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A FORMULA THAT ALLOWS TO PREDICT THE TIME TO CORROSIVE FAILURE OF BODIES WITH A NON-STATIONARY CHANGE IN THE CONCENTRATION OF AGGRESSIVE MEDIUM SUBSTANCES DURING THE CORROSION PROCESS.

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Abstract. A formula for the corrosive failure of diffusing substances as a result of constant deformation in an aggressive medium with a non-stationary concentration is given, which allows predicting the time to corrosive failure of substances of arbitrary configuration at known initial values of the concentration of substances and the characteristics of the "material-aggressive medium" system.

Keywords: corrosive failure, concentration of diffusing substances, deformation, damage accumulation, "material-corrosive medium" system, mechanical stress, concentration.

1. Introduction

It is known that the spontaneous process of failure of materials and products made of them under the influence of the environment is called corrosion. Mainly metals are subject to corrosion. However, many materials are also subject to it, including stones, plastics and other polymeric materials and wood. For example, cultural monuments - buildings and sculptures made of various materials, which over time suffer from acid rain.

Corrosive-mechanical failure is one of the dangerous types of destruction of industrial structures. This type of destruction of products occurs, as it is known, under the combined action of load and aggressive medium. Mechanical stresses play a significant role in the process of corrosive failure. It is shown that corrosive failure occurs under the action of tensile stresses in [1, 2]. Corrosion cracks spread perpendicular to the direction of action of tensile stress under small elastic and non-elastic deformations. Studying the mechanism of this phenomenon is relevant, as it can contribute to the formulation of an adequate analytical description that allows predicting the properties of the "material-aggressive medium" system.

2. Analysis of some literary data and problem statement

The effect of the concentration of diffusing substances on the process of corrosive failure has been studied for a number of materials and aggressive mediums [1-7]. The composition and concentration of active substances in the aggressive medium have a significant effect on the process of corrosive failure of materials. For example, according to [2], an increase in the concentration of ammonia in aqueous solutions continuously increases the rate of corrosion cracking of brass. Increasing the concentration of sodium chloride in an aqueous medium reduces the time to cracking. There is a study [2] that examines the effect of chlorine ion concentration in *NaCl* solutions on the rate of corrosion cracking of magnesium alloy MA-3. It is noted that the rate of corrosion cracking continuously increases as the salt concentration increases. It is shown that an increase in the concentration of carbon dioxide and relative humidity increases the rate of the corrosion process in [10], at the same time, reducing the time to corrosion cracking of steel structures. The tendency to corrosion cracking of martensitic-aging steel of grade EP679-VD and its welded joints is studied in [5]. Despite the fact that this steel has high resistance to corrosive failure, an increased concentration of an aggressive medium leads to its cracking. The dependence of the corrosion rate of steels of different grades on the concentration of sea water is determined in [6]. In this case, a decrease in the cracking time of the studied steels with an increase in the concentration of active components of sea water is noted. The features of the corrosion process of steel grade X18H10 in nitric acid environments are studied in [7]. An increase in the concentration of nitrous oxide adsorbed by the surface of steel increases the dissolution rate of steel of the grade considered in a sulfuric acid solution by two to three orders of magnitude.

Graphs are given of the dependence of the time to failure on the concentration of active diffusing components of aggressive medium in the above-mentioned and many other studies. In many cases [8, 9], these graphical dependencies (curves) are approximated by analytical expressions. For example, in [8], a formula is given for dependence of time to corrosive failure at a constant tensile stress on the concentration of adsorbed hydrogen atoms: $t_0 = \left[BC_0/\left(C_0 - C\right)\right]^2$, where t_0 is time to cracking; C_0 is concentration of hydrogen atoms on the surface of steel; C is hydrogen concentration when a visible crack appears; B is constant. The work [9] is devoted to establishing the functional dependence of the time to failure of materials on the constant concentration of diffusing substances. Based on the analysis of the curve shapes of the dependence of the time to corrosive failure (t_0) on the constant concentration of diffusing substances (C) at a given tension, the following analytical formula for this dependence, is proposed:

$$t_0 = t_0(\sigma, C) = B\exp\left[-\alpha\left(\frac{C}{C_s} - 1\right)\right]. \tag{1}$$

where C_s is minimum value of concentration of aggressive medium on the body surface: $C_s = \min\{C\}$. α is experimentally determined positive constant; B is time to corrosive failure at $C = C_s$.

In the work [9] a system of experiments is formulated that allows to determine the constants included in (1) "metal-aggressive medium". The results of processing some experiments are also presented here, which showed satisfactory agreement between the calculated data and the experimental data. It is concluded that formula (1) can be used as a characteristic function of the system "material-aggressive medium".

Note that formula (1) allows us to determine the time to corrosion failure in cases where the value C is stationary that is independent of time. Formula (1) is not suitable for predicting the desired time of corrosive failure when the value C changes non-stationary during the corrosion process. In this case, formula (1) can only be used as a function characterizing the property of the "material-aggressive medium" system.

Here an attempt is made to theoretically predict the time to corrosive failure with a non-stationary change C in the value during the corrosion process. However, it is assumed that the stress σ remains stationary during the corrosion process or is completely absent.

3. Determination of time to corrosive failure

We will assume that the process of corrosive failure is a continuous process t [2]. The corrosion process, following [10], is defined as a process of continuous accumulation of a certain type of damage. We assume that corrosive failure occurs when the accumulated corrosive damage reaches a certain level. According to [10], we introduce a monotonically increasing non-negative function $\eta(x,t)$ over time t, which we will consider to characterize the degree of corrosion. Here $x = (x_1, x_2, x_3)$ are the coordinates of the body points. At the initial moment of the corrosion process $(t = 0)$ we have $\eta(k,o) = 0$. Corrosive failure occurs at a time t_*, when $\eta(x,t_*) = 1$.

Let us assume that the rate of accumulation of corrosive damage $(d\eta / dt)$ at a given mechanical stress is a function of the concentration of diffusing substances $C = C(x,t)$ from the function itself $\eta(x,t)$:

$$\frac{d\eta}{dt} = F(C(x,t),\eta(x,t)). \tag{1}$$

As a first approximation, we accept:

$$F(C,\eta) = \varphi(C)\psi(\eta).$$

In this case, equation (1) can be rewritten as

$$\frac{d\eta}{\psi(\eta)} = \varphi(C(x,t))dt. \tag{2}$$

Let us integrate (2) taking into account $\eta(t_*) = 1$:

$$\int_0^{t_*} \Phi(C(x,\tau))d\tau = 1, \tag{3}$$

where $\Phi = \varphi / A,\ A = \int_0^1 \frac{d\eta}{\psi(\eta)}$.

Let t_0 be time to corrosive failure of the considered structural element at constant concentrations $C = C_n = const(n = 1,2,...)$. In this case, time t_* moves to t_0. From relation (3) we have:

$$\Phi(C_n,\sigma) = 1/t_0(C_n). \tag{4}$$

The function $t_0(C)$ that is included in formula (4) can be represented in the form (1). In this case, all quantities included in (1) are determined by experimental data in accordance with the method presented in [9].

Let us now consider the case when $C = C(x,t)$. In further entries we will omit the arguments *x*: $C = C(t)$. In this case, to determine the time to corrosive failure t_*, we will use the method proposed in [10]. We will represent the function $\eta(t)$ at a given voltage in the form:

$$\eta(t) = 1 - e^{\gamma(1 - C/C_0)}. \tag{5}$$

There is C_0 an initial concentration value here $C(t)$ $C_0 = C(0)$; γ is some positive constant value that is determined by the rate of accumulation of corrosive damage. As we can see, the value $e^{\gamma(1-C/C_0)}$ for large values of C, when $t \to t_*$ is a small value compared to unity.

As an initial approximation, we take $\psi(\eta) = 1$. In this case $A = 1, \Phi = \varphi$.

Then, using (1) and taking into account (5) in equation (2), we obtain

$$\frac{\gamma}{C_0} e^{\gamma\left(1 - \frac{C}{C_0}\right)} \frac{dC(t)}{dt} = \frac{1}{B} e^{\alpha\left(\frac{C}{C_s} - 1\right)}. \tag{6}$$

Let us integrate the relation (6)

$$\frac{\gamma}{C_0} e^{\alpha+\gamma} \int_{C_0}^{C_b} e^{-\left(\frac{\gamma}{C_0} + \frac{\alpha}{C_s}\right)C} dC = \frac{t_*}{B}. \tag{7}$$

Here C_b is the value of $C(t)$ at $t = t_* C_b = C(t_*)$.

Calculating the integral on the right-hand side transforms relation (7) to the form:

$$t_* = B\frac{e^{\alpha(1+\delta)}}{1+(C_0/C_s)}\left[e^{-\alpha[1+(C_0/C_s)]} - e^{-\alpha N[\delta+(C_0/C_s)]/(C_0/C_s)}\right]. \quad (8)$$

Here $N = C_b / C_s$, $\gamma = \gamma / \alpha$ is new constants to be determined from corrosion experiments, for example at a constant rate of change of concentration. The obtained formula (8) makes it possible to determine the time to corrosive failure of structural elements in the case when $\sigma = const$, in particular $\sigma = 0$ and $C = C(x,t)$.

4. Conclusion

A formula has been derived that allows predicting the time to corrosive failure of bodies with a non-stationary change in the concentration of diffusing substances of an aggressive medium during the corrosion process in the case where the mechanical stress acting in the body is constant or absent at all.

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