Damage Behavior of 30CrMnSiA Steel under Coupling action of Marine Atmospheric Environment and Tensile-compressive Load

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Abstract. The coupling test of marine atmospheric environment and tensile-compressive load for 30CrMnSiA steel was carried out with the coupling test equipment of marine atmospheric environment and tension, compression and bending load. The damage behavior of 30CrMnSiA steel on the coupling action of marine atmospheric environment and tensile-compressive fatigue load was discussed. The metallographic results showed that the damage behavior characteristics of static test and coupling test were consistent. The decrease of tensile strength, proof strength, plastic extension and percentage elongation after fracture of 30CrMnSiA steel were accelerated by the coupling action of marine atmospheric corrosion and tensile-compressive fatigue load. And the accelerated ratio of the coupling test was more than 10 times that of the static exposure test. The fracture morphology results showed that the fracture of the coupling test was corrosion fatigue fracture, and the cracks of 30CrMnSiA steel in the coupling test extended from the fatigue source to the core, forming directional corrosion fatigue damage.

1. Introduction

30CrMnSiA steel is a very important high strength alloy structural steel. Because of its good strength and toughness, and good fatigue resistance, it is widely used in aviation, transportation, construction and other industries[1-2]. However, marine atmospheric environment with characteristics of "high temperature, high humidity, high salt fog, strong solar radiation" will cause serious corrosion or damage to 30CrMnSiA high strength steel when it is used in the marine atmospheric environment. At the same time, 30CrMnSiA ultra-high strength steel will be subjected to repeated tension, compression, bending, torsion and other fatigue loads during its service process. The coupling effect of environmental corrosion and fatigue load is much higher than the simple superposition of independent action of environmental corrosion and fatigue load[3-5]. It easily causes an early failure of key
structure and some functional parts of the equipment, which seriously affects the reliable and safe service of equipment.

Coupling action of corrosion and fatigue load in natural environment is a common failure behavior in equipment service periods. Its harmfulness and destructiveness are usually unpredictable in advance, and the results are usually catastrophic once they occurred. And this kind of effect has been paid more and more attention[6-9]. In the past, due to the lack of fatigue test equipment in outdoor environment, researchers can only carry out the coupling test of environmental corrosion and fatigue load in laboratory environment, in order to find out the rule and mechanism of the coupling action of environmental corrosion and fatigue load on high strength steel[10-11]. He et al[12]. studied the effect of pre-corrosion in acidic NaCl solution on the fatigue life of 30CrMnSiNi2A connectors, it was found that the fatigue life decreased with the increase of corrosion time, and the influence factor of pre-corrosion with the change of pre-corrosion time could be fitted by exponential or power function. Niu et al.[13]. studied the corrosion fatigue crack growth behavior of 30CrMnSiA in five environments of standard laboratory air humidity (40 ± 10% RH), low temperature (dry) air humidity (< 10% RH), high temperature (wet) air humidity (> 90% RH), 3.5% NaCl corrosion solution and deionized water, the results showed that the corrosion fatigue crack growth process was a process of mechanical fatigue, hydrogen embrittlement and wedge effect induced by corrosion products competing with each other. Wei et al.[14]. studied the corrosion fatigue performance of FV520B steel in four environments of standard laboratory air humidity, 5% NaCl and 50mg/L H₂S corrosion solution, 5% NaCl and 100mg/L H₂S corrosion solution, 5% NaCl and 500mg/L H₂S corrosion solution. Where the fatigue sample was enclosed in the environmental box of the fatigue testing machine. The results showed that corrosion fatigue lives of FV520B steel aqueous H₂S+Cl⁻ environment were dramatically decreased compare with those in air and decreased further with the increasing of H₂S.

Laboratory environmental tests can usually only simulate a single environmental condition. It is difficult to effectively simulate the harsh marine atmospheric environment of "high temperature, high humidity, high salt fog, strong solar radiation", and it is more difficult to truly reflect the coupling action of marine atmospheric environment corrosion and fatigue load. In order to solve this problem, Luo et al [15]. invented a kind of coupling test equipment of marine atmospheric environment and tension, compression and bending fatigue load, which can carry out fatigue test in the outdoor environment under the humid and hot ocean atmosphere environment. The coupling test of marine atmospheric environment and tensile-compressive load on 30CrMnSiA steel was carried out by using the coupling test equipment in this paper. The coupling action of marine atmospheric corrosion and tensile-compressive load on the corrosion depth, tensile properties and fracture morphology of 30CrMnSiA steel were studied by means of metallographic microscope, coupling test equipment and scanning electron microscope. The results of the coupling test truly reproduce the environmental damage behavior under the coupling action of the marine atmosphere and the tensile fatigue load, which is closer to the actual service state of the material. The test results can provide a new test technical means for the environmental adaptability test verification and rapid screening of materials in the equipment development process, and have important theoretical and engineering application values for enriching and developing corrosion fatigue and stress corrosion related theories, as well as equipment maintenance, life determination and life extension.

2. Experimental

2.1. Specimens
The specimens were 30CrMnSiA steel. Its chemical composition was shown in Table 1[16], the geometry and dimensions of the specimens were reported in Figure 1. The oil on the surface of the specimens was washed with acetone before the test, then rinsed with deionized water, finally dehydrated with acetone, and dried in a desiccator for 24 h.
Table 1. Chemical composition of 30CrMnSiA steel.

| Element | Cu       | Mn       | Si       | Cr     | S        | P        | Ni  | Fe     |
|---------|----------|----------|----------|--------|----------|----------|-----|--------|
| Weight  | ≤0.025   | 0.80~1.10| 0.90~1.20| 0.80~1.10| ≤0.025   | ≤0.025   | ≤0.03| Margin |

Figure 1. Geometry and dimensions of the specimens.

2.2. Natural environmental test

2.2.1. Test environment
The test environment was the humid and hot marine atmospheric environment of the Wanning test site in Hainan. The test site is located at east longitude 110°30′ and north latitude 18°58′ and has the characteristics of high chlorine ion concentrations and humidity levels.

2.2.2. Coupling test equipment
The self-developed coupling test equipment of marine atmospheric environment-tension, compression and bending load was installed in the outdoor environment of the Wanning test site. The main technical parameters of the test equipment were shown in Table 2.

Table 2. Main technical parameters of test equipment.

| Serial number | Technical index   | Technical requirements                  |
|---------------|-------------------|----------------------------------------|
| 1             | Rated load        | Static ±100kN                          |
| 2             | Dynamic ±100kN    |                                        |
| 3             | Beam control      | Hydraulic lifting, hydraulic locking   |
| 4             | Test space        | 20 mm~400 mm                           |
| 5             | Test frequency    | 0.01 Hz~30 Hz                          |

2.2.3. Exposure test

(1) Static exposure test
All the specimens were mounted on exposure frames with an angle of 45° from the horizontal plane. The test duration was 12 months, and the test periods of which were 3, 6, 9 and 12 months. Six specimens were retrieved from the rack at each test period for analysis. Five of them were applied to determine the tensile properties, one of them was used to identify the morphologies and fracture morphology.

(2) Coupling test
The coupling test was carried out by using coupling test equipment of marine atmospheric environment-tension, compression and bending load. The test duration was 35 days, and the test periods of which were 14, 21, 28 and 35 days. Six specimens were retrieved from the coupling test equipment at each test period for analysis. Five of them were applied to determine the tensile
properties, one of them was used to identify the morphologies and fracture morphology. The coupling test conditions were shown in Table 3 and field test photo was shown in Fig. 2.

Table 3. Conditions of coupling test.

| Specimens  | Test conditions                     | Test time (d) |
|------------|------------------------------------|---------------|
| 30CrMnSiA  | Load range: -14kN~14kN              | 14            |
|            | Stress ratio: R=-1                  | 21            |
|            | Frequency: 10Hz                     | 28            |
|            | Loading cycles: Once a day          | 35            |
|            | Loading time: 25 minutes each time  |               |

Figure 2. Coupling test.

2.3. Specimens detection and analysis

2.3.1. Metallographic microstructure
Cross sectional morphologies of the specimens were characterized using metaloscope, prior to the test, cross sections of the specimens were embedded into epoxy resin, and then mechanically ground down to 2000 grit SiC papers and polished with 1.5 μm diamond paste.

2.3.2. Tensile properties
The tensile properties tests were carried out by using coupling test equipment, and five parallel samples were used for each test series to obtain the representative average values.

2.3.3. Fracture morphology
FEI quanta200 environmental scanning electron microscope was utilized to observe the fracture morphology of the specimens.

3. Results and discussion

3.1. Corrosion morphology and characteristics
The cross sectional morphologies of 30CrMnSiA steel in the static exposure test and the coupling test are shown in Figure 3 and Figure 4. And the maximum corrosion depth of 30CrMnSiA steel is shown in Table 4. It was known from the Figure 3(a) that the original metallographic structure of 30CrMnSiA steel was tempered sorbite with martensitic phase, and the tissular grade was grade 1. The corrosion characteristics of 30CrMnSiA steel were basically same during the static exposure test and the coupling test, which were pitting corrosion. According to the data in Table 4, the corrosion depth of 30CrMnSiA steel increased gradually with the prolongation of test time. The maximum corrosion depths of 30CrMnSiA steel of static exposure for 3 months and 12 months were 75μm and 125μm respectively. During the coupling test, the maximum corrosion depth of 30CrMnSiA steel increased from 29 μm (coupling test for 14 days) to 51 μm (coupling test for 35 days).
Figure 3. Cross sectional morphology of 30CrMnSiA steel in the static exposure test: (a) original; (b) 3 months; (c) 12 months.

Figure 4. Cross sectional morphology of 30CrMnSiA steel in the coupling test: (a) 14 days; (b) 21 days; (c) 28 days; (d) 35 days.
Table 4. Maximum corrosion depth of 30CrMnSiA steel.

| Test types          | Test time | Maximum corrosion depth (μm) |
|---------------------|-----------|-----------------------------|
| Static exposure test| 3 months  | 75                          |
|                     | 12 months | 125                         |
|                     | 14 days   | 29                          |
|                     | 21 days   | 30                          |
| Coupling test       | 28 days   | 45                          |
|                     | 35 days   | 51                          |

3.2. Tensile properties

The curves of tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel in the static exposure test and the coupling test are shown in Figure 5 to Figure 7. It can be seen from the figure that tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel in both tests showed a downward trend with the prolongation of test time. The tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel decreased by 7.5%, 5.9% and 20.0% in the coupling test of marine atmosphere environment and tensile-compressive fatigue load for 35 days. And the tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel decreased by 6.4%, 5.1% and 16.7% in the static exposure test of marine atmosphere environment for 12 months.

The slip deformation of 30CrMnSiA steel was produced under the tensile-compressive fatigue load during the coupling test. The activation energy of the sliding deformation area was higher than that of the undeformed area. The corrosive primary battery was composed by the deformed area and the undeformed area under the environment corrosive medium. The deformed and undeformed regions were anode and cathode respectively, and the anode region continued to dissolve due to continuous corrosion. The corrosive medium diffused into the material under the action of alternating stress, which accelerated the formation of corrosion fatigue source in advance and promoted the initiation and propagation of corrosion fatigue crack[17]. The results showed that the descending rate of tensile properties of 30CrMnSiA steel was accelerated by the coupling action of marine atmospheric corrosion and tensile-compressive fatigue load. And the accelerated ratio of the coupling test was more than 10 times that of the static exposure test.

![Figure 5. Curve of tensile strength of 30CrMnSiA steel.](image1)

![Figure 6. Curve of proof strength plastic extension of 30CrMnSiA steel.](image2)
Figure 7. Curve of percentage elongation after fracture of 30CrMnSiA steel.

3.3. Fracture morphology
The fracture morphologies of 30CrMnSiA steel in the static exposure test for 12 months and the coupling test for 42 days are shown in Figure 8 and Figure 9. It can be seen from Figure 8 that the fracture of 30CrMnSiA steel was ductile fracture, and no obvious fatigue source was found in the fracture during the static exposure test. It can be seen from Figure 9 (a) to Figure 9 (c) that the fracture of the coupling test was even, and the crack source of 30CrMnSiA steel was covered by corrosion products. The crack of the coupling test originated from the surface and extended radially towards the core, forming directional corrosion fatigue damage. It can be seen from Figure (d) and Figure 9 (e) that the extending zone near the crack source was a quasi-cleavage morphology, and there were small secondary crack. A tearing morphology in the instantaneous fracture zone was found from Figure 9 (f). The secondary cracks were easily caused due to the excessive plastic deformation at the crack tip under the coupling action of environmental corrosion and tension-compressive fatigue load during the coupling test. The crack size of the secondary cracks was smaller than that of the main cracks. In the process of fatigue loading, the secondary crack could play a role in dispersing the concentrated stress at the crack tip and delay cracking to a certain extent[18].
Figure 8. Fracture morphology of 30CrMnSiA steel in the static exposure test for 12 months: (a) Surface fracture morphology (19×); (b) Surface fracture morphology (400×); (c) Surface fracture morphology (1500×); (d) Surface fracture morphology (3000×); (e) Core fracture morphology (800×); (f) Core fracture morphology (3000×).
4. Conclusions

(1) The corrosion characteristics of 30CrMnSiA steel were pitting corrosion during the static exposure test of marine atmospheric environment and the coupling test of marine atmospheric corrosion and tensile-compressive load, and the maximum corrosion depth of both gradually increased with the extension of exposure time.

(2) The tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel decreased by 7.5%, 5.9% and 20.0% in the coupling test for 35 days. And the tensile strength, proof strength plastic extension and percentage elongation after fracture of 30CrMnSiA steel decreased by 6.4%, 5.1% and 16.7% in the static exposure test for 12 months. The results showed that the descending rate of tensile properties of 30CrMnSiA steel were accelerated by the coupling action of marine atmospheric corrosion and tensile-compressive fatigue load. And the accelerated ratio of the coupling test was more than 10 times that of the static exposure test.

(3) There are corrosion fatigue fracture characteristics of the fracture surface of 30CrMnSiA steel in the coupling test, the cracks extended radially from the fatigue source to the interior of the specimen, forming directional corrosion fatigue damage. And the secondary cracks were caused due to the excessive plastic deformation at the crack tip under the coupling action of environmental corrosion and tension-compressive fatigue load, which played a role in dispersing the concentrated stress at the crack tip and delay cracking to a certain extent.

Figure 9. Fracture morphology of 30CrMnSiA steel in the coupling test for 42 days (Broken): (a) Surface fracture morphology (13×); (b) Surface fracture morphology (100×); (c) Surface fracture morphology (500×); (d) Surface fracture morphology (1000×); (e) Crack extension zone morphology (800×); (f) Crack extension zone morphology (1500×); (g) Crack extension zone morphology (3000×); (h) Core fracture morphology (3000×).
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