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Key factors determining state of metal pipe during operation of main oil and gas pipeline

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During prolonged exposure of operational loads and mediums in pipe metal there occur gradual accumulations of frozen-in damages (for example, local or uniform decrease of wall thickness, embrittlement of metal).

The reliability of operation of main oil and gas pipeline is known to be determined not only by safety coefficient of pipe metal, but also by the resistance to its brittle failure [1]. Fulfilled analysis of operational conditions and behavior of pipe fracture shows the presence of breakdown cases of oil pipelines as a result of reduction of metal resistance to low-cycle failure [2, 6]. The character of failure of pipe edges points on this. In most cases the edges at seat of destruction are of grain (crystalline) structure and the angle between edge plane and pipe surface is about 90^o. Only at the ends of gaps this angle is 45^o, and edges have fibrous structure.

Reduction of pipe longevity in result of development of cracks, wear and aging depends greatly on the working service, regime and natural climatic conditions of operation of oil pipelines, on the system of maintenance and also steel grade and manufacturing technology of pipe metal.

Working service of pipes of some oil pipeline makes 40 years and more. Main oil lines may be divided into 4 groups according to production time. In 1947 pipes for oil lines mainly were produced from the steel grades 20, st3 and st4, from 1947 till 1960 – of steel grade 20, 10Mn2Si, 09Mn2Si, 14XCrMnSi, and from 1960 till 1975 – steel grades 19g, 17MnSi, 17Mn1Si, 17Mn1Si. Later for pipe production there were used steel grades 14Mn2SiNV, 14Mn2SiVNb, 16Mn2SiNV, 07Mn2VNb, 08Mn2MoVNb with the content of niobium, vanadium, molybdenum etc. Nevertheless main part of oil pipeline stretch are the pipes made of steel st3,st4,14CrMnSi, 10Mn2Si , 19Mn, 17MnSi, 17Mn1Si, foreign steel grades Cr50, Cr52. At the same time, as statistical analysis of failures shows, most of the failures, connected with pipe metal damage, happened within rather short period of time of pipeline exploitation (15-20 years).

According to the quality of realized design choices, technical level of installed equipment, used while pipe construction and fulfilled preoperational tests, main oil pipelines may be divided into three groups:

I group – pipelines, built till 1970. They came onstream mainly without means of active corrosion prevention. As insulated coating bitumen insulation with life cycle 8-12 years is usually used. Welded formed parts of field production, hand-operated stop valving are used. Pipeline were tested for pressure P_{doc} = 1.1 from working pressure.

II group makes pipelines built in 1970-1975. These pipelines are characterized by large diameter application of electrochemical protection, usage of electrical valve.

III group of pipelines was set into operation after 1975. While these pipelines construction, prefabricated formed components were used, test pressure was within the same limits as pressure during pipe production at the plant. Polymer films were used as isolation.

Pipelines built from 1960 till 1976 almost were not subjected to retesting. Hence it appears that they have more defects, which can appear while further exploitation.

Influence of service life of pipelines on their technical condition may be characterized by the failure rate of the pipeline depending on their servicing time. With the increase of service life of oil pipelines the intensity of failures also increases, which speaks for reduction of their bearing capacity. But estimation of the impact of service life on the technical condition of oil pipelines cannot be based on the failure rate. This dependence is more complicated and depends on many factors and requires special investigation.

In the works [3, 5] there fulfilled forecast of breakdowns of main oil pipelines. In [6] on the base of analysis of operating regime and breakdowns of gas pipelines there was concluded that when increasing operating time there expected increase in failures of oil pipelines because of low-cycle failure of pipes along the longitudinal weld, even without inside defects of welding. In [6] there developed forecast model of reliability of linear part of main oil pipelines. According to this work, fault rate at pipelines while initial operation (up to 10-15 years) will vary according to the following law:

$$\omega(t) = \omega_0 1 + aexp(-\frac{k\omega_0 t}{t_0 - t})$$

where $\omega(t)$- approximating function;
t – operating time;
ω_0- failure rate;
a - transformation coefficient.

Results of these works show that for definition of true accidence picture at oil pipelines, it is necessary to study in a detailed way not only external factors affecting the pipeline, but also structural changes in pipe metal, which occur in pipe steel during oil pipes operation.

The influence of operating mode of oil pipes on their technical condition and on physical condition of pipe metal is revealed through the change of working pressure during exploitation and is characterized by the number of cycles of working pressure change. Metal of main oil pipes is subjected not only to static but also cyclic loads (repeated static) in result of oscillations of internal pressure. Most of fractures of metal pipes are of brittle character. So, the built-in double assurance factor aimed for static load does not provide cyclic life of metal pipes. Pipeline maintenance is being reduced progressively in the course of time. The reason for this is that under small cyclic load as opposed to static one, because of the presence of stress risers there occur accumulation of non-reversible microflow in structure-nonhomogeneous regions of metal, carbon atomic re-arrangement and other foreign atoms, connected with age hardening, which lead to blistering of local regions of metal and consequently to the reduction of brittle fracture strength of pipe steel. On the base of analysis of operating mode of pipeline it is determined that average number of cycles per year with amplitude of pumping pressure change up to 2-4 atm makes 30 per year, up to 10 atm – 130-150, up to 40 atm – 140-150, i.e. at average the number of such cycles at oil pipeline makes approximately 350 per year.

Alternating frequency of internal pressure in oil pipe during operation is meant by rigidity of operating regime of main gas-oil pipelines. Stiffening of operating regime may be characterized by the ratio of the number of revision cycles of inner pressure within considered time to critical number of revision cycles of inner pressure, at the achievement of which destruction of pipeline may occur. As normative number of revision cycles of inner pressure determines stiffening of operating regime of pipeline there taken 250 cycles per year, obtained from the condition of equality of critical number of cycles 7 -8 thousands for 33 year service life of pipeline.

In the theory of material breakage damages to 10% are related to small ones.

Pipes of main pipeline are deformed by inner pressure in radial direction, longitudinal motion is almost absent, because the pipes are pinched in the ground.

Full level of stresses, calculations for smallest pipe wall, under the overload factor of working pressure n = 1.5 [2] for the values of maximum pressure rating in the main pipelines are presented in the table 1.

Table 1. Maximum levels of stresses at minimum pipe wall thickness

$D_н$, mm	δ, mm	p, MPa	σ, kg/mm^2	$ε_{min}$, %	$ε_{max}$, %
529	5,5	6,5	35,20	15,7	17,6
720	7	6,0	34,79	15,6	17,4
820	8	5,8	33,52	15,0	16,7
1020	9	5,6	35,85	16,0	17,9
1220	11	5,4	33,25	14,9	16,6

Table 2. Minimum levels of stresses at maximum pipe wall thickness

$D_н$, mm	δ, mm	p, MPa	σ, kg/mm^2	$ε_{min}$, %	$ε_{max}$, %
529	9	5,4	16,86	7,6	8,4
720	12	5,0	15,95	7,15	8,0
820	12	4,8	17,51	7,85	8,75
1020	14	4,6	17,93	8,0	9,0
1220	15,2	4,4	18,94	8,5	9,5

In such a way maximum deformations on the routing of main pipelines are not related to small ones, ε> 10%.

Minimum level of stresses, calculated for maximum thickness of pipe wall (according to the range of pipeline wall thickness) at overload factor of working pressure n = 1.1 for the values of minimum working pressure (minimum throughput capacity) is stated in the table 2.

In such a way minimum deformations on main pipelines are related to small ones, ε <10%.
From the analysis it is obvious how essential is the increase of stresses at pipe wall in the places of various defects (up to two and more times as compared with defect-free zone of pipe). In steels under certain conditions such chemical elements as sulfur, phosphorus, oxygen, nitrogen and others , connecting with iron, manganize, silicon form sulphide, carbidic , oxide, phosphate inclusions. Besides in result of fluctuation of foreign elements during manufacturing of metal there arise chemically nonhomogeneous regions, during sheet rolling there appear films, and in welded seams – slag inclusions [2]. Nonmetallic inclusions are not only concentrators of stresses, but also reduce strength properties of steel [3]. For example, the presence of manganous sulphide in the steel 14Mn1Si reduces its impact hardness:

MnS. % 0.003 0.01 0.025

KCV. kgsm / sm ^{2} 14 6 2.6

It is known that fatigue crack nucleation often occurs near nonmetallic inclusions [3], besides they are very dangerous for high-resistance steel [4]. Despite numerous researches devoted to the study of influence of nonmetallic inclusions on the fatique properties of steel. There is no agreement of this opinion.

On the base of classical elasticity theory there were specified [5] the coefficients of stresses concentration $K_α = σ_{max} / σ_{nom}$ depending on the modular ratio of nonmetallic inclusions and matrixE_m. The highest concentration of stresses (e.g. for inclusion $K_α$ = 3.3) appeared to be created by pores, cracks, hopes, i.e. defects where $E_в$ = 0. Concentration of stresses in the inclusions, where $E_в$> 0, will be smaller ($K_α$ = 1.8-2.2), but smaller than in steel in the case when the equation takes place

$K_E = \frac{E_B}{E_M} < 1.$

According to elasticity theory maximum concentration of stresses should be in the vicinity of inclusions, which have lower E values, than in steel (in most plastic inclusions) and minimum in the vicinity of inclusions which $E_B > E_{cm}$ (near brittle inclusions). However the experiments showed the contrary [6]. With the help of fractographic investigations of fatigue fracture there was stated that the inclusions which provoke fatigue cracks are stand to brittle inclusions (E_B> E_{cm}) and in the vicinity of plastic inclusions (E_B<E_{cm}) there are no discontinuance of metal.

Nonmetallic inclusions may change radically stress distribution in metal having different from metal physical, chemical and other properties. Brittle inclusions (alumina and its derivations) with low and high value of elasticity modulus E during cooling create significant thermal-residual stresses of extension, which in certain cases may reach or exceed yield strength [4]. Plastic inclusions do not significantly differ from metal according to the coefficient of volume expansion and elasticity modulus E and create negligeable stresses. In some cases when α_B> α_M (e.g. sulphite), thermal stresses may not arise. V. Shpet [5] defined these stresses as residual stresses of the IV type.

In order to increase the reliability of main oil pipelines and decrease failures, connected with fracture of pipe metal, native standards first submitted requests to mechanical properties of steel and also to the accuracy of pipe size and geometric form [52]. So, for electric welded pipes with the diameter 800 mm allowance for bending is 1.5 mm for 1 m of pipe, limit deviation according to outer diameter of bearing face should not exceed ± 2.0 mm [2], and out-of-roundness – not more than ± 1% from outside diameter. Despite this, there is no dercease of accident risk of oil pipelines, constructed according to requirements.

In modern operational practice for main oil pipes in order to increase their reliability, there taken the following measures [3, 5]:

- periodic cycle testing (3 cycles) by increased pressure $p_{\partial oc}$ = 0,9 σ_m;
- passing of stand-alone test instruments inside the pipelines;
- application of new insulation materials while general maintenance (including “Plastobit” type and film materials);
- advances in technological productivity and selective or unscheduled repair technique.

However, in order to fulfill these measures to high standards of workmanship, it is necessary to know physical condition of pipe metal in each pipeline and as far as possible to reduce cyclicity of loads and reduce working pressure of oil pumping in old pipelines.

Conclusions

In such a way condition of metal pipes of main pipelines especially their welded seams depends not only from working service, but also on forse parameters, which are different at various destances of pipes from pump house. Higher level of working pressure differntial in pipelines increases average level of stresses affecting the pipe wall and contributes to more intensive ageing process and defect accumulation.

While pipe operation there are drops in pressure, temperature, dynamic and static loads create conditions for age hardening in metal, which lead to increase of resistance to microflow and increase of danger of appearing in metal of local voltage spikes. In result of exploitation of pipes there reduces the possibility of relaxation of local stresses in the notch or crack apex, which lead to increase of steel collapsibility.

The results presented allow to make a conclusion that for reliability evaluation of metal pipes after continuous exploitation, it is insufficient to fulfill typical mechanical tests. Features of crack strength both circular welded seam and basic metal on the samples with sharp notch or crack, drawn nearer to local variations of steel structural condition, should be the evaluation criteria of reliability. To reduce the risk of pipeline breakage, which are being operated more than 30 years, one should consider stress risers of metal pipes in result of age hardening.

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