivability is given away to correct the interpretation both under air and under corrosion-active media conditions (seawater). In a zone of the maximum loads the survivability upon air is complication-predicted. At the same time, in seawater the survivability is given away to prediction with the less trustworthiness in a

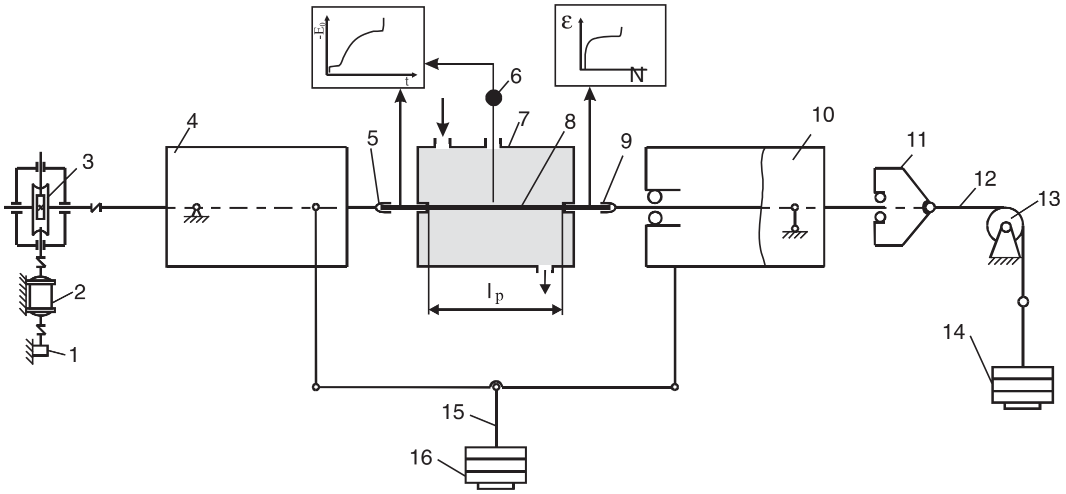

Fig. 4. Scheme of testing device MB-1K: 1 – cycle counter; 2 – electric motor; 3 – worm gear; 4 – leading drum; 5, 9 – clamp; 6 – reference electrode; 7 – removable operating chamber; 8 – experimental sample; 10 – driven drum; 11 – movement converter; 12 – wire; 13 – roller; 14, 16 – variable load; 15 – craving; l_p – the length of the sample working part

Table 1. Indexes of the survivability for the basic metal

Air		Seawater	
σ, MPa	*N*, cycles	σ, MPa	*N*, cycles
250	25000	140	100000
280	10000	180	21000
330	4500	250	10200
380	1850	310	6724
400	260	380	1050
420	500	420	120

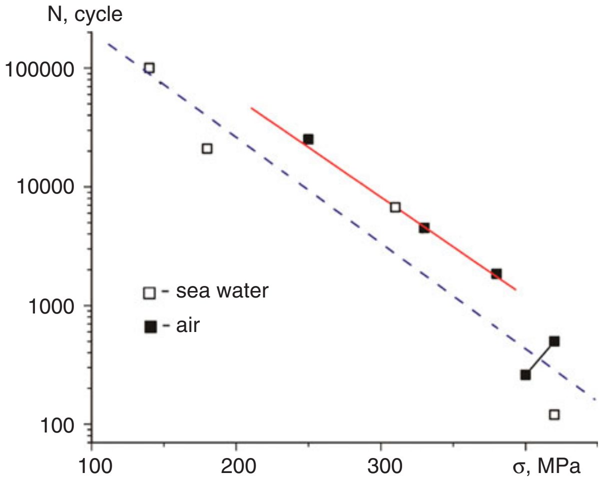

Fig. 5. Fatigue σ – N curve of Steel 20

Table 2. Survivability indexes for the welding joint

Air		Seawater	
σ, MPa	*N*, cycles	σ, MPa	*N*, cycles
250	1300	100	4950
280	1000	180	2100
380	250	280	460
400	129	300	220
450	51	350	120
490	48	400	65

whole range of the loads – from operation to the extreme ones. Analytic dependence for survivability of the basic metal under the air conditions is described by the expression $\lg N = 6.43 \div 0.00838 \cdot \sigma$, and under seawater conditions by the expression $\lg N = 6.2 \div 0.009 \cdot \sigma$.

With the aim of the pipelines engineering, calculation simplification and also the risks estimation and prediction facilitation were proposed to use survivability coefficients which will give the possibility to describe the welded joint via the dependence for the basic metal. This gives a new qualitative level for the corrosive action medium estimation since the use of above-mentioned coefficients can be an easy pass from the failure risks under air conditions (pipelines with the undamaged insulating coating) to the risks in corrosive medium (after the damage of insulating coating). It is possible also from the definition of the respective nomograms. For the basic metal we will obtain in seawater the dependence $\lg N = 6.2 \cdot K_1 \div 0.009 \cdot \sigma \cdot K_2$, where K_1 and K_2 equal to 0.96 and 1.07, respectively.

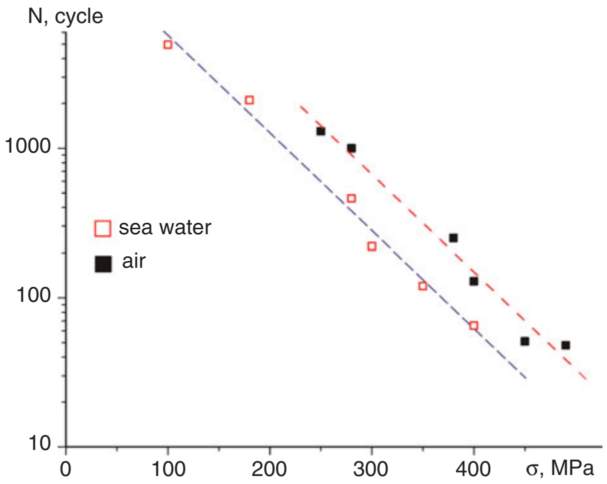

Fig. 6. Fatigue σ – N curve for welded joint of Steel 20

The survivability of the composition WS–ZthI in the seawater is 2.0÷2.2 times less than that under air conditions (refer Table 2). Graphical interpretation of the obtained results for the composition WS–ZthI (Fig. 6) turned out to be a good survivability prediction in all loads diapasons. The deviations at linear approximation do not exceed 1.0%.

Analytical dependencies for the survivability under the air and seawater conditions are as follow: $\lg N = 4.782 \div 0.00652 \cdot \sigma$ and $\lg N = 4.41 \div 0.00655 \cdot \sigma$ respectively. As shown in Fig. 6, the results of the linear approximation are practically parallel which are also confirmed by survivability coefficients $K_1 = 0.92$; $K_2 = 1.0046$.

The experimental results have a good agreement with the in-service analysis in describing the fatigue damage phenomena (Zav'yalov, Moiseeva 2004). These results show that the probability of the defects appearance and the strange inclusions availability in the WS–ZthI composition are allowed more than in the basic metal, and, thus, the risk of the damage initiation and their evolution here are much higher.

Conclusions

In the present study, the basic metal and welded joint survivability of oil and gas pipelines were investigated. The obtained results can be summarised as follows:

1) The in-service failure of gas and oil pipelines is influenced by a combination of several factors including fatigue, the severity of the damage, the applied mechanical loads and the environment.
2) The damage is the most severe in the welded joint during fatigue. Numerous microdefects are located in this zone corresponding to the decrease of fatigue life of welded joint.
3) A damage evolution process for fatigue in Steel 20 and welded joint is proposed in the present study on the basis of fatigue in the air and in the sea water. Fatigue life curves were measured at room temperature, and the effect of environment on fatigue behaviour was described.

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