

Review on Stress Corrosion and Corrosion Fatigue Failure of Centrifugal Compressor Impeller

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Abstract: Corrosion failure, especially stress corrosion cracking and corrosion fatigue, is the main cause of centrifugal compressor impeller failure. And it is concealed and destructive. This paper summarizes the main theories of stress corrosion cracking and corrosion fatigue and its latest developments, and it also points out that existing stress corrosion cracking theories can be reduced to the anodic dissolution (AD), the hydrogen-induced cracking (HIC), and the combined AD and HIC mechanisms. The corrosion behavior and the mechanism of corrosion fatigue in the crack propagation stage are similar to stress corrosion cracking. The effects of stress ratio, loading frequency, and corrosive medium on the corrosion fatigue crack propagation rate are analyzed and summarized. The corrosion behavior and the mechanism of stress corrosion cracking and corrosion fatigue in corrosive environments, which contain sulfide, chlorides, and carbonate, are analyzed. The working environments of the centrifugal compressor impeller show the behavior and the mechanism of stress corrosion cracking and corrosion fatigue in different corrosive environments. The current research methods for centrifugal compressor impeller corrosion failure are analyzed. Physical analysis, numerical simulation, and the fluid-structure interaction method play an increasingly important role in the research on impeller deformation and stress distribution caused by the joint action of aerodynamic load and centrifugal load.

Keywords: stress corrosion cracking, corrosion fatigue, stainless steel, centrifugal compressor, impeller

1 Introduction

Stress corrosion and corrosion fatigue are two common forms of compressor impeller failure. Normally, serious uniform corrosion impeller failures can be avoided by selecting appropriate materials. However, preventing stress corrosion and corrosion fatigue is difficult for stainless steel and high alloy steel through material selection. Stress corrosion cracking (SCC) and corrosion fatigue fractures usually occur in metal components that have been used for long periods and lead to unexpected, sudden failure. Stress corrosion and corrosion fatigue fractures that occur in industrial production equipment could cause significant loss.

A centrifugal compressor is an important and

indispensable mechanical piece of equipment that is widely used in modern industries, such as the oil chemical industry, the coal chemical industry, the salt chemical industry, and the metallurgy industry. It is the core component of centrifugal compressors. Therefore, while its impeller operates at a high speed in poor working conditions, it is subjected to rotary centrifugal force and vibration force, which may cause SCC and corrosion fatigue fractures. Once these fractures occur, the mechanical properties of the centrifugal compressor drop notably and serious accidents may take place^[1].

In this paper, the corrosion conditions and the corrosion pattern of SCC and corrosion fatigue are studied by analyzing two cases of impeller corrosion failure. In the next section, existing theories and recent advances in the research on corrosion behavior and metal material mechanisms are reviewed and discussed. The last chapter contains the results on the centrifugal compressor impeller corrosion and the experimental methods.

2 Impeller Corrosion Failure Mode

2.1 Impeller stress corrosion failure

Figs. 1 and 2 show images of SCC accidents in the

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low-pressure rotor of a large centrifugal compressor. In Fig. 1, the second stage impeller is seriously damaged, and the first stage impeller contains many small pits with many brown ochre sediments. As shown in the meticulous observation of the first stage impeller in Fig. 2, many branch cracks are visible on the disc. A spectrum analyzer, a scanning electron microscope, and a metallographic microscope are used to observe and analyze the cracks. The analysis reveals that the chlorine element content is very high in the corrosion products and crack fracture; this finding corresponds to the fracture characteristics of SCC. Comprehensive analysis shows that the SCC occurs on the centrifugal compressor impeller as a result of the joint action of centrifugal stress and corrosive environment, which consists of chloride ion and water vapor^[2].

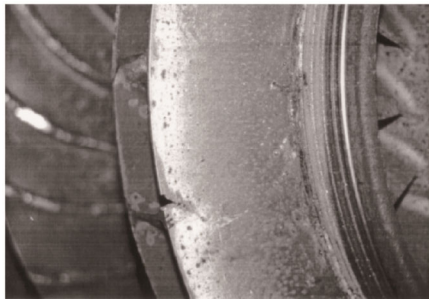


Fig. 1. Low-pressure rotor



Fig. 2. Low-pressure rotor; 1st stage impeller

2.2 Impeller corrosion fatigue failure

Figs. 3 and 4 show the corrosion fatigue in a rich gas compressor impeller used in the catalytic cracking unit. As shown in Fig. 3, many branched cracks appear in the blade angle weld root of the edge of the impeller wheel cover in 18 out of the 27 blades. The radial length of most cracks was approximately 25 mm and originated from the fillet weld root of the blade and disc. Most cracks penetrated through the blades. A metallographic observation shows that the cracks are transgranular extensions, which are flat, without bifurcation, and with blunt tips. An accumulation of corrosion products, obvious fatigue striations, and many secondary steps were observed on the fracture surface. In addition, the crack fracture exhibited multiple sources of cracking fatigue fracture characteristics. The X-ray qualitative analysis of the samples using an energy dispersion spectrometer combined with a scanning electron microscope reveals its chemical composition: the main

elements found were iron oxides and sulfides. A comprehensive analysis shows hydrogen, CO₂, and H₂S in the rich gas and water vapor from the environmental conditions of corrosion fatigue. When the centrifugal compressor rotor was operational, its value and load direction constantly changed. This action constitutes the mechanic characteristics of corrosion fatigue. Eventually, corrosion fatigue cracking occurred in the fillet weld area of the impeller blade^[3].

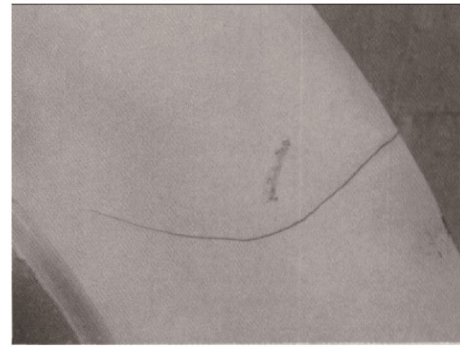


Fig. 3. Crack macro morphology

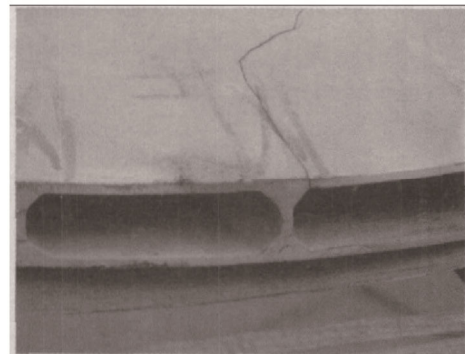


Fig. 4. Crack in impeller disc

3 Research Status of Corrosion Failure Behavior and Mechanism

3.1 Stress corrosion mechanism research

Many scholars have studied stress corrosion behavior and the mechanism of metal materials and offered various theories to explain stress corrosion from different disciplines, such as corrosion, electrochemical, metal physics and mechanics. Currently, SCC mechanisms are generally divided into three categories: the anodic dissolution(AD) type mechanism, the hydrogen-induced cracking(HIC) type mechanism, and the AD and HIC mixing mechanisms.

3.1.1 AD mechanism

The AD type mechanism is an SCC process controlled by anodic dissolution. It can be further divided into the anode fast dissolving mechanism, the slip-dissolving mechanism, the tunnel corrosion mechanism, the passivation film leading to brittle fracture mechanism, the stress-adsorption leading to rupture mechanism, and the corrosion promoting plastic deformation leading to stress

corrosion fracture mechanism^[4-6].

(1) Anode fast dissolving mechanism

HOAR, et al^[7], believe that, as a result of the asymmetry of the electrochemical characteristics on the metal surface, micro-cracks develop and grow at some local position under the influence of the synergy between stress and corrosion. The stress concentration of the crack-tips causes the crack-tip frontier area to yield. Intra-crystalline dislocations continuously appear on the front surface of the crack-tip along the slip surface. They generate massive momentary active dissolution particles that result in fast anodic dissolution in the crack-tip area. Possible sites where cracks may initiate include the dislocation group, the dislocation accumulation zone of the slip surface, the local strain area caused by quenching or cold working, the distortion zone caused by heterogeneous impurity atoms, and the so-called stacking fault area. On the basis of the anode fast dissolving mechanism, some scholars proposed the self-catalytic effect of anodic dissolution, in which the block battery inside the crack or the corrosion pit could accelerate the corrosion. The inner crack (small anode) and the metal surface (large cathode) constitute the concentration cell that promotes the rapid anodic dissolution of crack-tips.

(2) Slip-dissolving mechanism

The SCC of austenitic stainless steel is usually explained by the slip-dissolving mechanism^[8]. LOGAN^[9] first proposed the slip-dissolution model. Later, SCULLY, et al^[10] and PARKINS, et al^[11], developed and enriched this theory. The surface of stainless steel is covered with a layer of corrosion-resistant protective film that mainly consists of Cr³⁺ oxide, a small amount of Ni oxide, and a small amount of Cr⁶⁺ ions in the transpassivation area. Under the combined action of stress and the corrosive medium, stainless steel undergoes passivating, sliding, and rupturing. Throughout the cyclic movement, the SCC develops frontier and deep cracks until the component fractures. The slip-dissolving mechanism can explain intergranular SCC very well; however, explaining transgranular SCC, such as austenitic stainless steel SCC in chloride environments, is difficult because the fracture surface of transgranular SCC is not on the slip surface and exhibits cleavages^[4].

(3) Tunnel corrosion mechanism

In the tunnel corrosion mechanism, the metal atoms in a high strain state corrode preferentially on the plane of the dislocation outcrop area or on the newly formed sliding steps. The corrosion develops further along the dislocation line and forms tunnels. The effect of stress causes a mechanical tear on the metal between the tunnels. When the mechanical tearing stops, tunnel corrosion restarts. This repeating process expands the cracks continuously until the metal is unable to bear the load and overload fractures occur. However, some research shows that tunnel corrosion accompanies stress corrosion rather than being the main mechanism of stress corrosion^[12].

(4) Passivation film leading to brittle fracture mechanism

SIERADZKI, et al^[13], believes that the corrosion passivation film and the loose layer of some metallic materials can prevent dislocation from the crack-tip or plug dislocations in the passivation film and loose layer. The emission of dislocations is blocked. Therefore, the material becomes brittle and rupture failure may occur as a result of stress.

(5) Stress-adsorption leading to rupture mechanism

REVIE, et al^[14], proposed the stress-adsorption mechanism, in which SCC is not caused by the electrochemical dissolution of metal. Rather, it is caused by some specific ions, such as Cl⁻ and OH⁻, which can be absorbed in the crack-tip area, weaken the metal atomic bonds that bind affinity, and promote the rupturing of metal through tensile stress.

(6) Corrosion promoting plastic deformation leading to stress corrosion fracture mechanism

According to JONES^[15], when the metal slides, the metal surface passivation film can rupture. As a result, some special ions (e.g., Cl⁻) are absorbed on the metal surface and restrain the repassivation of the metal material. Moreover, the dissolution of the metal partial anodic is promoted in the crack-tip area. The many vacancies produced by the dissolution of metal facilitate the movement of the dislocation and slack in the strain-hardening layer of the metal surface, thus enhancing the local plastic deformation of the metal surface. The three-dimensional stress caused by local plastic deformation creates the nucleation of micro-cracks on the surface of the slip. According to MAGNIN, et al^[16], the slippage makes the passivating film break down in nearby areas. The special ions prevent the repassivation process from taking place on the metal surface. The preferential dissolution of crack-tip generates the glide step. Then, the newly generated stress concentration leads to local plastic deformation. Subsequently, the dislocation is blocked. When the stress concentration in front of the dislocation pile-up group is greater than the atomic bonding force, stress corrosion micro-cracks emerge. The nucleation of the micro-cracks bursts the dislocation pile-up group and releases the stress. As a result, the micro-cracks stop expanding. The SCC propagates by repeating this process. According to KAUFMAN, et al^[17], the metal atoms dissolve preferentially along the slip band and cause the stress to become concentrated. Therefore, plastic deformation is promoted and is limited in the crack-tip area. The larger the plastic deformation is, the greater the dissolution rate is. Local plastic deformation could promote local dissolution, increase crack-tip stress further, localize the deformation in a small place, and ultimately initiate micro-cracks.

3.1.2 HIC mechanism

The HIC mechanism explains the SCC process in which the cathodic reaction releases hydrogen, and the nucleation and propagation of the cracks are controlled by enriching

hydrogen in the metal. The diffusion rate of hydrogen in austenite ($10 \text{ cm}^2/\text{s}$ to $12 \text{ cm}^2/\text{s}$) is much lower than that of ferrite ($10 \text{ cm}^2/\text{s}$ to $8 \text{ cm}^2/\text{s}$). Therefore, austenitic stainless steel is not generally considered to be sensitive to hydrogen^[18–19]. However, in the actual manufacturing process, the hydrogen embrittlement fracture still occur from time to time in austenitic stainless steel in hydrogen environments (e.g., in places with a high-pressure hydrogen atmosphere or solutions with hydride). Currently, hydrogen pressure theory, hydrogen reducing interatomic bonding force theory, hydrogen adsorption reducing the surface energy theory, and hydrogen promoting local plastic deformation leading to brittle fracture theory are used. Moreover, some scholars in the past few years have proposed that dislocation transfer theory can explain HIC^[20–24].

(1) Hydrogen pressure theory

Hydrogen pressure theory states that the supersaturation of hydrogen atoms in metal materials can form molecular hydrogen. Molecular hydrogen can produce a large amount of internal pressure, thus decreasing fracture stress, making the material brittle, and assisting external stress by extending HIC.

(2) Hydrogen reducing the interatomic bonding force theory

Through the induced proliferation of stress, atomic hydrogen can become concentrated in the largest three-dimensional stress area and greatly decrease the interatomic bonding force. Such process ultimately leads to the brittle fracture of material with low stress (or low stress intensity factor). However, some scholars propose that local plastic deformation always occurs before the initiation of cracking in metal materials. Crack resistance includes surface energy and plastic deformation. Plastic deformation is usually 103 times more powerful than surface energy. Some scholars consider that if hydrogen can only reduce surface energy and has no effect on local plastic deformation, then critical stress will not decline significantly. Therefore, they argue that this theory is unsuitable for metal materials^[25].

(3) Hydrogen adsorption reducing the surface energy theory

Other scholars consider that hydrogen can absorb on the internal surface of cracks and reduce surface energy, decreasing the critical stress of the unstable propagation of cracks. In principle, hydrogen reducing the bonding force and hydrogen reducing the surface energy are the same. However, hydrogen adsorption reducing the surface energy theory emphasizes the effect of adsorption.

(4) Hydrogen embrittlement theory

The hydrogen produced by the corrosion cathodic reduction reaction spreads to the crack-tip area and makes it brittle. With the effect of stress, delayed HIC occurs. Moreover, in the metallic stress corrosion process, the solution in the crack-tip area becomes highly acidic. The pH value is reduced to a very low level (i.e., carbon steel

with approximately pH 4, titanium alloy with pH 3.5, austenitic stainless steel with pH 1)^[26]; this reduction can also promote the stress corrosion process.

(5) Dislocation transfer theory

In recent years, some scholars have found that hydrogen can promote plastic deformation. Therefore, hydrogen can promote the multiplication and the motion of dislocation as well as speed up the fracturing process. The hydrogen air mass around the dislocation moves together with the dislocation. When they meet, defects, such as grain boundaries or second phase particles, form as a result of the strong interaction between the hydrogen atoms and the defects. The dislocation accumulates or disappears, enabling the hydrogen to become concentrated in these areas. Therefore, dislocation could hinder the free movement of the hydrogen air mass and lead to local hardening. By conveying the dislocation, the hydrogen concentration of the lattice defect can reach 104 times that of its equilibrium value. This action makes the inner pressure amount to 1.02 GPa, which is enough to cause the brittle fracture of the metal material.

3.1.3 AD and HIC mixing mechanism

Neither the AD mechanism nor the HIC mechanism can explain SCC behavior in near neutral environments very well. The majority of scholars have accepted the AD and HIC interaction mechanism proposed by PARKINS, et al^[27]. According to the calculations of Parkins, the crack extension rate is 10 mm/s to 6 mm/s , and the anode current density is 10 A/cm^2 to 3 A/cm^2 according to the slow strain rate test and the cyclic loading experiment in a nearly neutral environment. According to Faraday's Law, the crack propagation rate is calculated as 10 mm/s to 7 mm/s , which is much lower than that of AD. Accordingly, Parkins considers that stress corrosion in neutral pH environments is a mixing process that includes AD and hydrogen seeping into metal materials. QIAO, et al^[28], found that the stress corrosion rate of austenitic stainless steel in a MgCl_2 solution increased by 10 times and that the threshold value declined by 20% according to experiments in a hydrogen-charging condition.

3.2 Corrosion fatigue mechanism research

Corrosion fatigue generally has two processes: crack initiation and crack propagation. After years of research, many models and mechanisms have been used to explain the phenomenon of corrosion fatigue.

3.2.1 Mechanism of crack initiation

The material and the environment affect crack initiation. Different metals and alloys require different crack initiation theories. Currently, no corrosion fatigue crack initiation model is suitable for all material-environment systems. The main crack initiation theories are the following^[29–31].

(1) Corrosion fatigue cracks are most likely initiated at the bottom of pitting holes where the stress is concentrated.

(2) The cathode is the area around the plastic yielding that leads to preferential corrosion in the plastic deformation area.

(3) The protective oxide film may burst and lead to preferential electrochemical corrosion at a location in the metal materials subjected to fatigue loading.

(4) Some active ions can be absorbed by the metallic surface, and they reduce the surface energy and damage the mechanical ability of the metal.

3.2.2 Mechanism of crack propagation

Given that the time involved in the propagation of corrosion fatigue accounts for 90% of the entire life of the fatigue, studying the laws and influencing factors of corrosion fatigue crack propagation is very significant. Currently, the mechanisms of corrosion fatigue crack propagation are similar to that of SCC. These mechanisms mainly include the AD mechanism, the HIC, and the mixed mechanism.

3.2.3 Influencing factors of corrosion fatigue crack propagation

Corrosion fatigue research is related to mechanical, chemical, electrochemical, and metal material science and metallurgy. The factors of corrosion fatigue crack propagation, such as load frequency, stress ratio, temperature, corrosive medium concentration, pH value, and metal material machining technology, could affect the corrosion fatigue crack propagation rate.

(1) Loading frequency

The corrosion fatigue crack propagation rate is generally considered to increase with the decrease in loading frequency. AUSTEN, et al^[32], found that the corrosion fatigue crack propagation rate increases significantly as the frequency in the environment of medium stress intensity factor range (ΔK) decreases. However, this phenomenon is not obvious in the low or high ΔK environment. According to some scholars, the crack propagation rate accelerates as loading frequency decreases in a limited range. If the frequency is lower than the critical value, this process has little effect on crack propagation.

(2) Stress ratio

ZHAO, et al^[33], studied corrosion fatigue in 0Cr18Ni9 steel in a NaCl environment and found that the corrosion fatigue crack propagation rate accelerates when the stress ratio increases from 0.1 to 0.7. HAN, et al^[34], found that, as the stress ratio increases, the strain rate decreases and the hydrogen content increases in the crack-tip area. The resulting high hydrogen content area increases the hydrogen embrittlement sensitivity of the metal materials and accelerates the corrosion fatigue crack extension. Other scholars consider that the increase in stress ratio enables the corrosion medium to enter the crack-tip area easier. At the same time, the increase in cumulative plastic deformation in the crack-tip area can accelerate the anodic dissolution and extend the corrosion fatigue crack faster.

(3) Corrosion medium

Any corrosive medium can accelerate the corrosion fatigue crack extension. The corrosion fatigue crack propagation rate is related to corrosion medium temperature, concentration, and pH value. The corrosion fatigue crack propagation rate can be able to increase along with the corrosion medium temperature. According to SOCIE, et al^[35], in the middle ΔK , the crack propagation rate increases by approximately twice with the temperature from 1–4 °C up to 20–24 °C. In the low ΔK , the crack growth rate is stable when the temperature changes from 5 °C to 20 °C. EBARA^[36] carried out a corrosion fatigue experiment using 17-4PH stainless steel in an H₂S environment. The results show that the corrosion fatigue propagation rate in the H₂S environment is greater than that in air and that the propagation rate accelerates as the H₂S concentration increases. HUANG^[37] studied the corrosion fatigue propagation rate of the LY12CZ high strength aluminum alloy. He found that the crack propagation rate increases as the pH value decreases because the increased acidity leads to the fast AD in the crack-tip area. Moreover, a large amount of hydrogen spreads into the metal and accelerates the propagation of the crack.

4 Research Status of Centrifugal Compressor Impeller Corrosion Failure

Research on centrifugal compressor impeller corrosion failure focuses on two aspects: corrosion behavior and its mechanism in different centrifugal compressor working environments. These aspects involve the corrosion failure research methods combined with the actual working conditions of centrifugal compressors.

4.1 Corrosion research based on the centrifugal compressor working environment

Centrifugal compressors are widely used in many industries, especially in the petrochemical industry. Their working media are oil mixed gas, natural gas, hydrogen, oxygen, chlorine, carbon dioxide, ethylene, propylene, methane, ammonia, and nitrogen dioxide^[38]. According to the existing literature, corrosion failure of the centrifugal compressor impeller usually occurs in the presence of sulfide, chlorides, and carbonate^[39].

4.1.1 Sulfide corrosion environment

Sulfide stress corrosion cracking (SSCC) usually occurs in the centrifugal compressor used in the petrochemical industry^[40]. This kind of rupture can lead to unexpected, sudden failure as SSCC can make the metal material break down early even if the stress is below the yield strength. Local and foreign scholars have conducted many studies on SSCC. They consider that the dissociation products of hydrogen sulfide in the aqueous solution, such as HS⁻ and S²⁻, could be adsorbed on the surface of the metal material. Therefore, the metal potential is more negative and the

hydrogen release cathodic reaction is accelerated. The generated hydrogen diffuses and permeates inside the metal and accumulates in the high-hardness area, the high-strength area, and the high-stress area, especially in the weld and heat affected zone; this process eventually makes the steel fragile and leads to intercrystalline or transgranular cracking^[41]. ZUO, et al^[42], studied the SCC of 1Cr18Ni9Ti austenitic stainless steel in a hydrogen sulfide aqueous solution at room temperature and found that the failure mechanism is HIC. LI, et al^[43], studied the stress corrosion cracking of 16Mn steel in a saturated H₂S environment using the constant strain rate and slow strain rate tension methods. He found that the SCC in the acidic H₂S environment is transgranular and that the failure mechanism is HIC. Japan's Kawasaki Steel^[44] and WANG^[45] studied the SCC of HSLA steel in solutions with different H₂S concentrations and proposed that the crack initiation is mainly caused by partial AD. Moreover, the additional stress caused by the increase in hydrogen in the crack-tip area can influence the expansion of the crack; therefore, the SSCC mechanism is a type of AD and HIC interaction mechanism. SUI, et al^[1], studied the SSCC factors of impeller steel (X12Cr13 and FV520(B)) through a constant load sulfide stress corrosion test. He concluded that medium concentration, pH value, pressure, and temperature are the environmental factors of impeller SSCC. Metal strength, chemical composition, microstructure, and metallurgical defects are the material factors of impeller SSCC.

EBARA^[46] conducted a comparative study on the corrosion fatigue behaviors of 12Cr stainless steel, Ni-Cr-Mo steel, and Ti-6Al4V alloy in the environments of steam and gas mixture that contained H₂S, SO₂, and CO₂. The results indicate that the corrosion fatigue cracks extend fast in the corrosive environment as a result of the hydrogen created by the reaction among steel, H₂S, and H₂O. Thus, the corrosion pits in the crack expansion area reduced the corrosion fatigue strength by connecting change in the morphology in the corrosion fatigue crack and the crack propagation. ZHANG, et al^[47], studied the corrosion fatigue crack growth rate of 4130X steel in the H₂S environment and found the crack propagation rate formula when K was less than K_{ISCC}. This finding proves that the crack propagation rate in the H₂S environment is greater than that in air. Environment and frequency are the important influencing factors for the corrosion fatigue crack propagation rate.

4.1.2 Chloridion corrosion environment

In the petrochemical industry, corrosion damage always occurs in centrifugal compressor impellers made of austenitic stainless steel in chloridion environments^[48]. Many studies have been conducted on the stress corrosion behavior and the mechanism of austenitic stainless steel in chloridion environments. The AD mechanism is commonly considered. The chlorine ion could destroy the surface

passivation film of the austenitic stainless steel. The cracks occur in the area where the passivation film is destroyed, and the cracks become corroded battery anode areas as a result of tensile stress. The continuous electrochemical corrosion ultimately fractures the metal materials. JANI, et al^[49], studied the stress corrosion of austenitic stainless steel in a boiling MgCl₂ solution through transmission electron microscopy. He found that hydrogen could infiltrate metal and induce martensite transformation, which leads to the brittle fracture of stainless steel. SWANN, et al^[50] and LOUTHAN^[51] adopted replication and metallic thin film technology to study the stress corrosion fracture of austenitic stainless steel in a boiling MgCl₂ solution. They found that chloridion in the medium could destroy the passivation layer and create empty holes so stress corrosion cracks are initiated through stress. The stress corrosion resistance of 0Cr18Ni10 stainless steel in a 225 °C environment and an environment with 0 ppm to 600 ppm Cl⁻ concentration showed that, in water with high temperature, chloridions could be adsorbed on the surface of the Cr-Ni austenitic stainless steel, exclude the oxygen ions from the surface membrane, and generate FeCl₂ to form the pores in the membrane. The stress is concentrated in these pores such that chloridion shortens the incubation period of SCC and accelerates the fracture process^[52]. ROKURO^[53] studied the influence of Cl⁻ on the SCC. DEAN, et al^[54], studied the SCC of 304 stainless steel in environments with different chloridion concentrations and found that the increase in chloride ions concentration could shorten the SCC fracture time of austenitic stainless steel. LV, et al^[55], examined the relationship between the corrosion sensitivity of 304 stainless steel stress and the Cl⁻ concentration using a slow strain rate test. He found that a critical chloride concentration could lead to the stress corrosion of 304 stainless steel. QIAO, et al^[56], investigated the stress corrosion of 304, 310, and 321 austenitic stainless steel in an acidic chloride solution. He found that, although hydrogen is not the main control factor in the stress corrosion process, it could accelerate the AD process and increase the stress corrosion sensitivity of austenitic stainless steel in the acidic chloride solution under stress.

YE, et al^[57], studied the effect of concentration and loading frequency on the fatigue crack propagation rate through the corrosion fatigue tests of austenitic stainless steel in different sodium chloride concentration solutions with different loading frequencies. He found that the morphology of the surface of 0Cr18Ni9 steel exhibited brittle failure and that the main crack extension had transcrystalline morphology in the environmental media. Moreover, the corrosion fatigue expansion in the solution with low NaCl concentration was the result of the integration of AD, metal passivation on the surface of the crack, and mechanical fatigue.

4.1.3 Carbonate corrosive environment

Stress corrosion commonly occurs in CO₂ compressors

used in the petrochemical industry after a long service time. Research shows that the behavior and the mechanism of stress corrosion in high pH value environments and near neutral environments are different. SCC in high pH environments, such as concentrated solution of carbonate or bicarbonate with pH values of 8 to 10.5, is a type of intergranular stress corrosion cracking. The mechanism of high pH SCC is relatively accepted as the AD mechanism^[58]. SCC in near neutral environments, such as dilute electrolytes that contain CO₂ with a pH value of 6 to 8, is a type of transgranular stress corrosion cracking, the mechanism of which is not completely understood. SCC in a near neutral environment is considered to be caused by the interaction between anodic oxidation and HIC.

4.2 Corrosion research combined with the actual working condition of a centrifugal compressor

The most common method for studying corrosion damage in centrifugal compressors in actual working conditions is to analyze the part that failed through physical analysis. Along with the existing research results, the failure mode and cause are then evaluated. FANTECHI, et al^[2], analyzed a damaged natural gas compressor impeller and found many dendritic cracks in the impeller disk accompanied by some brown deposits. Using scanning electron microscopy and an energy spectrometer to analyze the cracks and corrosion products, he found the SCC of the impeller to be caused by chloride ions. LIU, et al^[59], found a large air compressor impeller internal stress distribution using finite element method. He found that the maximum stress area of the impeller is near the root of the inlet side, which is close to the actual crack location. Using a scanning electron microscope and energy spectrum analysis method to analyze the impeller fracture surface and deposits, he discovered the impeller crack to be typically the result of intergranular stress corrosion cracking caused by sulfide. SUN^[60] examined the cracks in a raw material gas compressor and found that the cracks were mainly concentrated in the primary turbine exhaust side and the secondary turbine inlet side. The cracks from the root expanded along the chamfering. The fracture morphology and deposit analysis showed that the cracks were intergranular and that OH⁻ was present in the corrosion products. Thus, the damage in the impeller was identified as stress corrosion damage caused by OH⁻. ZHANG, et al^[61], studied how the source of stress and material defects affected SCC and concluded that the normal working stress of impellers and the stress generated by the manufacturing process were the main causes of crack propagation. Different types of defects, including metal organization defects and construction technology defects, are the main source of SCC.

In the actual working process, the compressor internal flow fields are very complex because of the constraint in the impeller and diffuser structures on the internal gas flow as well as the influence of high-speed airflow at the export

of the rotating impeller on the gas flow at the diffuser inlet. The strain distribution of the blades is influenced by centrifugal force and aerodynamic load at the same time. KRAIN^[62] examined the section meridian velocities of six different flow channels and the distribution of relative flow angles. He used a laser measurement system to measure the high subsonic semi-open backswept impeller. The results show the flow characteristics inside the impeller. XI, et al^[63], used a probe to measure and analyze the flow field of a high-efficiency centrifugal compressor 3-D impeller outlet and a diffuser in three different operation conditions. Then, he obtained the distribution curve of the velocity field and the pressure field in three different radial positions. LIU^[64] studied the flow field within the iso-width centrifugal impeller with non-touch measurement methods (i.e., particle image velocimetry and laser phase Doppler anemometer) and compared the relative velocity vector and the velocity distribution obtained using both methods.

With the development of computer technology, the numerical simulation method has been used more often for studying the compressor internal flow field. WU, et al^[65] analyzed the unidirectional fluid–solid coupling of an unshrouded centrifugal impeller blade using finite volume method and finite element method. He obtained the deformation and stress distribution of the blade acted upon by the aerodynamic load, the centrifugal inertia force, and the coupling of these two loadings, respectively. The maximum deformation is located in the blade tip of the impeller inlet edge; the total deformation decreases from the blade tip to the wheel; and the maximum stress is distributed in the area round the wheel hub. WANG^[66] conducted a numerical simulation and analysis on the fluid–solid coupling of the first-class shrouded impeller of one large flow centrifugal compressor using finite element analysis method. He found that the maximum deformation is located in the joint between the blade trailing edge and the shroud, and the maximum equivalent stress is located in the joint between the leading edge and the shroud. These studies help to judge the location of stress corrosion cracking and corrosion fatigue crack.

5 Conclusions

(1) Corrosion failure, such as SCC and corrosion fatigue, usually occurs in the impeller with the joint action of corrosive medium and stress. The damaged parts are usually located in the impeller disc and the weld zone between blade and disc. Serious corrosion could lead to the overall fracture of the impeller blade.

(2) The mechanism of SCC is similar to that of corrosion fatigue. For now, the corrosion behavior and the mechanism of metal materials are divided into three aspects: AD, HIC, and AD and HIC mixing mechanism. The corrosion mechanism of the rotor impeller changes according to the different centrifugal compressor working environments.

(3) Currently, the physical method is the main research method used to study the corrosion of the centrifugal compressor. Combining some new methods, such as numerical simulation and fluid–solid coupling, can analyze the impeller deformation and the stress distribution as well as judge the impeller corrosion type and the corrosion mechanism.

(4) The working environments of the centrifugal compressor have various physical fields, such as stress field, temperature field, and flow field, among others. The research on the impeller corrosion behavior and mechanism based on the multi-physics coupling must be conducted urgently.

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