Corrosion Science 88 (2014) 306–316

Contents lists available at ScienceDirect

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci

Long-term forecast of corrosion mass losses of technically important metals in various world regions using a power function

Yu.M. Panchenko *, A.I. Marshakov, T.N. Igonin, V.V. Kovtanyuk, L.A. Nikolaeva

A.N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, 119991 Moscow, Russia

ARTICLE INFO

Article history:
Received 11 April 2014
Accepted 24 July 2014
Available online 4 August 2014

Keywords:
A. Steel
A. Carbon steel
B. Weight loss
B. Modeling studies
C. Atmospheric corrosion

ABSTRACT

An analysis of the results of corrosion tests on flat and helix specimens made of technically important metals carried out within the ISO CORRAG program is given. Stochastic relationships between coefficient n in the power function, which characterizes the protective properties of the corrosion products, and the limiting corrosion rate α, with the corrosivity of each type of atmosphere were found. A forecast of corrosion losses for a period of up to 50 years was given using the linear function in the stationary stage, a power function, and limiting corrosion rate values α. The reliability of the forecasts was estimated.

1. Introduction

Data on the corrosion resistance of metals over long periods of time are important for determining the service life of metal structures and for developing the methods and means for their protection and preservation. Reliable estimates of corrosion resistance can be provided by corrosion tests under natural conditions. These tests are time-consuming and quite expensive. In view of this, researchers give much attention to the development of models that would ensure a long-term forecast without requiring testing under natural conditions.

Currently, the power function (1) is widely used to describe the corrosion effects obtained in tests for various periods of time in various regions of the world [1–25]:

$$K_\tau = A\tau^n \quad (1)$$

or in logarithmic coordinates:

$$\log K_\tau = \log A + n \log \tau \quad (2)$$

where K_τ represents the corrosion losses after time τ, A is a constant coefficient of corrosion losses over the first year (K_1) and n is a constant coefficient that characterizes the protective properties of corrosion products.

The attractiveness of this model lies in its simplicity since the corrosion behavior of metals is based on just two parameters, namely K_1 (A) and exponent n, and hence there is no necessity to study the parameters of atmosphere corrosivity. The use of Eq. (1) for specific locations gives a good match of forecast results with experimental data (see, for example, [7,9,10]) including long-term tests over, for example, 16 [20] and 20 years [22].

If a forecast based on Eq. (1) is not totally suitable for the description of experimental data, Eq. (2) is used with different n values for two periods (bilogarithmic law), where n_1 for an initial period exceeds n_2 for a subsequent period [23,26,27]. It is assumed that for each exposure location, the results of 4-year tests in various types of atmosphere can be extrapolated to 20–30 years using the bilogarithmic law [7].

In yet another approach [28–29], it was suggested that, to ensure a reliable long-term forecast of atmospheric corrosion for long periods, a mixed linear-power law should be used, according to which the plot of corrosion versus time consists of an initial parabolic part followed by steady-state corrosion, *viz.*, a straight line. According to Ref. [30], a constant gain in corrosion loss determined by the barrier properties of the product film is established during the stationary phase. The existence of a stationary phase is experimentally confirmed by the results of long-term (over 10 years) field tests of metals, *e.g.*, Zn (13–16 years in various types of atmospheres) [31,20], an aluminum alloy (20 years under industrial and marine conditions) [22], mild steel (10–13 years in atmospheres of various types) [32,27], as well as mild steel, Zn, Cu, and Al (10 and 17 years in marine atmospheres) [33].

Comparison of long-term forecasts with experimental data for four steels using the power and linear-power relationships has shown that the forecast reliability of the latter model is higher [34].

---

* Corresponding author. Tel./fax: +7 495 3349805.
E-mail address: panchenkoyum@mail.ru (Yu.M. Panchenko).

http://dx.doi.org/10.1016/j.corsci.2014.07.049

ISO 9224 Standard [35] suggests a bilinear model for forecasting the corrosion rate of steel for 20 years for various corrosivity categories. This model provides linear relationships of steel corrosion versus time with a mean rate during the first 10 years and with a steady-state rate during the next 10 years. The total corrosion effect is the sum of corrosion losses over the first 10 years and over a subsequent required period of time at the corrosion rate that is established.

The following should be noted: according to standard [35], the A and n values in Eqs. (1) and (2), as well as the mean and linear corrosion rates for the two time periods, are calculated separately for each test location. The corrosion losses are calculated over a time not exceeding the exposure time. Forecasts of corrosion mass losses of technically important metals have been given for quite a limited number of locations due to the small number of long-term ($\geqslant$10 years) corrosion tests. Thus, a long-term forecast for any location using any of the above models is impossible without experimental data over long exposure times.

A bi-modal model was suggested for a long-term forecast of the corrosion loss of low-alloy steels and grey cast iron in marine atmosphere [36,37]. This model was also used to describe the kinetics of corrosion (corrosion trends) of a number of metals, including mild steel, in marine environments [38–40]. The bi-modal model takes into consideration the increase in the corrosion rate in long-term exposure of metals due to microbiological activity.

By now, various models involving power-law functions have been developed for long-term forecast. They are based on identifying the relationships between corrosion loss, on the one hand, and climatic variables and content of corrosive compounds in atmosphere in various world regions, on the other hand (dose–response functions). The dose–response functions are not considered in this paper because our studies are aimed at using the experimental values of corrosion loss over the first year of exposure as the characteristics of atmosphere corrosivity.

This paper deals with a search for relationships of coefficient n, which characterizes the protective properties of corrosion products, and the limiting corrosion rate (α) with the corrosivity of each type of atmosphere. The paper provides a forecast of corrosion losses of technically important metals for up to 50 years based on all models using the n and α values calculated for each test location based on the relationships obtained. A comparative estimate of the forecasts is given.

2. Experimental procedure

2.1. Experimental data

To reach the formulated goals of this study, we used the results of 4-, 6- and 8-year corrosion tests with intermediate withdrawal of specimens (flat and helix specimens from technically important metals, namely carbon steel, zinc, copper and aluminum) after 1, 2, 4 and 6 years at 53 sites located in 14 countries. The tests were carried out within the scope of the ISO CORRAG international program [35,41–43]. Information about the elementary composition of metals, specimen sizes, exposure program, as well as the corrosion losses of metals and environmental data at the test locations are given in Ref. [35,43].

The corrosion losses of the metals (K_τ) are expressed in g m^{-2}, while the corrosion rate (σ) is expressed in g m^{-2} y^{-1}. It should be noted that, in order to determine the corrosion losses of helix specimens more accurately, the calculation was performed using Eq. (3) taking wire thinning into account [44,45]:

$$K = (r_0 - \sqrt{r_0(r_0 - 2K_w)}) \cdot \rho \tag{3}$$

where r_0 is the original wire radius, K_w (μm) is wire corrosion with consideration of the surface area of the wire with r_0 radius, and ρ is the metal specific density.

The range of the observed corrosivity parameters of the atmospheres at the test sites within the research program was rather wide and covers almost the entire corrosivity range of atmospheres across the globe (Table 1). This indicates that the models developed for the long-term forecast for the test locations covered by ISO CORRAG program can be used for other locations around the world. The test sites were divided according to the atmosphere type: rural (R), industrial (urban) (I(U)), marine (M) and, considering the possible synergistic effect of SO_2 and Cl^- on the metals, also industrial (urban)-marine (I(U)-M) (Table 2).

2.2. Treatment of source data

All long-term forecast models were based on the constancy of atmosphere corrosivity, at least during the corrosion tests, ensuring that experimental points are arranged on smooth lines that agree with the kinetics of the corrosion process. Under real conditions, the atmosphere corrosivity based on certain annual average parameters can vary considerably, resulting in a scatter of experimental points and necessity of interpolations in order to draw the lines, as well as extrapolations to refine the K_1 values that have to agree with the mean atmosphere corrosivity at the test location over the test period. In this study, we did not aim at finding by extrapolation such K_1 values that would ensure the maximum possible accuracy of the forecast up to 8 years based on the power function in each test location. However, considering that K_1 is a significant parameter in Eq. (1), we used the K_1 value found by extrapolation of K_τ–τ curves in calculations for a small number of locations (Table 2) with considerably overestimated (or underestimated) experimental K_1 values. Furthermore, the K_6 and K_8 values were found by extrapolation for test locations with 4- and 6-year exposures. In all cases, extrapolation was carried out using the coefficients $k = \frac{K_{i+1}}{K_i}$ within the observed ranges calculated for test locations with each type of atmosphere.

The K_τ–τ and σ_τ–τ plots were built for each test location. The smoothness of the K_τ plot was controlled by the smoothness of the σ_τ plot, or the smoothness of the σ_τ plot was controlled by the smoothness of the K_τ plot.

Calculations of long-term corrosion losses were carried out for two specimen types (flat and helix specimens) of all metals, being tested at 48 of the 53 test sites within the ISO CORRAG program. A significant and unexplained scatter of experimental points was observed in the remaining test sites, and therefore long-term losses were not calculated.

2.3. Presentation of graphical data

Since a large number of K_τ–τ and σ_τ–τ curves were obtained, we only present the curves that show the calculation results for mass losses of flat carbon steel specimens in each type of atmosphere at two test sites where the K_1 values differed significantly.

3. Results and discussion

3.1. Forecasting the corrosion losses of metals during the steady state. Model 1

3.1.1. Steady-state start time

Three periods of the corrosion process could be distinguished: the incubation, transition, and steady-state periods [30]. During the incubation period, the oxide film on a metal is degraded, the corrosion rate has the highest values, and the spots of corrosion