Assessment of corrosion fatigue strength of gas-transport system constructions under atmospheric forcing

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Abstract. Calculated influence method of strengthening technology (surface plastic deformation) of gas-transport system (GTS) weld bead in the conditions of atmospheric forcing in order to increase its bearing capacity and service life is suggested. It is shown that relative strength factor of weld bead at the same time is a probabilistic function of fatigue life. Analogue function of the new coefficient is proposed - relative life to assess the service life of the GTS with its periodic loading. Using the system comparable and initial quantitative lines of corrosion fatigue, the equations of the functions of these coefficients are obtained, allowing to clarify the strength and durability of GTS in the real service interval and variable loading, taking into account the strengthening of weld beads.

Introduction
Reducing period of new outfit design and full use of the reserve of bearing capacity and durability of existing gas-transport system (GTS) suggest, along with the refinement of their characteristics of fatigue resistance and fracture strength application of effective calculation methods, implemented by computational procedures directly at the workplace of the engineer-calculator. The creation of database while using the mentioned methods allows give out operative calculated information in the form of fixed, discrete and continuous values of parameters of interest, without resorting to traditional reference books and manuals, whose capabilities are limited, and can become one of the important elements in the development of computer aided design system (CADS) and conducting scientific researches [1,2]. To the number of such parameters apply coefficients [3,4,5], taking into account the influence of various factors on the fatigue resistance of parts (scale effect, type of stress state, stress concentration, physical and mechanical condition of surface layers and application of hardening technology, coating, corrosive environment, unsteady loading mode, etc.).

The structure of these coefficients indicates the prevailing use of calculations according to the strength criterion. But when designing structures that are subject to service life limits, minimum mass requirements or establishing a residual life in the presence of cracks (air, shipbuilding, GTS, vehicles, sea and river structures, etc.), the main ones are probabilistic calculations for durability, which have recently become paramount and prevailing in the design of equipment.

The mechanism of corrosion-fatigue fracture
The works \cite{6,7,8,9,10} in the field of physico-chemical mechanisms of corrosion-fatigue fractures are known, which further development involves the expansion of capabilities and improvement of methods for the probabilistic assessment of the bearing capacity of structures and the minimization of their material consumption. The solving of this kind of issue dictates the need for a comprehensive review of the range of issues related to the calculation and design, manufacture, testing, maintenance and repair of these structures and equipment.

For a significant number of class structures and technological equipment operating in atmospheric conditions and corrosive environments, the occurrence and development of damage on the surfaces of heavily loaded and critical components and parts is characteristic, which are continuous in nature and significantly reduce their strength, durability and reliability \cite{11,12}.

The presence of a large number and diverse actions of damaging factors, as well as a wide range of changes in their quantitative indicators dictate the need to apply the principle of a systematic approach - studying the mechanism of corrosion-fatigue fracture and adopting its optimal mathematical model, developing a calculation algorithm and creating software for the integrated solution of these problems, arising in the design of new designs and operation of already created machines and equipment. In this regard, it is important to ensure the necessary bearing capacity of the most loaded and critical elements of GTS - pipeline welds.

According to the adsorption-electrochemical hypothesis of corrosion-fatigue failure of steel structures, the primary influence of a corrosive medium with a deformable metal occurs during the adsorption of molecules of the medium into the surface layers, which leads to a change in the surface energy of the metal – medium boundary zone. In dislocations exit places on the surface of the part, activation of adsorption and electrochemical processes occur, whose gradient depends on the pH indicator of the environment. The combined action of these processes leads to the continuous occurrence and peeling of created corrosion films (lamination), therefore, the process of corrosion-fatigue fracture, unlike other types, is continuous in nature and there is no evidence of a constant physical endurance limit \cite{13,14,15}.

It is known that in the zone $N \leq 5 \cdot 10^6$ of loading cycles in the mechanism of corrosion-fatigue fracture, the adsorption process prevails due to microstructural shifts and defects of the surface layer, which ultimately leads to the occurrence of submicrostructural damage and the appearance of the first microcracks. Electrochemical (anode) processes in this zone are insignificant, but contribute to the appearance of microcracks \cite{16,17,18}.

In the cycle zone $N > 5 \cdot 10^6$, the gradient of adsorption processes is low and electrochemical processes become prevailing, which at the bottom of surface microroughnesses and microcracks that have already arisen stimulate microcurrents in the galvanic “peak-to-bottom” pair of microsurfaces and microcracks that continuously destroy the bottom of these microdamages. The indicated processes in zones of limited and long endurance $(10^3 \leq N \leq 10^9)$ have different gradients and smoothly pass from one to another \cite{10}.

**Calculation method for assessing the strength and durability of GTS**

The calculation and graphical analysis of the data of a large number of experimental works as a mathematical model of corrosion-fatigue failure confirmed the appearance of a two-link curve of corrosion fatigue, presented in coordinates $(\lg \sigma, \lg N)$ and providing a high degree of tightness of the linear correlation between $\sigma$ and $N$ ($r = 0.92...0.96$). Therefore, the mathematical model of the process of corrosion fatigue failure of steel structures is expressed by the equations of straight lines in the form of a broken line \cite{5,13}:
left branch \( (N < N_{Gk}) \):
\[
\lg N = \left( \lg N_k + z_p s_{Nrk} \right) - m_k \left( \lg \sigma - \lg \sigma_k \right) = C_k - m_k \lg \sigma;
\]
right branch \( (N \geq N_{Gk}) \):
\[
\lg N = \left( \lg N_k + z_p s_{Nrk} \right) - m_k \left( \lg \sigma - \lg \sigma_k \right) = C_k - m_k \lg \sigma;
\]
\begin{align*}
\text{coordinates of the inflection point of the lines:} \\
\lg \sigma_{rk} = (C_k - C_k) / (m_k - m_k), \quad \lg N_{rk} = (C_k / m_k - C_k / m_k) / (1 / m_k - 1 / m_k).
\end{align*}
(1)

Where
\[
\begin{align*}
m^{(1)}_i &= \bar{m}^{(1)} + z_p s^{(1)}_{mk}, \quad C^{(1)}_k = \bar{C}^{(1)}_k + z_p s^{(1)}_{Ck}, \quad \bar{m}^{(1)} = \bar{r}^{(1)} / s^{(1)}_{mk}, \\
C^{(1)}_k &= m^{(1)}_k \lg \sigma^{(1)}_k + \lg N^{(1)}_k, \quad s^{(1)}_{Nk} = \left( s^{(1)}_{Nk} / s^{(2)}_{Nk} \right) \sqrt{(1 - r^{(1)}_k)(n - 1)/(n - 2)}, \quad \sigma^{(1)} = s^{(1)} + s^{(2)} \lg \sigma^{(1)}_k, \\
r^{(1)}_k &= \mu^{(1)} / s^{(1)}_{Nk}, \quad \lg N^{(1)}_k = \frac{1}{n} \sum_{i=1}^{n} \lg N^{(1)}_k, \quad \lg \sigma^{(1)}_k = \frac{1}{n} \sum_{i=1}^{n} \lg \sigma^{(1)}_k, \\
\bar{s}^{(1)}_{Nk} &= \sqrt{\frac{1}{n - 1} \sum_{i=1}^{n} \left( \lg N^{(1)}_k - \lg N^{(1)}_k \right)^2}, \quad \bar{s}^{(1)}_{\sigma_k} = \sqrt{\frac{1}{n - 1} \sum_{i=1}^{n} \left( \lg \sigma^{(1)}_k - \lg \sigma^{(1)}_k \right)^2}, \\
\bar{\mu}^{(1)} &= \frac{1}{n - 1} \sum_{i=1}^{n} \left( \lg N^{(1)}_k - \lg N^{(1)}_k \right) \left( \lg \sigma^{(1)}_k - \lg \sigma^{(1)}_k \right).
\end{align*}
\]
(3)

\( n \) - volume of tests for corrosion fatigue, - quantile of the normalized Gauss function:
\[
P(z_p) = \int_{-\infty}^{z_p} \exp \left[ -z^2 / 2 \right] dz / \sqrt{2\pi} \text{ (in (3) a short form of parameter representation is accepted, for example: } \bar{m}^{(1)} \text{ means } \bar{m} \text{ either } m^{(1)} \text{ for the left or right branch of corrosion fatigue lines). In order to unify the calculation procedures, one can use the method of comparing scattering regions } \lg N \text{ [3], which consists in jointly solving the equations of families of comparable two-link corrosion fatigue lines taking into account the location of inflection points } G^{(1)}_k(N_{Gk}, \sigma^{(1)}_{(rk)}). \text{ The method is based on the principle of assessing the general nature of the action of these factors - their property is to cause a change in the size and relative position of the scattering fields in the region of multi-cycle fatigue, when the characteristic parameter of the acting factor varies (temperature, time, geometric, technological and operational indicators, etc.). This, in turn, requires revealing the law of changes in the main characteristics and the location of the nodal points of the equations of fatigue lines - the parameter } C_k \text{ of the slope } m_k \text{ and inflection points } G_k(\sigma_{rk}, N_{Gk}) \text{ of comparable fatigue lines, which, due to their structure, are integral characteristics of the fatigue process. A mathematical model of the influence of the studied factor, taking into account (1) - (3), can be represented as a system of equations.}
\]

Strength assessment is carried out in accordance with the coefficient of corrosion (GOST 20.504-82)
\[
K_{ek} = \sigma_{RNk} / \sigma_{RNk},
\]
(4)

Where \( \sigma_{RNk} \) and \( \sigma_{RNk} \) - accordingly, a comparable and basic endurance limits in a corrosive environment at a given value of cyclic durability. The use of the coefficient \( K_{ek} \) in strength
calculations gives only a point estimate in the vicinity of the inflection point of the corrosion fatigue line, which has a falling character in the entire interval of the number of cycles \( N = 10^5 \ldots 10^9 \). Therefore, it is also important to carry out calculations for durability, using a similar coefficient:

\[
K_{N_k} = N_k / N_{kj},
\]

where \( N_{kj} \) and \( N_k \) - cyclic durability determined from the corresponding equations of corrosion fatigue lines at a given level of cyclic overvoltages.

Significant coefficients (4), (5) of two ratings factor in the random case: \( K_{of}, K_{nf} \leq 1 \), and taking into account the variability of their components are \( N \) and \( \sigma \) functions, which can be obtained by a joint solution of individual sections of families of comparable and initial equations of two-link corrosion fatigue lines. The mutual arrangement and variability of the families of quantile lines of corrosion fatigue depend on the specifics of the action of the studied factor, in this case, the process of hardening the surface layers of the welds, due to which the family of fatigue lines move to the zones of high stresses and durability \( \sigma_{kj} \) and \( N_{kj} \). In this case, the slope of the fatigue lines becomes smoother, and their location inside the families becomes dense. These properties are the result of hardening processes that improve the microgeometry of the surface layers and the physical and mechanical state of welds, which significantly slow down the formation and development of corrosion microcracks [19]. The use of portable reinforcing devices with individual drives and break-in rollers, which are installed and fixed on the weld, facilitate the PPV procedure both during the assembly of pipelines and during their operation and repair work.

A graphic analysis of 4 families of fatigue lines (fig.) indicates the presence of three \( N \) and \( \sigma \) zones and, within which the form and gradient of \( K_{of} = f(N, \sigma) \) and \( K_{nf} = \varphi(\sigma, z_p) \) functions remain constant. Using the equations of the corrosion fatigue lines (1) and their parameters (2), (3), it is possible to obtain \( K_{of} \) and \( K_{nf} \) functions in the I, II, and III indicated zones (table).

![Figure 1. Functions of strength and durability coefficients for GTS welds:](image)

\[ A - K_{ok} = f(N, z_p); \quad B - K_{Nk} = \varphi(\sigma, z_p); \quad \text{families of two-link corrosion fatigue lines: 1 - for hardening of welds, 2 - initial} \]
Table 1. $K_{ak} = f(N, z_p)$, $K_{nk} = \varphi(\sigma, z_p)$ functions for I - III zones

| N | $N \text{ or } \sigma$ Zones | Functions |
|---|---|---|
| 1 | I $N < N_{Gk}$ | $\lg K_{ak} = S_1 - M_1 \lg N$ |
| 2 | II $N_{Gk} \leq N \leq N_{Gkf}$ | $\lg K_{ak} = S'_1 - M'_1 \lg N$ |
| 3 | III $N > N_{Gkf}$ | $\lg K_{ak} = S_2 - M_2 \lg N$ |
| 4 | I $\sigma > \sigma_{Rkf}$ | $\lg K_{ak} = \Delta C_1 - \Delta m_1 \lg \sigma$ |
| 5 | II $\sigma_{Rkf} \geq \sigma \geq \sigma_{Rk}$ | $\lg K_{ak} = \Delta C_1 - \Delta m_1 \lg \sigma$ |
| 6 | III $\sigma < \sigma_{Rk}$ | $\lg K_{ak} = \Delta C_2 - \Delta m_1 \lg \sigma$ |

In the table:

\[
S_1 = C_k / m_k - C_{ij} / m_{ij}, \quad S'_1 = C'_k / m'_k - C'_{ij} / m'_{ij}, \quad S_2 = C_k / m_k - C'_{ij} / m'_{ij}, \quad M_1 = 1 / m_k - 1 / m_{ij}, \quad M'_1 = 1 / m'_k - 1 / m'_{ij}, \quad M_2 = 1 / m_k - 1 / m'_{ij},
\]

\[
\Delta C_1 = C_k - C_{ij}, \quad \Delta C'_1 = C'_k - C'_{ij}, \quad \Delta C_2 = C_k - C'_{ij}, \quad \Delta m_1 = m_k - m_{ij}, \quad \Delta m_1 = m_k - m_{ij}, \quad \Delta m_2 = m'_k - m'_{ij}.
\]

(6)

The proposed method of calculation estimation has a logical sequence and it is possible to draw up a clear algorithm and create a software package for design and engineering development of GTS and optimize their designs.

Conclusions and recommendations

A new method for evaluating the performance of critical structures of GTS has a sign of versatility, because allows:

a) to carry out design estimates at any point in the zone of $10^5 \leq N_{Gk} \leq 10^9$, $\sigma = 0.5...2.5\sigma_{Gk}$ multi-cycle corrosion fatigue, which was previously performed only at the inflection point of inclined sections of fatigue lines;
b) to make estimates separately and jointly acting factors for any combination thereof;
c) to perform probabilistic assessments of performance indicators, which significantly increases the accuracy and reliability of the results;
d) to evaluate the effect of variable complex loading on cyclic durability, which cannot be performed by known strength theories;
e) to obtain the functions of relative strength and durability of parts and components of machines, which are mathematical models of operating factors.

Using the indicated $K_{ak}$, $K_{nk}$ function graphs, in an operational manner, when searching for design and development of GTS, right at the workplace of the designer-developer, using simple graphical constructions, one can select the necessary data for preliminary calculations of the bearing capacity of critical structures of GTS, and when performing more precise calculations, use the equations of functions.
\[ K_{se} = f(N, z_p) \quad \text{and} \quad K_{sc} = \varphi(\sigma, z_p), \]

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