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Research on Aluminizing Process of Friction Coating and Its Corrosion Resistance

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Abstract: *In this paper, a friction coating aluminizing process is used to create an aluminum coating layer on the surface of the steel, and a low-temperature diffusion treatment forms a Fe-Al infiltration layer to improve the corrosion resistance of carbon steel. This paper introduces the basic concepts, classifications, and application areas of aluminized steel, analyzes the corrosion mechanisms of aluminized steel in different environments and summarizes the commonly used evaluation methods. This paper also determined the appropriate range of parameters for the friction coating aluminizing process and investigated the effects of various process parameters on the surface structure and properties of the steel. Finally, this paper evaluates the corrosion resistance of friction-coating aluminized steel in typical environments. The results show that friction-coating aluminized steel has better corrosion resistance and can effectively prolong the service life of carbon steel.*

Keywords: *Friction coating; Aluminizing; Corrosion resistance; Metal-matrix composite*

1. Introduction

The friction coating aluminizing process is a new method to create a corrosion-resistant aluminum layer on the steel surface. It uses friction heat to coat the steel surface with aluminum powder and then performs low-temperature diffusion treatment to form an aluminized layer composed of intermetallic compounds. This process has the advantages of easy operation, energy saving and environmental protection, and wide application. This paper aims to investigate the effect of friction coating aluminizing process parameters on steel's surface structure and properties, and the corrosion resistance of friction coating aluminizing steel in different environments.

This paper first introduces the corrosion mechanism and evaluation methods of aluminized steel, including the electrochemical method, neutral salt spray method, high-temperature oxidation method, and sulfide stress corrosion cracking method, etc.; Then the selection basis and test method of friction coating aluminizing process parameters are analyzed, including friction pressure, rotating speed, time, etc. Subsequently, the effects of the friction coating aluminizing process parameters on the morphology, microhardness and phase composition of the steel surface, as well as the effects on the residual stress and bond strength of the steel surface were studied; Finally, the electrochemical behavior of friction-coated aluminized steel in acidic, alkaline and brine solutions, the oxidation behavior in high-temperature and high-pressure water vapor, and the high-temperature sulfide stress corrosion cracking behavior in a simulated refinery environment were tested.

2. Corrosion mechanism and evaluation method of aluminized steel

Aluminized steel is a composite material that uses hot-dip aluminized or powder aluminized to form an intermetallic compound diffusion layer or aluminized layer on the steel surface to improve steel's corrosion resistance and heat resistance [1]. At the same time, aluminized steel has advantages such as high strength, high hardness, high wear resistance, high oxidation resistance, low density and low resistivity, making it suitable for aerospace, petrochemical, power equipment, and other fields.

The corrosion mechanism of aluminized steel in different environments mainly depends on the aluminized layer's composition, structure, and thickness and the medium's type, temperature, and concentration. The aluminized layer is composed of two intermetallic compounds, $FeAl3$ (θ phase) and

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Fe2Al5 (η phase), among which the θ phase has better self-passivation ability, while the η phase is prone to pitting corrosion or stress corrosion cracking. The aluminized layer is mainly exposed to anodic dissolution in acidic media, redox reaction in alkaline media, chloride ion attack in salt water, oxidation in high temperature and high-pressure steam, and mainly affected by sulfide stress corrosion cracking in simulated refinery environment [2].

Evaluating the corrosion resistance of aluminized steel requires careful consideration of its electrochemical, oxidation, and cracking behavior under various environmental conditions. The electrochemical behavior can be tested and analyzed by means of polarization curves, AC impedance spectroscopy, potential dynamic scanning, etc., reflecting the self-protection ability and failure mode of the aluminized layer in different media. Oxidation behavior can be tested and analyzed by weight gain, X-ray diffraction, scanning electron microscopy, etc. This reflects the process and mechanism of the aluminized layer forming a protective or precipitated oxide layer in water vapor at high temperature and pressure [3]. The cracking behavior can be tested and analyzed by slow strain rate method, fracture morphology observation method and other methods, reflecting the conditions and reasons for the occurrence of sulfide stress corrosion cracking or inhibition of cracking in the aluminized layer in the simulated refinery environment. The corrosion mechanism and evaluation method of aluminized steel are shown in Figure 1.

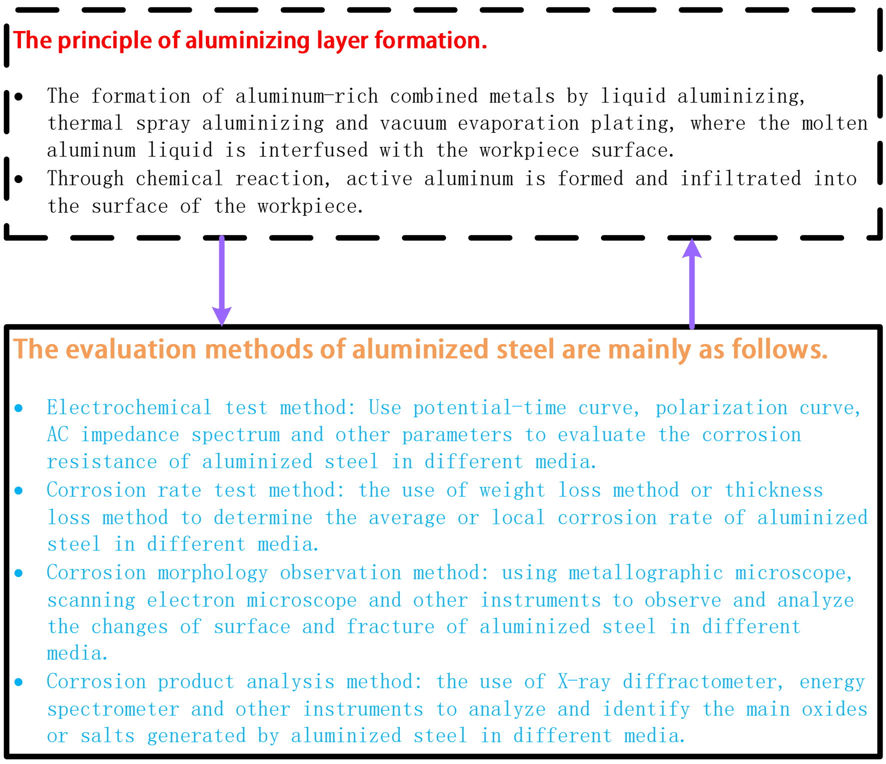

Figure 1: Corrosion mechanism and evaluation method of aluminized steel

3. Effect of Friction Coatings Aluminizing Process Parameters on Steel Surface Microstructure and Properties

3.1 Selection Basis and Experimental Method of Friction Coating Aluminizing Process Parameters

The selection basis and experimental method of friction coating aluminizing process parameters are as follows:

Friction coating aluminizing process is a new surface treatment technology that uses a high-speed rotating tool to generate frictional heat on the steel surface, causing the steel surface to react with aluminum powder in the solid state to form an aluminization layer [4]. This process parameters basically include tool speed, feed rate, axial pressure, preset aluminum powder thickness and reaming time.

To study the influence of these parameters on the surface structure and properties of the steel, an orthogonal experimental design method was applied and four factors (tool rotational speed, feed speed, pressure axial and preset aluminum powder thickness) and three levels (low, medium and high) and obtained 27 groups of samples. Each test program was performed for the same friction time (60s), using the same steel (45# steel) and the same tool material (WC-Co alloy). During the test, an electronic balance was used to measure the change in mass of the sample before and after each test to calculate the mass gain rate of the aluminized layer [5].

The mass gain rate of the aluminized layer can be expressed by the following formula:

$$\eta = \frac{m_2 - m_1}{m_1} \times 100\% \tag{1}$$

Where, η is the mass gain rate of the aluminized layer, m_1 is the sample weight before the test, m_2 is the sample weight after the test, this formula reflects the absorption efficiency of aluminum atoms on the steel surface during the aluminization process, and can also indirectly reflect the thickness and density of the aluminized layer.

3.2 Effects of Friction Coating Aluminizing Process Parameters on Steel Surface Morphology, Microhardness and Phase Composition

The effects of friction coating aluminizing process parameters on steel surface morphology, microhardness and phase composition are as follows:

In order to observe the microstructure and morphology of the steel surface, scanning electron microscopy (SEM) was used to scan the surface and cross-section of the samples under different test schemes [6]. The results show that the aluminized layer is composed of two regions: one is the inner layer closely combined with the matrix, and the other is the outer layer with a clear boundary with the inner layer. The inner layer is mainly composed of Fe-Al intermetallic compound, and the outer layer is mainly composed of Al and a small amount of Fe-Al intermetallic compound [7]. With the increase of tool speed, feed speed, axial pressure and preset aluminum powder thickness, the thickness and compaction of the aluminized layer are improved, but when the parameters are too large, the defects such as cracks and holes will appear.

In order to measure the microhardness of the steel surface, a microhardness tester was used to test the hardness of the cross-section of the samples under different test schemes. The results show that the hardness of the aluminized layer is much higher than that of the base steel and gradually decreases as the aluminized layer penetrates into the base. The hardness of the inner region is higher than that of the outer region, which is related to the composition of the two phases [8]. The average hardness of the aluminized layer increases with increasing tool speed, feed rate, axial pressure, and thickness of preset aluminum powder. To analyze the phase composition of the steel surface, an X-ray diffractometer (XRD) was used to perform surface and cross-sectional diffraction analyses of the samples under various test schemes. According to the orthogonal test design method, the influence (i.e., variance ratio) of each factor (such as mass gain ratio or average hardness) on the aluminizing effect can be calculated using the following equation:

$$F = \frac{\sum_{i=1} k n_i (\overline{x}_i - \overline{x}) 2 / (k-1)}{\sum_{i=1} k \sum_{j=1} n_i (x_{ij} - \overline{x}_i)^2 / (N-k)} \tag{2}$$

Among them, F is the variance ratio (also known as F test value), k is the number of levels (3 in this example), n_i is the number of repetitions at the i -th level (9 in this example), $\overline{xi}$ is the arithmetic mean of the result values xij (n_i in total) of each repetition number at the i -th level, $\overline{x}$ is the arithmetic mean of all result values x_{ij} (total N). This formula reflects the degree of difference caused by each factor in the aluminization effect at various levels.

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3.3 Effects of Friction Coating Aluminization Process Parameters on Steel Surface Residual Stress and Bond Strength

Residual stress refers to the internal self-equilibrium stress that remains in a body after the action of an external force or inhomogeneous temperature field is removed. During the friction coating aluminizing process, factors such as frictional heat, plastic deformation, and phase transformations between the tool and sample create residual stresses on the steel surface. Residual stress has a significant impact on the surface properties of steel [9]. On the one hand, adequate compressive residual stress can improve the fatigue strength, corrosion resistance and wear resistance of the steel surface, while on the other hand, excessive tensile residual stress can lead to cracking, spalling and failure of the steel surface.

Adhesion strength refers to the ability to prevent delamination between the aluminized layer and the base steel, reflecting the quality of adhesion between the two. During the friction coating aluminizing process, because the tool exerts axial pressure and tangential pressure on the sample, solid-state diffusion and phase transformation occur between the coated aluminum layer and the base steel, forming a firm metallurgical bond. Bonding strength has an important impact on the stability and durability of steel surfaces, and high bonding strength can prevent the aluminized layer from falling off or breaking during use.

4. Study on Corrosion Resistance of Friction Coating Aluminized Steel in a Typical Environment

4.1 Electrochemical Behavior of Friction Coating Aluminized Steel in Acidic, Alkaline and Aaline Solutions

The electrochemical behavior of friction coating aluminized steel in acidic, alkaline, and salt solutions is an important indicator for evaluating its corrosion resistance. Electrochemical behavior can be determined by electrochemical test methods such as B. Open circuit potential method, polarization curve method, and AC impedance method.

The open circuit potential method is to measure the equilibrium potential of a material spontaneously formed in a solution without electricity. The open-circuit potential reflects the thermodynamic compatibility between the material and the solution, in general, the more negative the open-circuit potential, the more susceptible the material is to oxidation. The following formula can express the open circuit potential:

$$E_{oc} = E_{eq} + \frac{RT}{nF} \ln \frac{a_{ox}}{a_{red}} \tag{3}$$

Where, E_{oc} is the open circuit potential, E_{eq} is the equilibrium potential, R is the gas constant, T is the temperature, n is the number of electrons transferred in the reaction, F is the Faraday constant, a_{ox} and a_{red} are the activities of the oxide and reducer, respectively.

The polarization curve method is the process of causing a deviation from equilibrium on the surface of a material by applying an external voltage or an external current [10]. The polarization curve reflects the dynamic behavior of the material under different external conditions, which can be used to determine the material's corrosion rate, corrosion type, and passivation characteristics. The following formula can express the polarization curve:

$$E = E_{corr} + \eta_a + \eta_c \tag{4}$$

Where, E is the actual potential after polarization, E_{corr} is the corrosion potential (the equilibrium point without external disturbance), η_a and η_c is the polarization overpotential caused by the anodic and cathodic processes, respectively.

The AC impedance method generates small fluctuations on the material's surface by applying a low-amplitude AC signal and measures the phase difference and amplitude ratio between the input and output of the signal. AC impedance reflects the influence of various physical and chemical processes on signal transmission at the interface between the surface of the material and the solution and can be used to

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determine the surface layer structure, interface state, and reaction mechanism of the material.

The AC impedance method can be expressed in the following polar coordinates :

$$Z = |Z| e^{j\theta} \tag{5}$$

Among them, |Z| represents the impedance's modulus, θ represents the impedance's phase angle. They are related to the signal frequency.

The corrosion resistance test procedure of friction coating aluminized steel in a typical environment is shown in Figure 2.

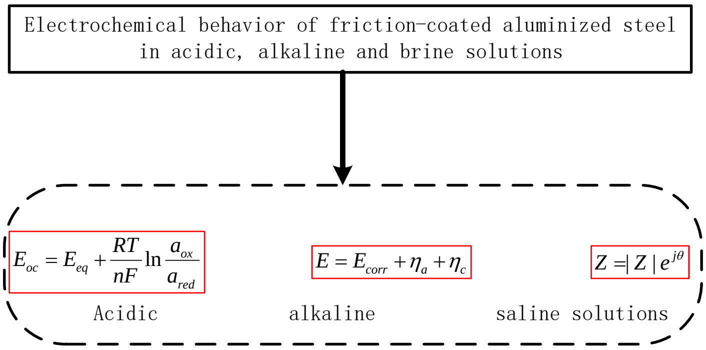

Figure 2: Corrosion resistance test process of friction coating aluminized steel in a typical environment

4.2 Oxidation Behavior of Friction Coating Aluminized Steel in High Temperature and High-pressure Water Vapor

The oxidation behavior of friction coating aluminized steel in high temperature and high-pressure water vapor is an important index to evaluate its heat resistance. Thermogravimetric analysis can determine oxidation behavior, which measures a material's mass change at different temperatures and times. The following formula can express oxidation behavior:

$$\frac{dm}{dt} = k(T)\left(\frac{m}{S}\right)^n \tag{6}$$

Where, dm/dt is the mass change rate per unit time, $k(T)$ is the temperature-dependent reaction rate constant, m is the mass after oxidation, S is the initial surface area, n and is the reaction order.

The oxidation process of friction coating aluminized steel by high temperature and high-pressure water vapor is divided into two stages: early rapid oxidation and late slow oxidation. During initial rapid oxidation, a dense Al2O3 protective film is formed on the surface of the coating, which effectively prevents further oxidation. At the later stage of slow oxidation, due to defects such as residual stress and interface cracks between the coating and the substrate, the protective film will crack and peel off, exposing the substrate to water vapor and severely oxidizing.

4.3 Corrosion Cracking Behavior of Friction Coating Aluminized Steel Against High-temperature Sulfide Stress in a Simulated Refinery Environment

The refinery is a high-temperature and high-pressure corrosive environment, which puts high demands on metal materials. An effective method is an aluminum treatment to improve steel's corrosion resistance. The aluminizing treatment can form a dense protective aluminum oxide layer on the steel surface, preventing the penetration of corrosive substances such as sulfides. Friction coating aluminized steel is a new type of aluminizing material with the advantages of a simple preparation process, low cost and high efficiency. This paper mainly studies the high-temperature sulfide stress corrosion cracking behavior of friction coating aluminized steel in a simulated refinery environment. The details are as follows:

(1) Friction coating aluminized steel is a method of coating aluminum powder on the steel surface by

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friction heat and plastic deformation, improving steel's high-temperature sulfur corrosion resistance.

(2) The simulated refinery environment refers to the high temperature and high-pressure gas containing hydrogen sulfide, chloride, water vapor, and other components, which has a strong corrosion effect on metal materials, resulting in stress corrosion cracking and other failure phenomena.

(3) The high-temperature sulfide stress corrosion cracking behavior of friction coating aluminized steel in a simulated refinery environment can be evaluated by the buffer machine test method, that is, to observe whether the material cracks at different stress levels and times and to measure the number, length, and depth of cracks.

(4) The high-temperature sulfide stress corrosion cracking behavior of friction coating aluminized steel in a simulated refinery environment is affected by many factors, such as coating thickness, microstructure, residual stress, interface quality, applied stress, and environmental parameters. In general, increasing coating thickness, improving organizational structure, reducing residual stresses and interface defects, and reducing external stresses and environmental stimuli are all beneficial to improving the cracking resistance of materials.

5. Conclusion

This paper mainly studied a new chemical heat treatment process to improve the steel surface's corrosion resistance and heat resistance. In this process, aluminum powder is applied to the steel surface by frictional force and heated to allow the aluminum atoms to penetrate the steel matrix, forming a uniform and dense aluminized layer. This article systematically investigated the effects of friction coating aluminization process parameters on the microstructure and properties of steel surfaces and the corrosion resistance of friction coating aluminized steels in different environments. The results show that the friction coating aluminization process can effectively improve the corrosion resistance of steel and provide a new method for surface modification of steel.

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