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Methods of Corrosion Testing Used for the Development and Industrial Utilization of Novel Shipbuilding Steels and Alloys. A Review. Part II. Corrosion Cracking and Marine Field Testing

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Abstract—The review deals with methods for stress corrosion cracking (SCC) testing based on different conditions of sample loading: at a constant static load or under straining, at a constant or under an increasing load on samples with a previously grown fatigue crack, at a slow sample strain rate under stretching. Such testing is required for determining the resistance of shipbuilding materials to be operated in loaded ship structures under the conditions of contacting with seawater. A brief description of the mechanism of stress corrosion cracking in steels and alloys is presented. The fact that it is necessary to test steels and their welded joints, as well as models simulating individual units and elements of structures, is indicated. At this stage, conditions are provided that are as close as possible to operating conditions due to the exposure in various climatic zones of the World Ocean (variations in temperature, chloride concentration, in the amount of dissolved oxygen, the level of biofouling and a simultaneous impact of these factors). It is shown that during full-scale testing (the final stage of complex mandatory acceptance tests), novel materials that are promising for usage under marine conditions undergo the final corrosion resistance evaluation in the form of elements inherent in ship structures and systems under ship operating conditions.

Keywords: corrosion, stress corrosion cracking, loading conditions, operating conditions, fatigue crack, field testing, slow strain rate testing

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INTRODUCTION

Stress corrosion cracking (SCC) is one of the most hazardous types of corrosion damage that leads to serious destruction of loaded structures not only in shipbuilding, but also in aviation, thermal and nuclear power engineering, construction, chemical, oil and gas production and oil refining, as well as in food and other industries [1]. The destruction caused by SCC accounts for about 30% of the material damage caused by corrosion [2]. The metal materials in any corrosive environment can undergo stress corrosion cracking (SCC) only when subjected to tensile mechanical stresses.

In the shipbuilding industry, hull structures that are in contact with sea water can undergo SCC at the places where the highest mechanical loads are concentrated, which places, as a rule, represent welded joints. In the case of deep-sea marine equipment, the stresses in the structure arise due to the hydraulic pressure occurring during immersion [3–8].

When introducing new hull steels and alloys into the design and construction of ships, ships and offshore structures, it is mandatory to assess their susceptibility to SCC [3, 8]. For many decades, testing smooth surface under permanent load or strain were used for this purpose [1, 9–13]. When using the constant load method, stresses of a certain magnitude are applied to the samples and kept in synthetic sea water or 3.5% sodium chloride solution until failure or until a preset time base. Based on the testing results for a series of samples, a long-term corrosion resistance curve is plotted in stress–time-to-failure coordinates. The method of constant strain testing consists in the generation of a stress state with the help of a fixed strain and under controlled crack occurrence during testing. It is believed that in the case of this testing method, stresses that arise during the manufacturing of structures (residual welding, assemblage ones) are simulated [12].

The disadvantage of testing under constant loads or strains consists in the need for a large number of samples and testing machines, while the test duration amounts to several thousands of hours. The transition to more accelerated tests has made it possible to obtain a greater amount of information at a much lower cost of metal and time.

However, testing for SCC under constant loads or strains are performed at the stage of testing for the corrosion properties of shipbuilding materials in natural sea water. The offshore bench tests were carried out since 1946 on according the initiative by G.V. Akimov, when under his leadership special corrosion stations have been built in the Barents Sea (Dalnie Zelentsy) and in the Black Sea (Gelendzhik). Within the following decades, offshore corrosion stations have been set up in Sevastopol, Odessa, as well as in Vladivostok.

The marine testing of materials is performed to determine the resistance with respect to general or local corrosion (pitting, crevice, or contact one). Stresses in the samples for testing for SCC are generated based on the formation of welds or welded overlays.

The final stage in assessing the corrosion resistance of novel materials for shipbuilding consists in full-scale testing carried out in the case of ships in operation. For example, in order to assess the corrosion resistance of novel hull steels during construction or dock repair of a ship, the samples are fixed on the underwater part of the hull so that they are completely electrically isolated from the hull to prevent contact corrosion [14].

TESTING FOR STRESS CORROSION CRACKING

The phenomenon of SCC in structural steels and alloys is given with great attention from many researchers [1, 2, 8–19]. A mechanism of SCC in sea water is proposed based on successive repetitive processes at the tip of a corrosion crack, namely:

— local anodic metal dissolving;

— corrosion product hydrolysis causing the formation of additional hydrogen ions;

— hydrogen embrittlement of the metal affected by the tensile stresses and local zones of plastic deformation arising at the crack tip.

Factors affecting the resistance with respect to SCC consisting in the metallurgical quality of steel, the level of cathodic polarization in the course of electrochemical protection, and the magnitude of external and internal stresses including welding ones have been established. It is shown that the strength level is of paramount importance in the resistance of SCC materials [20–28].

Nowadays, different variants of testing based on two methods are widely used in shipbuilding for determine the resistance of steels and alloys with respect to SCC. They are:

— a testing method for samples with a preliminary grown fatigue crack (based on the principles of fracture mechanics) using different loading methods [29–36];

— a testing method for samples at a constant slow strain rate (Slow strain rate testing, SSRT) [13, 29, 37–41].

The basis for the use of samples with a fatigue crack consists in the assumption that there are crack-like defects in real structures in the form of casting pores, defects originated from rolling, forging, or from products welding and assembling, as well as caused by the formation of local surface corrosion damage in the course of operation. This can shorten or eliminate the cracking stage. The aptitude to SCC is determined using the linear fracture mechanics (LFM) theory according to force criterion K_I (stress intensity factor or fracture toughness coefficient) that determines the stressed state at the crack tip. Crack growth in a corrosive medium begins at $K_1 = K_1$scc, in air at K_{1C}. The greater is the difference between K_1scc and K_{1C}, the higher is the aptitude to SCC [42–46]. For SCC tests, samples according to GOST (State Standard) 25.506, GOST (State Standard) 9.903, as well as to ASTM E 1681 are used. The use of LFM methods makes it possible to estimate the crack growth rate that was first experimentally determined by Brown [47].

For modern structural materials having significant plasticity at a high strength level, the implementation of the LFM conditions during SCC testing becomes unattainable. This has led to developing the methods of nonlinear fracture mechanics [30–32], whose application consists in determining J-integral (analogous to K_I), opening crack edges δ at the crack tip, or CTOD (Crack tip open displacement). In order to determine these values, R-curves are plotted by means of a repeated loading and unloading of the sample and by measuring the crack opening using an extensometer (Fig. 1).

The experience of testing samples with a crack for SCC in the shipbuilding industry has revealed their significant confinements. They include:

— the manufacturing laboriousness of samples with a complicated geometric shape;

— the need to apply a crack with the use of special equipment;

— the failure of crack opening sensors due to exposure to a corrosive environment;

— a distortion of calculation results obtained for fracture parameters during crack branching or passing

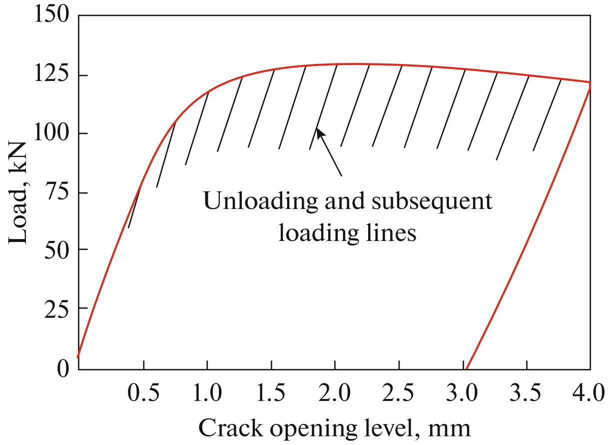

Fig. 1. Determination of δ using an elastic compliance method by means of *R*-curve plotting.

through certain structural components of the metal under investigation.

Publications regarding testing for SCC under tension of a sample of the material under study with a constant low strain rate is possible, first appearing about half a century ago [14, 33]. An insignificant time compared to static testing, as well as the established correspondence between the data on the aptitude of steels to the action of a corrosive environment obtained by means of both methods [48], make the use of the SSRT method the most preferable in comparative testing of different materials.

The strain rates recommended by existing standards for testing steels and alloys range from 10^{-7} to 10^{-5} s^{-1} [49, 50]. It has been established in [40] that shipbuilding hull steels are most sensitive to SCC in sea water at strain rate $\acute{\varepsilon} = 10^{-6}$ s^{-1}.

Decreasing strain rate to 10^{-7} s^{-1} exert almost no effect on the characteristics of steel aptitude to SCC, but leads to a tenfold increase in the duration of the experiment. When testing at a slow strain rate, loading begins from a zero load up to sample fracture, with plotting a tension diagram in stress-strain coordinates. In order to determine the effect of the corrosive environment, for comparison, a similar diagram of the material under testing is plotted for the case of an inert environment (Fig. 2).

Upon testing completion, the values of relative elongation δ and relative narrowing π for the samples are measured, the surface of the sample is examined (for the presence of corrosion cracks), and fractographic studies of fractures are carried out using an optical and electron microscope.

The comparison of stretch diagrams and the values of ε_{scc}, σ_{max}, δ, and ψ obtained in air and in the testing medium makes it possible to determine the material aptitude to SCC.

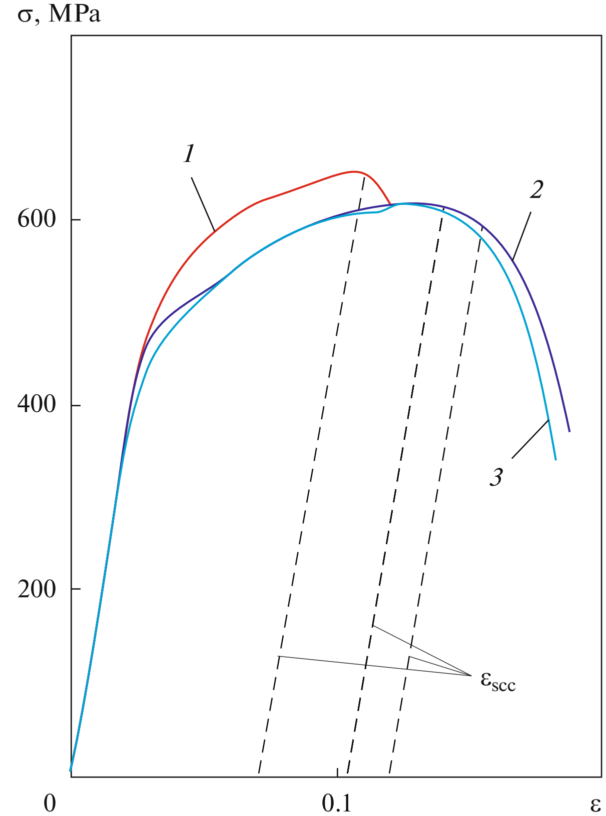

Fig. 2. A stress–strain (σ–ε) diagram obtained in the course of D40S grade steel testing for stress corrosion cracking by means of stretching at a constant slow strain rate stretching different testing conditions: (*1*) 3.5% NaCl, cathodic polarization; (*2*) 3.5% NaCl; (*3*) air.

A much more accurate criterion determining the level of the material susceptibility to corrosion obtained from the diagram is a relative strain level at which the destruction of the sample begins in a corrosive environment ε_{scc}). As another criterion, one can use a stress value at which crack growth begins (σ_{scc}) [40, 41]. This stress value can be determined from the point of divergence between the curves for an inert and a corrosive environment. It is also possible to use the ratio of ε_{scc} and σ_{scc} to the relative strain value and the failure stress value obtained based on testing in an inert environment.

The strain criterion that depends on the environment, temperature, and properties of the material, can characterize its state under the conditions of static, quasistatic and cyclic loading. As to compare with the force criterion, the mentioned criterion much better reflects the physical nature of corrosion-mechanical failure and the external and internal factors affecting this process, whereas the force criterion is convenient as a direct characteristic in calculating the performance of products and structures [2, 25–26, 51–54].

Fig. 3. Field tests for immersing samples in seawater with the use of a cassette.

The important stage in determining the corrosion resistance of shipbuilding materials consists in bench testing in natural sea water or sea atmosphere, as close as possible to real operating conditions. The samples are installed for a long time (at least for one year), during which intermediate inspections are performed with the fixation of corrosion damage, considering the ASTM standard [55]. The exposure of metal samples in different regions of the World Ocean makes it possible to evaluate their corrosion resistance depending on changing such parameters as sea water temperature, salinity, the amount of dissolved oxygen, and the level of biofouling [56, 57].

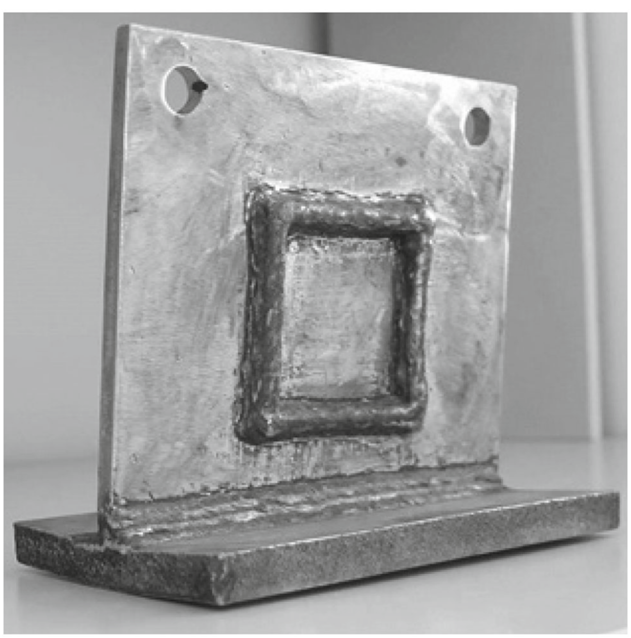

Fig. 4. Model welded structures for testing under full immersion in seawater.

Figure 3 shows a test bench in the form of a cassette with fixed samples made of different shipbuilding steels including those with welded seams, 350 × 250 × (4–20) mm in size before testing and at the moment of immersion [49].

As an example of large-sized welded hull steels in samples, Fig. 4 shows a model of a welded joint with an additionally overlaid contour. With the use of such samples, in addition to resistance with respect to general corrosion, the aptitude to SCC under affecting residual welding stresses can be evaluated.

As a rule, the final stage of the corrosion resistance checking consists in full-scale testing that is carried out using the elements of ship structures and systems made of the material under study under the ship operating conditions. Field testing procedures last from one year to several years. According to the results thereof, corrosion resistance is finally evaluated for steels or alloys.

After full-scale testing, a final decision on the possibility of using a novel material in shipbuilding as a part of structures operating in sea water, and, if necessary, on the use of corrosion protection agents has been made, as well as the service life up to the next scheduled repair has been determined.

CONCLUSIONS

The welded hull structures of marine vessels and fixed facilities are simultaneously exposed to sea water and mechanical stresses, which leads to the need to assess their resistance to SCC.

Nowadays, different testing variants based on two methods are widely used in shipbuilding to determine the resistance of steels and alloys with respect to SCC.

These methods are as follows:

— a testing method for samples with a preliminary grown fatigue crack based on the principles of fracture mechanics, in the case of different loading methods;

— a testing method for samples at a constant slow strain rate (SSRT).

Offshore bench testing welded samples and structures, and full-scale testing in the structure of existing ship systems make it possible to finally decide the potentialities of using novel materials in shipbuilding.

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CONFLICT OF INEREST

The authors declare that they have no conflicts of interest.

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