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Corrosion Kinetics Analysis of Low Alloy Steel Submitted to the Artificial Industrial Environment

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ABSTRACT

In this paper, the corrosion kinetics analysis of a low alloy steel submitted to an artificial industrial atmosphere is presented. To obtain the corrosion process model, the corrosion mass gain monitoring was first carried out and the kinetics analysis of the corrosion process using the bi-logarithmic equation was then performed. In addition, Scanning Electron Microscopy (SEM) was employed to investigate the rust morphology change during the corrosion process, and the results from this observation were also used to validate the models constructed by the bi-logarithmic equation. The results of corrosion mass gain monitoring showed that the corrosion process consists of two significant processes: accelerating corrosion process and decelerating corrosion process. The rust morphology observation indicated that the rust of steel was thin and not adherent to the substrate in the initial corrosion process, resulting in an accelerating corrosion process. However, when the rust became thicker and denser in the subsequent corrosion process, the corrosion rate decreased. Obviously, the change in the rust morphology greatly affected the corrosion kinetics. Hence, thefindings corresponded to the results obtained from the corrosion

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kinetics analysis. Therefore, the mathematics method obtained from the bi-logarithmic equation can be used as a useful approach for the corrosion study in the simulated industrial environment.

Keywords: Corrosion; Low alloy steel; Rust morphology

Introduction

Low alloy steels are widely used in many applications in different industrial sections due to their acceptable properties, availability, and cost [1, 2]. However, the main drawback of their applications in outdoor environments is their natural degradation, known as atmospheric corrosion [2, 3]. Atmospheric corrosion of low alloy steels is recognized as steel degradation as a result of the interaction between the material and its surrounding environment [4].This electrochemical degradation proceeds under the thin electrolyte layer temporarily covering the steel surface [4, 5]. The unique characteristic of this degradation is due to the cyclic wet-dry corrosion of steels, which makes it difficult to analyze their corrosion behaviors [5, 6]. In addition, the atmospheric corrosion behavior of steel becomes more complicated, particularly when the steel surface is covered with rust and the thin electrolyte layers containing corrosion agents, like sulfur in the industrial atmosphere [7]. Usually, the field exposure corrosion test is the most commonly employed approach for analyzing the corrosion behavior of steel. This test has been accepted to be useful for a long time because its results can reflect the actual corrosion behavior of steel [8]. Nevertheless, its disadvantage is that this test requires a very long exposure time to obtain meaningful information [9]. Besides, conditions of the environment cannot be controlled and the cost to operate this assessment is also high [8, 9]. To compensate for the disadvantage of the field exposure test, the cyclic wet-dry corrosion test has been developed to investigate the atmospheric corrosion behavior of steels and low alloy steels under simulated environments. The usefulness of this test has been proven by many corrosion scientists. For example, Hao, L., et al [10] employed this test to evaluate steel alloyed with Mn, Cu, and P subjected to a cyclic wet-dry condition in the artificial environment. Thee, Ch., et al [11] employed the electrochemical sensor to monitor the steel corroding in the simulated environment. Fan, Y., et al [12] carried out the research using a cyclic wet-dry condition in an artificial marine atmosphere. The results from their work show reasonable information as compared to the field exposure test, but the analysis period was shorter. Nowadays, the reliability and safety of the steel structure become a major concern in industries, and among many, atmospheric corrosion of steel exposed to the industrial environment is one of the major degradations which potentially occur in the steel structure. Therefore, the kinetics analysis of the corrosion behavior of the steel is obviously required, particularly when the steel was covered with layers of rust. The results from the analysis would be further developed to be a useful approach for appropriate maintenance period determination for outdoor steel structures used in the industrial environment, where sulfur dioxide can bea by-product of the combustion process of industries.

In this experiment, low alloy steel specimens were subjected to the cyclic wet-dry corrosion test under an artificial industrial environment. The power model was modified to evaluate the corrosion kinetics of low alloy steel under this environment. The rust morphology analysis was carried out to provide insight into the complicated corrosion process of low alloy steel exposed to the artificial industrial environment and validate theanalysis obtained from the bi-logarithmics equation.

Experimental Procedure

1. Material

The sample material of this testis a kind of low alloy steel, and its compositionsare shown in Table 1.

Table 1. Significant composition of samples

Elements	C	Mn	Si	Cu	Cr	Fe
% Wt.	0.15	0.61	0.25	0.21	0.14	Balance

The samples were sectioned into 3X3X5 cm coupons and then ground with Silicon Carbide abrasive grinding paper down to emery paper grade 600. All of the samples were cleaned with ethanol and then kept in a desiccator.

2. The artificial industrial atmosphere and rust analysis

In this experiment, the electrolyte containing Na_2SO_3 with a concentration of 0.1 % mol/liter and pH of 4 was employed to simulate the industrial environment. Samples were placed in the chamber and then subjected to the cyclic wet-dry test. The procedures were composed of (1) measuring the initial weight of the samples; (2) dropping the simulated industrial electrolyte on the sample surface; (3) drying the sample stored in the chamber with the weathering conditions controlled at 30 ^{o}C and 60% RH for one day (24 hrs); (4) re-measuring the sample weight; (5) rinsing the sample surface with the distilled water; (6) repeating step (1)-(5) for another cyclic wet-dry number. Samples from 10th, 20th, 40th, and 60th cycle of wet-dry test were taken to be cross-sectioned for the rust morphology observation performed by SEM.

3. Mass loss measurement, power function and bi-logarithmic equation

The modified power model can be applied to investigate the kinetics of the corrosion process can be achieved by following modifications.

According to the power model [13]:

$$\Delta w = AN^n. \quad (1)$$

Where

Δw is corrosion mass gain.

A is the constant value of the corrosion process or the initial corrosion mass.

N is the number of the cyclic wet-dry corrosion.

Taking logarithm to modify power law, we then obtained the bi-logarithmic equation [14]

$$log(\Delta w) = log(A) + nlog(N) \quad (2)$$

Equation (2) was employed to analyze the corrosion process and the meaning of n is important, which can imply the kinetic characteristics of the corrosion process as follows: the value of n is less than one, indicating the accelerating corrosion process, but the value of n becomes greater than one, meaning the decelerating corrosion process.

To obtain the fitted instantaneous corrosion rate developed by the bi-logarithmic equation, equation (1) needed to be modified to gain equation (3) as follows [13, 14]:

$$\frac{d\Delta w}{dN} = AnN^{n-1}. \quad (3)$$

Where $\frac{d\Delta w}{dN}$ means the instantaneous corrosion rate and A and n can be obtained from equation (2).

Results and Discussion

1. Corrosion process analysis

The obtained information on the corrosion mass loss monitoring is shown in Figure. 1. Obviously, the corrosion process of steel submitted to the cyclic wet-dry corrosion test continuously proceeds from the 1st cycle to 60th cycle. The concept of the power model as given in equation (1) is then taken to analyze the corrosion kinetics of this information and the linear fitting result is given in Figure 2.

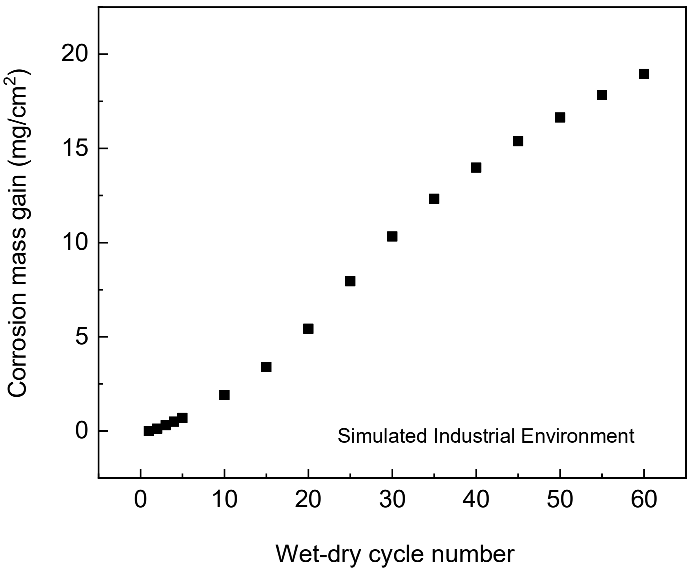

Figure 1 Corrosion mass gain of low alloy steel in a simulated industrial condition

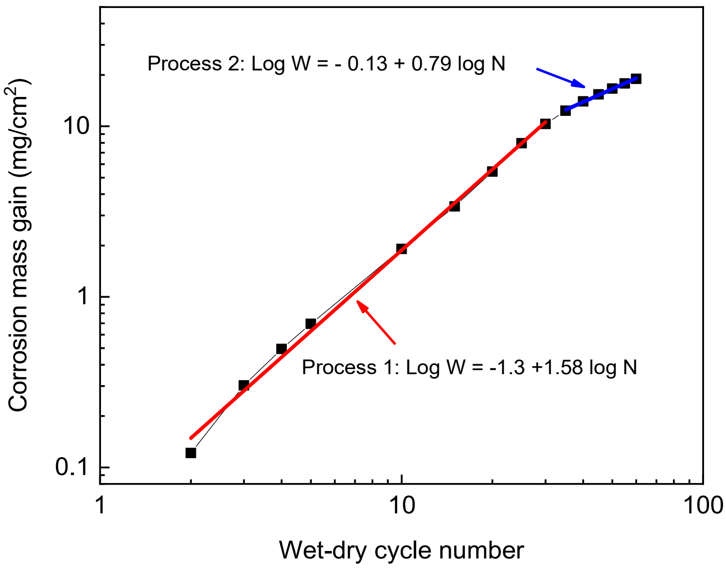

Figure 2 The kinetics analysis of the corrosion process

From Figure 2, it is obvious that corrosion process of the low alloy steel subjected to a cyclic wet-dry corrosion test consisted of two processes. The transition points occurred at the

30th wet-dry cycle number. The linear fitting equation of the corrosion process of low alloy steel obtained from Figure 2 can be given as follows;

For The first corrosion process,

$$log(\Delta w) = -1.3 + 1.58log(N). \quad (4)$$

For The second corrosion process,

$$log(\Delta w) = -0.13 + 0.79log(N). \quad (5)$$

Obviously, the n value of the first corrosion process was greater than 1, meaning that the corrosion was accelerated. In contrast, that of the second corrosion process became less one 1, indicating the decelerating corrosion [12, 13]. It is interesting to consider that the n value of the second corrosion process was less than that of the first corrosion process. Normally, the smaller value of the n implies a lower tendency for corrosion to occur [20, 21]. Hence, the smaller n value indicated the improved corrosion resistance of the surface of the low alloy steel. The results of corrosion kinetics analysis provide the essential parameters, listed in Table 2.

Table 2. Importance parameters of the corrosion process of Steel under the artificial industrial atmosphere

Corrosion process	$log(A)$	A	n
Accelerating corrosion process	-1.3	0.05	1.58
Decelerating corrosion process	-0.13	0.74	0.79

Considering Equation (3) and the listed significant parameters in Table 2, we obtained Equation (4) and (5) , which can be employed to predict the relationship between corrosion rate and wet-dry cycle number.

For The fitting equation of the first corrosion process:

$$\frac{d\Delta w}{dN} = (0.05)(1.58)N^{0.58}. \quad (6)$$

For The fitting equation of the second corrosion process:

$$\frac{d\Delta w}{dN} = (0.74)(0.79)N^{-0.21}. \quad (7)$$

The equations obtained from Equation (5) and (6) can be used to generate the mathematical model that describes the relationship between corrosion rate and the cyclic wet-dry numberof a low alloy steel submitted in a cyclic wet-dry condition under the simulated industrial atmosphere as shown in Figure 3.

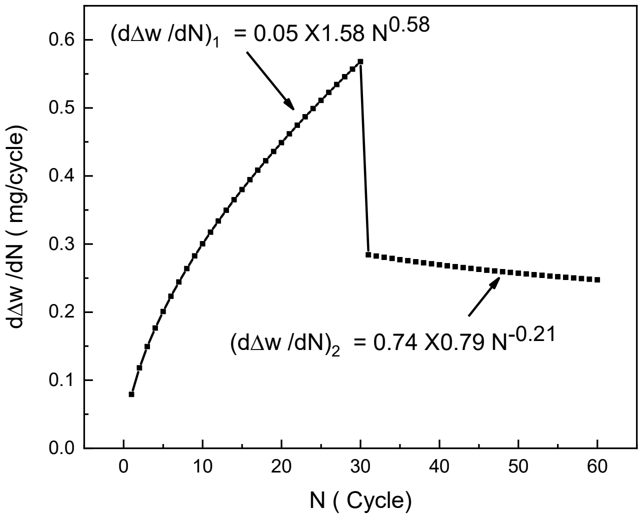

Figure 3 Mathematical model of a low alloy steel under the simulated industrial environment

2. The analysis of the rust morphology

The change of the rust morphology during the corrosion process of a kind of low alloy steel encountered a cyclic wet-dry condition in the simulated industrial condition was analyzed to confirm the validity of the obtained kinetics analysis. The results of the rust morphology analysis are given in Figure 4. During the first process of corrosion, the rust from the 10^{th} and 20^{th} wet-dry cycle number samples was thin, loose, and not well adherent to the surface. Besides, it obviously contained large cracks and pores, assisting the transport of the corrosive agents, i.e. sulphate ions. This kind of rust in this corrosion stage obviously facilitated the accelerating corrosion process [12-14].

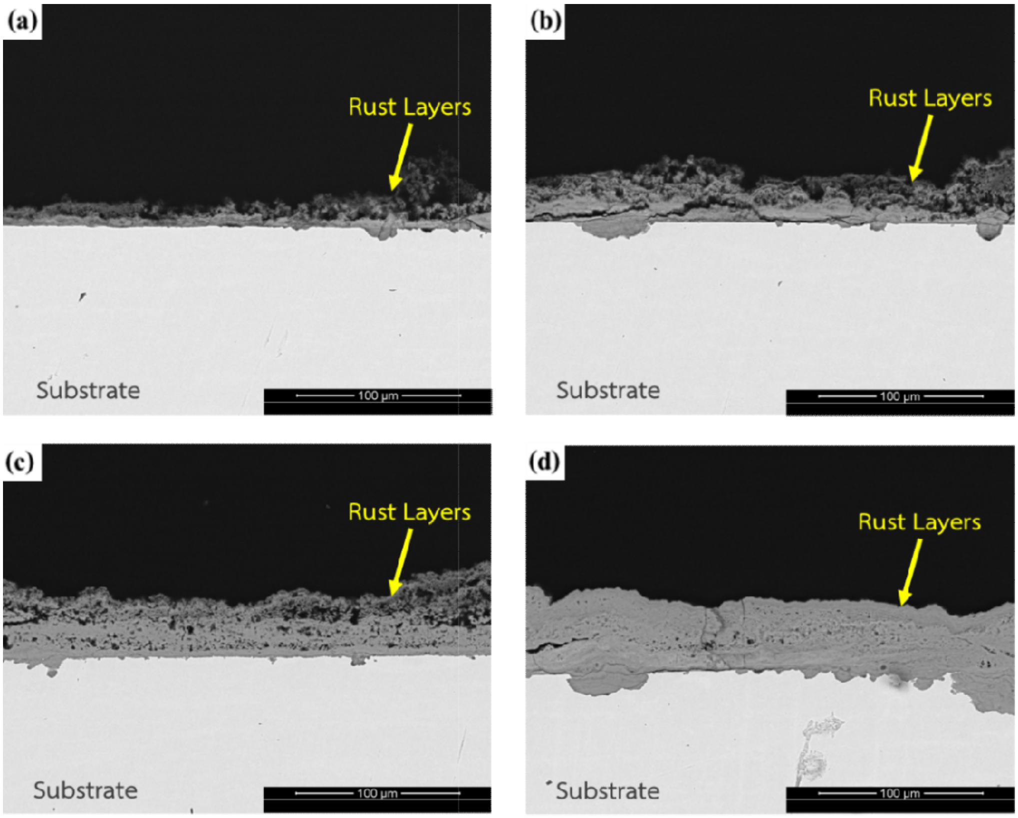

Figure 4 The rust morphology change during the cyclic wet-dry corrosion test: (a) 10th cycle, (b) 20th cycle,(c) 40th cycle, and (d) 60th cycle

On the contrary, in the second stage, the rust of the 40th wet-dry cycle number sample was thicker and more compact. Even though it had small cracks, no large cracks and pores were evidently observed. Thus, the improved corrosion retarding effect can be gained, attributing to the decelerating corrosion process. The rust formed on the steel surface of the 60th wet-dry cycle number sample became thicker, more compact, and smoother and no obvious cracks and pores were found. This kind of rust is protective, which contributes to the significant reduction of the corrosion rate. Therefore, it was clear that the formation of the protective rust in the second corrosion process attributes to the transition from the accelerating corrosion process to the decelerating corrosion process. It is also clear that the results from this observation corresponded to the mass gain result and confirmed the reliability of the fitting model obtained by the bi-logarithmic equation.

Conclusions

The corrosion process of a kind of low-alloy steel submitted to a simulated industrial atmosphere was already analyzed by using the corrosion mass gain and the modified power model. The corrosion process of the low alloy steel consisted of two significant corrosion processes. The corrosion process accelerated in the first process and decelerated in the second. The rust observation showed the significance of the formation of the protective rust on the steel surface during the second corrosion process. The results from the rust morphology change were agreeable to those from the corrosion mass loss test and verified the correctness of the kinetics model derived from the bi-logarithmic equations.

Acknowledgments

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