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Citation for published version:
Ren, C, Wang, H, Huang, Y & Yu, Q-Q 2020, 'Post-fire mechanical properties of corroded grade D36 marine steel', *Construction and Building Materials*, vol. 263, 120120.
https://doi.org/10.1016/j.conbuildmat.2020.120120

Digital Object Identifier (DOI):
10.1016/j.conbuildmat.2020.120120

Document Version:
Peer reviewed version

Published In:
Construction and Building Materials

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Post-fire mechanical properties of corroded grade D36 marine steel

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Abstract

This paper presents an experimental study on the post-fire mechanical properties of corroded grade D36 marine steel. Corrosion and high temperature are two main adverse factors that degenerate the mechanical properties and lead to decrease in strength and durability of steel. The combined influence of corrosion and high temperature on the mechanical properties of marine steel was investigated in this study. A series of tests were conducted to determine the post-fire mechanical properties of corroded marine steel. Specimens were corroded by a salt spray test which simulated the marine atmospheric environment, and then heated to 500 ℃ or 900 ℃. After exposure to corrosion and high temperature, the elastic modulus, yield stress, ultimate strength and stress-strain curves of grade D36 marine steel specimens were obtained from tensile coupon tests. Three-dimensional laser scanning was used to evaluate the impact of corrosion. The microstructure and fracture morphology analyses were carried out by scanning electron microscope (SEM) to obtain the combined effects of corrosion and high temperature. It was shown that the corrosion and high temperature had significant influence on the microstructures and corresponding fracture morphology of grade D36 marine steel.

Keywords: Corrosion, marine steel, mechanical properties, microstructure, post-fire, salt spray accelerated test, scanning electron microscope, three-dimensional laser scanning.

1. Introduction

Large and complex steel offshore industrial facilities such as Blue Whale 1, Umm Lulu Gas Treatment Platform have been constructed because of the increasing demand for marine resources [1]. Due to harsh marine environment, marine steel with good durability is designed for offshore industry facilities to resist more adverse factors [2], among which corrosion and fire are the two main detrimental factors. Offshore industry facilities are suffered from corrosion damage, which accelerates with service time. Such damage would be more severe when a catastrophe like a fire happens on facilities that have serviced for decades. Mechanical properties are crucial indexes to evaluate the structural performance of steel structures after damage [3]. Thus, post-fire mechanical properties of marine steel after exposure to combined corrosion and high temperature were evaluated in this study, in order to determine whether offshore industrial facilities could continue to be used after a fire.

In the past few years, extensive experimental work has been performed on the effects of corrosion and fire on steel separately [4-10]. On one hand, studies have been carried out on mechanical properties, mass changes, corrosion pits and corrosion mechanism of steel [11-15]. The elastic modulus, yield stress, ultimate strength and ultimate strain of steel influenced by corrosion have the similar variation tendency which first decline and then slightly increase with corrosion duration, due to different stages of corrosion. Corrosion process of steel is generally composed of two stages. First, corrosion products emerge and accumulate on the surface of metal. Second, corrosion products wrap on the whole surface to prevent further corrosion, which means that the latter stage provides protection to deeper corrosion of the metal. It has been proved that it is feasible to use the mass loss ratio to evaluate the degree of corrosion. It is defined as the basic index in the time-dependent corrosion model of steel, which is the base for complex corrosion models of steel.

Studies on the micro level of steel material provided more evidence to demonstrate the influence of corrosion on steel, especially on corrosion pits and corrosion mechanism [16-20]. The corrosion effect on the micro level of steel was detected by X-Ray diffraction [18,21], three-dimensional laser scanning [15-16,22], scanning electron microscope (SEM) [23-24], thermal analysis [18], and chemical analysis [19]. These studies showed that the number and depth of the corrosion pits, which led to stress concentration and reduction of the effective cross-sectional area, increased with corrosion rate. Corrosion pits showed different status in various corrosion conditions. Relevant results pointed out that if the status of corrosion pits and corrosion mechanism were similar, mechanical properties of steel after different corrosion treatments could be compared. Besides, the studies on corrosion demonstrated it slightly changed the microstructure and fracture morphology of steel.

Moreover, research work on mechanical properties of steel in fire and after a fire was conducted. Most studies on mechanical properties of steel in fire were applied to the fire resistance design, such as European Code [25], Australian Standard [26], and American Specification [27]. The post-fire mechanical properties of steel are significant indexes to evaluate whether a structure could continue to be used after a fire. So far, studies on post-fire mechanical properties of steel were seldom reported, and limited investigation on marine steel was found in the literature. Tao et al. [28] and Yu et al. [3] proposed prediction models for the residual mechanical properties of hot-rolled steel and cold-formed steel after cooling down from 600 ℃ to the ambient temperature. Chiew et al. [29], Outinen and Makelainen [30], Qiang et al. [31] presented the mechanical properties of different grades of structural steel after a fire. Ren et al. [32] compared the differences in mechanical properties of the flat portion and corner portion that cut from the same cold-formed C-section steel. In Wang et al. [33], the post-fire mechanical properties of Q460 high strength steel with water cooling and air cooling method were evaluated. Li et al. [34] conducted an experimental study on the post-fire mechanical properties of Q690 structural steel with different cooling methods. Lu et al. [9] carried out a series of experimental work on the post-fire mechanical properties of cast steel. Test results indicated that cyclic heating-and-cooling had no obvious effect on the post-fire mechanical properties of G20Mn5N and G20Mn5QT steel. Huang and Young [35-36] presented the post-fire mechanical properties of ferritic stainless steel and lean duplex stainless steel, and the relevant design equations were proposed. Above investigations revealed that the mechanical properties of steel decreased only marginally after exposure to a temperature up to 600 ℃, and a considerable reduction was observed when the temperature was above 600 ℃. In addition, the post-fire mechanical properties of steel were also influenced by cooling methods.

To the best knowledge of the authors, research on combined effects of corrosion and fire on mechanical properties of steel is limited. In marine environment, corrosion is a constant process and is harmful to marine construction especially to steel structures. Besides, there is a significant number of offshore industrial facilities that are used for exploitation, storage and transportation of combustible oil and gas resources. A leak of oil and gas is highly possible to cause fire and even explosion. Fire damage on aged steel offshore facilities may be more severe and result in catastrophic accidents. Han et al. [37] considered the temperature effect on the corrosion behavior of 2205 stainless steel. Yu et al. [38] proposed an improved numerical corrosion model for rebar steel regarding temperature and relative humidity as indexes. These two studies only considered temperatures range from 0 ℃ to 50 ℃ which are much lower than the temperature in a real fire. Li et al. [39] carried out an experimental study on the post-fire mechanical properties of corroded 2205 duplex stainless steel, in which the corrosion and high temperature were conducted simultaneously with solution-treated and water-cooling methods. Kong et al. [40] examined the mechanical properties of corroded 316L stainless steel after exposed to 1050 ℃ and 1200 ℃. These results showed that the multi-influential effects of corrosion and fire on the mechanical properties were noteworthy. However, limited studies were conducted on the post-fire mechanical properties of construction steel after marine atmospheric corrosion.

In this study, the combined effects of corrosion and post-fire on the mechanical properties of grade D36 marine steel are presented. An experimental study on the mechanical properties of corroded marine steel after fire exposure with water cooling method was conducted. A salt spray test was conducted to simulate the marine atmospheric environment. The corroded specimens were heated and then water cooled to the ambient temperature, in order to simulate the condition of offshore facility extinguished from fire. The elastic modulus, yield stress, ultimate strength and ultimate strain of grade D36 marine steel after exposure to corrosion and high temperatures were obtained by tensile coupon tests. Five different corrosion durations and two different temperatures were selected for comparison. Three-dimensional laser scanning and scanning electron microscope (SEM) were used to investigate the influence on the dimensions and microstructures, respectively.

2. Experimental program

2.1. Test devices

Steel in offshore industrial structures above the sea level suffers from atmospheric corrosion over its service life. Under this circumstance, a fire attack would cause more detrimental impact. Consequently, rather than immersion corrosion, a salt spray test was carried out to simulate the atmosphere corrosion environment. The test was conducted in an atmosphere environment chamber which provides constant neutral salt mist, stable temperature and humidity, as shown in Fig. 1(a). In order to simulate different levels of corrosion, the specimens were exposed for 48 hours, 96 hours, 192 hours, and 384 hours according to ASTM B117-16 [41].

The target temperature in the high temperature test was determined by Fire Dynamics Simulation (FDS) of an offshore facility [42]. 500 ℃ and 900 ℃ were selected as when facilities were exposed to fire in open and indoor spaces, respectively. A small electrothermal furnace as depicted in Fig. 1(b) was used to perform the high temperature test.

Specimens experienced corrosion and post-fire treatments were then tested by an MTS universal testing machine (Fig. 1(c)), which was employed to obtain the mechanical properties of the tensile coupon specimens. It should be noted that specimens without experiencing corrosion and high temperature were also tested for comparison purpose.

2.2. Specimen design

All specimens were manufactured by grade D36 marine steel with a nominal yield stress of 355 MPa. The weathering steel with high durability is usually adopted by ship and offshore facilities. The geometry and dimensions of the specimens were determined according to ASTM B117-16 [41] and GB/T 228.1-2010 [43] (Fig. 2). Table 1 shows the corrosion duration and exposure temperature of the specimens. The temperature with the symbol * represents the measured temperature inside the chamber.

2.3. Test procedure

2.3.1. Salt spray test

The salt spray test was conducted in an environmental chamber to accelerate the corrosion condition of marine steel specimens. Generally, there were three steps for the accelerated corrosion. i) Pretreatment: All the specimens were numbered and weighted, and all their detailed properties were recorded. The mass loss ratios were calculated according to Eq. (1) and are listed in Table 2. ii) Corrosion treatment: The specimens were placed in the chamber on a shelf (Fig. 3) which was adopted to provide a certain angle recommended by ASTM B117-16 [41]. The chamber was fulfilled with salt fog generated by 5% wight NaCl solution. The temperature, relative humidity (RH) and pH value inside were consistently controlled at 35℃, 100% and 7, respectively. The corrosion periods were set at 48 hours, 96 hours, 192 hours, and 384 hours for observing the whole process of metal corrosion. iii) Post-processing: Two specimens were taken out each time for different heating treatments, and the remaining specimens were rotated between two top pipes every 48 hours, as illustrated in Fig. 4. After taken out from the chamber, the specimen was cleaned by tap water and dried by clean tissues according to ASTM specification [41]. They were then weighed again to assess the corrosion and each was wrapped by a preservative film to prevent extra corrosion. Fig. 5 displays the specimens after the salt spray test.

$$\text{Mass loss ratio} = (m_o - m_1) / m_o \tag{1}$$

where m_o is the initial mass of the specimen; m_1 is the mass of the specimen after cleaning.

2.3.2. Heating and cooling procedures

An electrothermal furnace was used to heat up the specimens, so as to evaluate the post-fire behaviour of grade D36 marine steel after corrosion. During the test, the corrosion product was not cleaned to simulate a situation closed to the engineering practice. The specimen was placed on a small mantelpiece as shown in Fig. 6 which was used to prevent the specimen from touching the furnace wall. The heating process was set according to ISO 834 [44]. 500℃ and 900℃ were defined as the target temperatures according to the Fire Dynamics Simulation (FDS) [42]. The temperature variation on the specimen was recorded by a thermocouple installed at the mid-length of the specimen. Once the temperature reached the target value, the specimen was kept in the electrothermal furnace for another 15 mins to ensure that it was uniformly heated. Afterward, it was taken out from the electrothermal furnace and immediately cooled down to the ambient temperature by water. Fig. 7 shows the specimens after the salt spray test and high temperature test.

2.3.3. Tensile coupon test

The mechanical properties, including the elastic modulus, yield stress, ultimate strength and ultimate strain, were obtained by tensile coupon tests which were performed by an MTS universal testing machine. The specimens' surface was cleaned by sandpapers followed by acetone and the specimens were weighed to assess the mass loss. An extensometer was mounted (shown in Fig. 8) to monitor the strain development. Displacement control with a rate of 1 mm/min was adopted. Fig. 9 presents all the specimens after fracture.

2.4. Three-dimensional laser scanning analysis

Three-dimensional laser scanning with an accuracy of 0.01 mm was conducted to evaluate the effect of corrosion on the surface of the specimens. After tensile coupon tests, the specimens' surface was cleaned and sprayed by eikonogen. The specimen was placed in the center of the scanning table and the camera was rotated around the specimen for one scan. A typical three-dimensional laser scanning result is given in Fig. 10.

2.5. Microstructure and fracture morphology analysis

Microstructure and fracture morphology analysis were employed to evaluate the combined effects of corrosion and high temperatures on the micro level of the specimens. Considering that the effect of corrosion on the microstructure and fracture morphology was limited, only the specimens 48 h-500 ℃, 48 h-900 ℃ and 0 h-25 ℃ were selected for analysis. There were four procedures in the pretreatment step. Cross sections of the specimens were cut at 10 mm from the end and 15 mm from the fracture position to analyze the microstructure and fracture morphology, respectively. Sandpapers were used to grind the surface of the cut edge, and the cross-section was polished to a mirror level. After etched by nitric acid alcohol liquid, the microstructure and the fracture morphology of the specimen surfaces were carefully observed by scanning electron microscope (SEM).

3. Test results and discussions

3.1. Specimen appearance

Figs. 5, 7 and 9 show the specimens after the salt spray test, heating-cooling treatment, and tensile coupon tests, respectively. It is shown in Fig. 5 that color of corroded specimens gradually became darker with the accumulation of corrosion products. Corrosion products were partially distributed on the specimens after 48 hours' corrosion, while distribution of the corrosion product on the specimens experienced 96 hours' and 192 hours' corrosion apparently spread. For the specimens after 384 hours' corrosion, the whole surface of the specimen was uniformly covered by the corrosion products. Fig. 5 suggested that the corrosion process and the corrosion mechanism of metal materials were in a good agreement, which was also proved by the tensile coupon tests. The corrosion products increased with the corrosion duration and the color of the corrosion products gradually became darker. It was found from Fig. 7 that the color of the specimens treated by 900 ℃ was darker than that treated by 500 ℃, which indicated that the reaction between steel, corrosion product and air in 900 ℃ were more severe than that in 500 ℃. Fig. 9 shows that the specimens under 0 hour and 384 hours' corrosion approximately fractured at the middle of the gauge length and the others failed near the end of the gauge length, indicating that partially distributed corrosion had a significant influence on the failure mode of the specimens.

3.2. Mechanical properties

3.2.1. Stress-strain curves

The stress, strain, and related values hereinafter were all calculated based on the dimensions of the specimens before corrosion. The nominal stress-strain curves obtained from tensile coupon tests are plotted in Fig. 11. A noticeable difference was observed from curves of the specimens after exposure to 500 ℃ and 900 ℃. An apparent yield platform was found in the stress-strain curves of the specimens cooled from 500 ℃ to the ambient temperature, but not in those cooled from 900 ℃. Therefore, the yield stress was defined as the lower yield point for the specimens after treatment of 500 ℃, and 0.2% proof strength (stress at a strain of 0.2%) for the specimens after treatment of 900 ℃, respectively. Generally, the strength of the specimens was significantly enhanced after exposure to 900 ℃ followed by water cooling, but a considerable reduction was observed in terms of the ultimate strain. The ultimate strength of the specimens after exposure to 900 ℃ was 1.7 – 2.5 times of that after 500 ℃. Nevertheless, the ultimate strain of the specimens cooled down from 900 ℃ was only 20%-50% of that from 500 ℃. It is also observed that the post-fire elastic