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Corrosion cracking of low alloy steels. Testing methods

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Abstract. The paper presents a brief overview of modern literature describing the mechanisms behind stress corrosion cracking of low-alloy steels in aqueous environments saturated with aggressive gases, such as hydrogen sulfide, and carbon dioxide, where atomic hydrogen is produced due to electrochemical reactions, subsequently penetrating the metal in the locations where it is dissolved or other surface defects are present. We described the main testing methods for stress corrosion cracking, their differences, and the criteria for assessing the corrosion cracking tendency of steels. Examples were given for applying metallographic and electrochemical analysis to explore the mechanism of stress corrosion cracking in the given steels.

Keywords: low-alloy steels, stress corrosion cracking, testing methods, crack initiation, crack growth, anodic dissolution, hydrogen embrittlement

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1. Introduction

Low-alloy steels are currently the most widespread engineering materials, commonly used in diverse industries in load-bearing structures, machinery, and different components. These materials are popular because they are weldable and allow fabricating workpieces with a efficient producibility. Also these steels with a wide range of strength and plastic properties can be obtained through thermal/thermomechanical treatment with a small concentration alloying elements used. Moreover, producing forgings, rolled and profiled sheets, or pipes from such steels costs substantially less than similar products made of high-alloy steels and alloys based on aluminum, nickel, or titanium.

However, aside from these benefits, low-alloy steels also have certain limitations due to their low corrosion resistance in a wide range of highly aggressive production environments. These include aqueous environments, such as seawater, humid environments, different salt solutions, acid solutions with low pH, and solutions saturated with corrosive gases, such as hydrogen sulfide, carbon dioxide, and sulfur dioxide, especially at high temperatures and pressures [1-25]. Protective paint or polymer coatings, corrosion inhibitors, and cathodic or

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sacrificial electrochemical protection are typically used to prevent corrosion in workpieces made of low-alloy steels or reduce it to acceptable levels [1,4,5,11,14,26-37].

Stress corrosion cracking (SCC) is one the most dangerous types of corrosive degradation, as it can lead not only to the failure of operating equipment but also to the collapse of structures or spills of transported products, polluting the surrounding areas with environmental consequences. SCC-induced damages account for 30% of all corrosion damage [39-47].

SCC is a type of local corrosive destruction of materials, evolving under simultaneous exposure to the corrosive environment and applied tensile stresses. The tendency towards SCC depends on the external conditions just as much as on both the chemical composition and the structural state of low-alloy steels.

The requirements imposed on chemical composition are primarily aimed at limiting harmful impurities as sulfur and phosphorus. Their content does not generally exceed 0.015% and 0.025%, respectively, in modern engineering low-alloy steels. Carbon concentration is limited to 0.3% to ensure weldability. Steels are alloyed with nickel, chromium, or sometimes copper to improve the technological properties; molybdenum, vanadium, niobium, and titanium are introduced in small quantities (no higher than 0.1%) to increase material strength. Depending on chemical composition and thermal or thermomechanical treatment, low-alloy steels can have structures ranging from ferrite-pearlite to martensite, providing different strengths in low-alloy steels (yield strength $\sigma_{0.2}$ can vary from 200 MPa to 1000 MPa and more).

Numerous studies have established that the strength of steel has the predominant effect on SCC sensitivity. Steels with higher strengths are more susceptible to SCC [34,41-44,48-52].

Depending on strength, low-alloy steels can be subjected to stress corrosion cracking in chloride solutions at room and elevated temperatures, including in seawater, in other salt and acid aqueous solutions with pH < 4, in hot alkalis, in solutions, saturated by hydrogen sulfide or carbon dioxide [43,46,53].

This paper briefly examines the key notions concerning the potential SCC mechanisms in low-alloy steels exposed to corrosive environments, primarily related to the production and transportation of oil and gas. We also described the most frequently used methods aimed at determining the SCC tendency in steel and understanding the processes behind this phenomenon.

2. Mechanism of stress corrosion cracking in low-alloy steels

Generally, SCC is a process of delayed fracture, that is, corrosion cracks originate and propagate in the metal volume until the acting stresses ahead of the crack front exceed the strength of the steel [39, 54]. Different theories have been proposed to explain the combined effect of stresses and the corrosive environment on the evolution of SCC in low-alloy steels.

One of the necessary conditions for SCC to occur is the main electrochemical reactions: anodic dissolution of the metal (AD) and cathodic reduction of the oxidant. The product extracted in oil and gas production contains, aside from hydrocarbons, a mineralized aqueous phase with dissolved carbon dioxide and, in many cases, hydrogen sulfide. Chlorides, sulfates of sodium, calcium, and other salts found in the aqueous phase make the solution highly electrically conductive, which contributes to the anodic dissolution of steel without any limitations [4]. It was established for the detected damaged sections of underground pipelines that corrosion cracks originate on the outer walls of pipes where protective coatings are destroyed when the metal comes into contact with groundwater containing carbonates and hydrocarbonates at pH 4-7. The rate of the anodic process depends on the degree of soil moisture [55-59].

The cathodic process associated with anodic dissolution is due to the reduction of oxidants on the metal surface in the external environment, for example, oxygen dissolved in groundwater, or hydrogen ions produced during the dissociation of carbon dioxide and hydrogen sulfide. CO_2 dissolved in water forms weak carbonic acid (H_2CO_3), which dissociates producing hydrogen, bicarbonate, and carbonate ions [3].

$$CO_2 + H_2O \leftrightarrow H_2CO_3, \quad (1)$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3{}^-, \quad (2)$$

$$HCO_3{}^- \leftrightarrow H^+ + CO_3{}^{2-}. \quad (3)$$

It follows from reactions (2) and (3) that hydrogen ions, directly participating in SCC of steels, act as the oxidant.

Molecular hydrogen sulfide in an aqueous solution also dissociates, producing H^+ and SH^- ions.

$$H_2S \rightarrow H^+ + SH^- . \quad (4)$$

The hydrogen ions formed through electrochemical reactions (2–4) on the metal surface are reduced to an atomic state by attaching electrons and partially combine into molecules. The rest of the hydrogen atoms are adsorbed on the surface, penetrating into the metal by means of diffusion. Sulfide ions SH^- in hydrogen sulfide solution prevent hydrogen atoms from combining into molecules; as a result, a significant part of atomic hydrogen penetrates into the volume of the metal. Cathodic polarization at potentials when reduction of hydrogen ions becomes possible can be a source of hydrogen [60-61].

The entire SCC process is generally divided into three stages: crack initiation, crack propagation under the influence of a corrosive environment, and mechanical failure as the acting stresses exceed the material strength [39,54].

The current consensus is that SCC in carbon and low-alloy steels begins with the anodic dissolution of the metal in the locations where various microinhomogeneities exist on the surface, with centers of non-uniform corrosion appearing, accompanied by simultaneous diffusion of hydrogen into the steel. Such corrosion centers serve as small stress raisers in loaded structures. Microcracks near the surface opened due to corrosion, can act as these raisers. If the level of local stresses at the tip of some defect exceeds the yield stress of steel, plastic flow initiates at a very slow rate, leading to further accumulation of atomic hydrogen. As a certain critical hydrogen concentration is reached due to hydrogen embrittlement (HE), crack jumping occurs by the distance of the embrittled zone. As a result, the metal surface at the top of the propagating crack and its opening edges at this moment is absolutely clean (fresh) from any corrosion products, rendering it highly corrosive [49].

It is assumed that the first stage of SCC ends at this point, and the cracking process moves into the second stage, when, after hydrogen is stored and supplied to the tip of the crack formed, local plastic deformation accumulates and brittle crack jumping occurs. Notably, both stages are always accompanied by electrochemical dissolution of the metal near the tip of the growing crack. An exception to this is SCC at high cathodic polarization when the process of metal dissolution becomes thermodynamically impossible. It is evident that the growth of a corrosion crack is a quasi-brittle process since the crack propagates abruptly.

The solution inside the growing crack is constantly acidified due to hydrolysis of corrosion products with hydrogen ions forming. In the case of intergranular corrosion cracking [62-64], the crack propagates deep into the metal at the stage of anodic dissolution, along the most active spots, which are typically grain boundaries. In the case of transgranular crack propagation in a neutral corrosive environment with a low concentration of hydrogen ions, the stage of surface dissolution at the crack tip may prevail over the stage of hydrogen embrittlement, which should lead to blunting of the crack tip. This weakens the effect of the crack as a stress raiser on the microplastic flow intensity and can completely stop the crack's further growth.

The third final stage of SCC begins when the size of the crack is large enough for the stresses to exceed the strength of the steel in the remaining section of the loaded structure, resulting in mechanical failure.

3. Methods for studying SCC in low-alloy steels

At least three factors are necessary for SCC to develop: a specific corrosive environment, the action of specific tensile stresses, and metallurgical factors (specific chemical composition and structure formed, ensuring the necessary mechanical properties). Consequently, corrosion cracking tests should involve stressed specimens contacting the corrosive environment. The main requirement is that the given testing method does not reject the materials that are resistant to corrosion in real operating conditions, and, conversely, the tests do not allow materials susceptible to SCC in practice. All methods applied can be divided into several groups depending on the approach to generating the stressed state: constant loading tests; constant strain tests; tests with step loading and constant strain rate [65].

Tests under constant tensile loading. Axial loading of specimens allows to accurately estimate tensile stresses if the specimen has a constant cross-section in the working area, that is, does not have a notch or other stress raiser. Tensile stress is then calculated by a simple formula:

$$=\sigma = \frac{R}{S}, \tag{5}$$

where R is the applied load, and S is the area of the cross-section tested in the specimen.

The general goal of SCC tests with a constant tensile load or constant strain rate is finding the threshold stresses for which the specimen is not destroyed during the given testing period. This period is typically chosen to be at least 720 (NACE TM0177 standard) [66] or 1000 (GOST 9.903) hours [67], but sometimes it is extended to several thousand hours. In the first case, it is exactly 30 days of tests or a calendar month, so counting time is convenient. Besides, a period of 720 hours or its multiple is recommended by standards for all types of corrosion tests. Choosing a 1000-hour period is more convenient for constructing a graphical dependence of time to failure on the applied stresses in logarithmic coordinates.

The threshold stresses are determined through a series of tests at different stresses, lowering the loading until the specimens remain intact and free of corrosion cracks at the last given load during the testing period of 720 hours. A curve representing the time to failure as a function of the applied stresses is plotted by the obtained data (see Fig. 1).

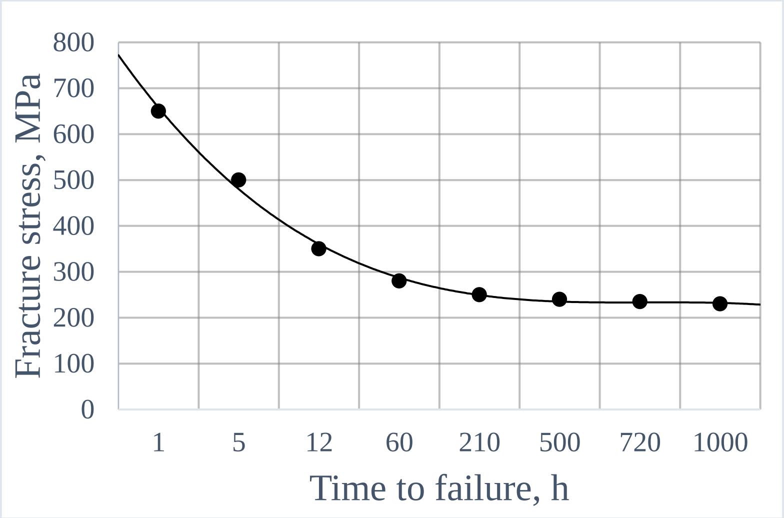

Fig. 1. Time to failure depending on applied tensile stress [66]

The dimensions of the section selected in the working area can also affect the specimen's time to failure. Tests with wire specimens or foils are not recommended, as general or pitting corrosion processes can cause such specimens to fracture before a stress corrosion crack can form.

Elastic devices shaped as rings or springs are the simplest for tests with constant loading. A loaded ring or spring generates tensile stresses in the specimens upon loading. To know the precise load applied, springs and rings are calibrated before the tests using a dynamometer, that is, the dependence of the load on the amount of their compression is plotted.

These devices are simple and convenient for use, but limited stresses can be set in the specimen because the relationship between the stress in the specimen and compressive strain in the ring or tensile strain in the spring is no longer linear at loads equal to or exceeding the yield stress. Therefore, it is impossible to use these devices to determine and maintain constant stress in the specimen if it exceeds the yield stress of the material. Since many metallic materials exhibit a tendency to SCC only at stresses above the yield, the loading machines required for the tests should be capable of setting and maintaining loads at any level, simultaneously recording the strain in the specimen with high accuracy.

The typical times to failure in SCC tests of smooth specimens in neutral aqueous environments, which are not usually highly corrosive, can amount to several thousand hours. Because the SCC mechanism in many steels and some alloys is associated with hydrogen transport to the maximum stress zone by mobile dislocation, SCC tests started to involve notched specimens. The maximum tensile stresses are always concentrated around the notch tip, i.e., the notch acts as a stress raiser. Notched specimens allowed shortening the test duration but it remained impossible to accurately determine the magnitude of the stress from the applied load. For this reason, several specimens are ruptured in air, and the fracture stress is measured in fractions of the fracture stress for air rather than in absolute units. The fracture stress is calculated as the ratio of the failure load to the cross-sectional area of the notched specimen. The stress calculated in this way is called *nominal* since this calculation is only valid for a smooth specimen.

In particular, notched specimens are convenient for finding the SCC resistance in different zones of a welded joint, when the notch is located either in the weld metal or in the heat-affected zone.

Constant strain rate tests. These tests are commonly performed for bending flat specimens since sheet metal products undergo bending deformation the most frequently. According to GOST 9.901.2-89, bending deformations are generated in flat beam specimens by two-, three- and four-point loading methods [68]. The specimens are tested at stresses below the elastic limit, arising under bending on their outer surface. Stresses are calculated by special formulas for each loading method, including the elastic modulus of the specimen material and the maximum deflection. C-shaped specimens are recommended by NACE TM0177 standard (Method C) for sulfide stress corrosion cracking tests in steels. It is especially convenient to use such specimens for tests at elevated temperatures and pressures, installing them into autoclaves in special vessels. The advantage of specimens stressed at a constant strain rate is that these specimens are loaded in the simplest fixtures and do not require machines for tensile strength testing. One of the most common drawbacks is significant to test length; furthermore, tests cannot be carried out at tensile stresses above the yield point.

Principles of fracture mechanics in SCC tests. These principles were first applied in the 1970s, as high-strength engineering materials gained wide popularity in metallurgy. The plastic properties are known to deteriorate with increasing strength. Such materials also have increased sensitivity to stress raisers, leading to brittle fracture. Finally, it was taken as an axiom that metallurgical and technological defects always exist on the surface of products, especially in welded joints, acting as stress raisers sufficient for crack initiation and propagation even in the absence of a corrosive environment. Therefore, the durability of structures depends on the crack propagation rate.

The principles of linear fracture mechanics (LFM) were applied to determine the crack growth rate and the critical conditions under which the crack does not grow, i.e., the material becomes crack-resistant. Since the fastest crack propagation occurs under brittle fracture, it is the most dangerous, and therefore, the tests must be carried out under conditions when deformation under the action of tensile stresses can only occur in a plane perpendicular to the action of stresses. The initial specimen should be subjected to fatigue pre-cracking for this purpose. A small core of plastic deformation is formed at the tip of the fatigue crack under the action of the applied load in these conditions, generating a stress field. The measure of the stress field is the stress intensity factor K (SIF), related to the applied stress and the crack length by a certain dependence. Generally, $K = \sigma \cdot f(\sqrt{\ell})$, where l is the crack length, mm, σ is the tensile stress, MPa.

The LFM principles are implemented in practice by using specimens with sufficiently large cross-sections in order to satisfy the conditions for plane deformation. The obtained value of K in the air is called fracture toughness and is denoted by K_{1c}. The value of the intensity factor above which the crack begins to grow in tests in the corrosive environment is denoted as K_{Iscc}. Brown, Scully, Newman, Karpenko, Vasilenko, Marichev, and others made large contributions to developing the methods for testing the SCC resistance in steels and alloys using linear fracture mechanics [41, 43–45, 47, 68].

The main methods for SCC tests determining K_{1SCC} (K_{1KR}), outlined in GOST 9.903-81 [69], consist of the following steps.

According to the first method, tests are carried out with a constant K_{1SCC} (K_{1KR}), provided that $K_{1i} < K_{1C}$, in a corrosive environment for 1000 hours. If a specimen fails in a shorter time at a given value of K_{1i}, the test is carried out at lower K_{1i}, reducing the load to the value of K_{1i} at which the crack arrests and the specimen does not fail in 1000 hours. The obtained value of K_{1i} is taken as the threshold stress intensity factor K_{1SCC} (K_{1KR}).

According to method 2, the load on a fatigue-pre-cracked specimen placed in a corrosive environment is increased sequentially until the crack grows by more than 1 mm. The load is then gradually reduced until the crack arrests completely. $K_{1KR}$is calculated from the load at which the crack is arrested and its final length.

Cracked specimens are used in these methods for axial tensile tests, cantilever bending, and eccentric tension.

Method 3 consists in setting a fixed deformation and controlling the crack growth for a specimen exposed to a corrosive environment. As the crack propagates, the K_{1i} value decreases, and the crack growth rate slows down until the crack arrests completely. The resulting stress intensity factor is accepted as K_{1KR}.

Only eccentric tensile specimens are suitable for SCC tests by Method 3. A modified version of such specimens is shaped as a double cantilever beam, where the constant strain rate is generated with a wedge. Such specimens are recommended by the NACE TM0177 standard (Method D) for determining the resistance of steels to hydrogen sulfide cracking [66]. Figure 2 shows the threshold stress intensity factor depending on the yield stress for 1Cr-0.7Mo-type steel obtained from the results of sulfide stress corrosion cracking tests by Method D [70].

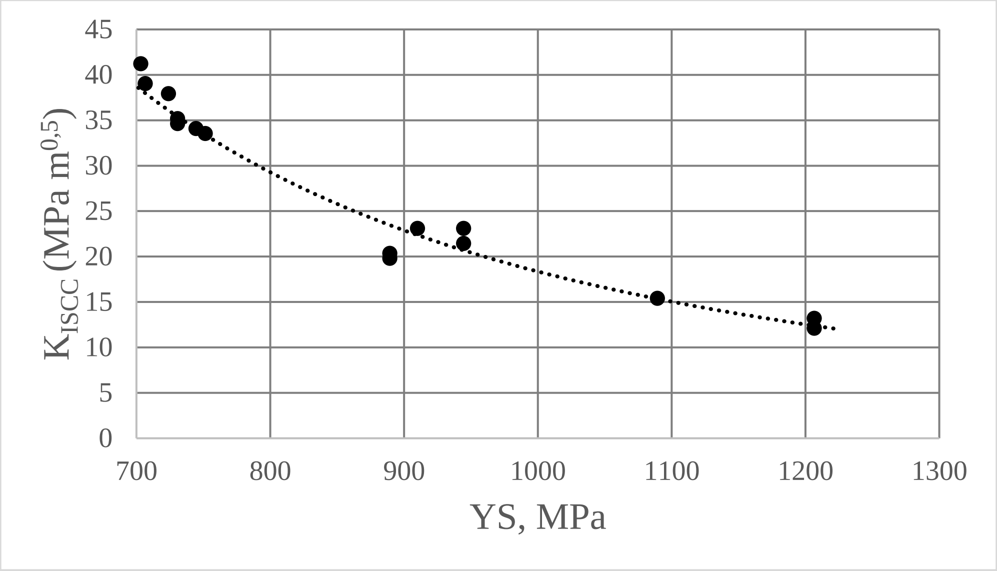

Fig. 2. Influence of yield stress in low-alloy steel on K_{ISCC} for tests of cracked specimens by Method D [70]

The conditions of LFM are virtually unattainable for assessing the fracture resistance in most modern low-alloy high-strength structural steels, as they are characterized by not only significant yield stresses but also increased ductility, which is the reason for a large plastic zone at the crack tip. Consequently, a model of quasi-viscous fracture underlying non-linear fracture mechanics (NLFM) is used. This model describes the values of the J-integral characterizing the work of plastic strain and fracture, as well as the stress and strain field under the elastoplastic deformation near the crack tip and the crack tip opening displacement ∂ (CTOD) [71-74]. The critical value of the J-integral is found by constructing the R-curve, which is the relationship between the value of the J-integral and the increment in depth (undergrowth) of the crack, Δa, characterizing the resistance of the material to slow stable crack growth under static loading. The critical value of ∂ (or *CTOD)* is found by constructing a ∂_R (the δ–Δa dependence). These are the so-called R-curves (*R* referring to rupture).

Force (SIF) and deformation (J-integral, CTOD) criteria are calculated by the formulas derived for each type of specimen and loading methods, described in GOST 25.506, GOST 9.903, ASTM E 1820, and other standards, as well as in specialized reference books [75-78].

The experience of SCC tests with cracked specimens has revealed the following key limitations of the method:

- it is difficult to manufacture specimens with a rather complex geometric shape, with exact dimensions of notches and side grooves, fatigue pre-cracking requires specialized equipment (resonant testing machines, vibrophores);
- LMR imposes stringent requirements on the dimensions of the specimens to produce plane deformation: consequently, the results obtained for metal products made of sufficiently ductile steels with low and medium strength may be inaccurate;
- it is necessary to determine the deformation criteria based on finding the undergrowth and CTOD; at the same time, it is difficult to visually measure the crack length in a corrosive environment, while CTOD sensors can be corroded and therefore malfunction quickly;
- complex testing machines have to operate for long periods (over a thousand hours) at high power during static loading tests;
- if the crack is branched or propagates along certain structural components of the metal (boundaries of sensitized grains, interphase boundaries, etc.), the methods of LMR may yield

incorrect results, because the clearly predominant SCC mechanism associated with anodic dissolution can weaken the effect of stress concentration.

Method for accelerated tests with step loading of cracked specimens by cantilever bending. This method was developed for SCC tests of small-sized specimens when it is impossible to satisfy the conditions for fracture mechanics [60,79,80]. Charpy-type specimens with a sharp notch and a failure crack were used for the tests. One end of the specimen subjected to cantilever bending was rigidly clamped, and a load was applied to the other end through an extension arm. Step loading is achieved by sequentially increasing the load, typically by a mass 1 of kg. A load is added in the elastic strain range every 2 hours, and, as short-term creep evolves, after it attenuates, which is recorded by a digital sensor capturing the specimen deflection (Fig. 3).

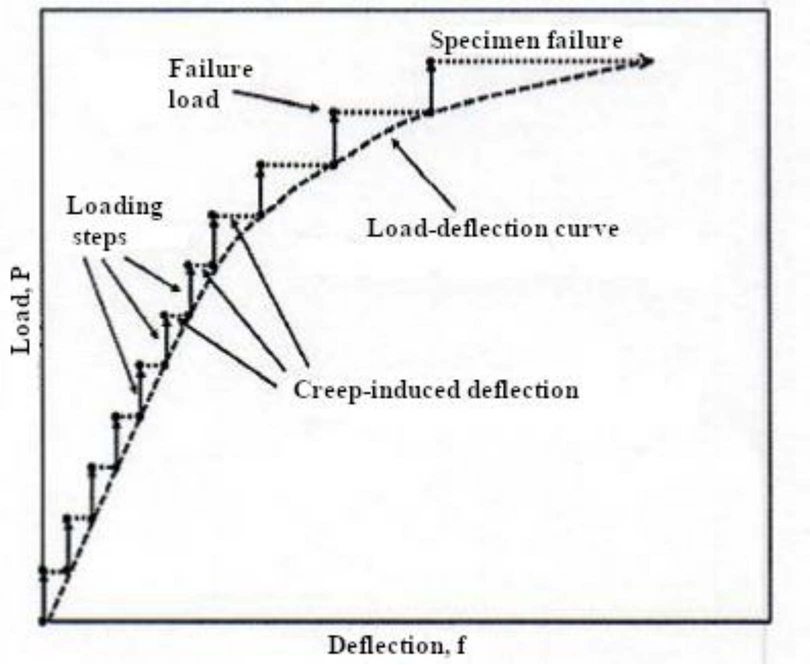

Fig. 3. Schematic step loading of a specimen during cantilever bending tests

The nominal tensile stresses leading to specimen fracture in a corrosive environment and in the air are calculated by the ISO 7539-6 standard.

Slow strain rate testing (SSRT) method. SSRT is widely used to assess the SCC tendency of steels and alloys. It is an accelerated test, where SCC completely follows the mechanisms including the stages of anodic dissolution and hydrogen embrittlement, accompanied by local plastic deformation in microvolumes of the metal.

SSRT was first used to study SCC in titanium alloys and steels, requiring very lengthy tests to obtain results under constant loading [81]. Agreement of the results of SCC tests obtained by the SSRT method with operational fractures and existing methods has long been a subject of much debate [82]. Essentially, cracking in tests with constant strain or constant loading tests also occurs under slow dynamic deformation but the conditions for constant rate tests are more stringent, and these tests cause the specimen to fracture rather quickly in any case.

The most important parameter in SSRT is the strain rate at which the SCC tendency of steel is the most pronounced [83]. Since ductile fracture develops at high strain rates before the corrosion reactions necessary for SCC can proceed, relatively low strain rates are required for the tests. The strain rates recommended by existing standards and procedures for testing steels and alloys are in the range (10^{-7} – 10^{-5}) s^{-1} [67,83-86]. Slow strain rate tests start at zero loads, continuing until specimen fracture; a tensile stress-strain curve is constructed. To detect the effect of the corrosive environment, a similar curve of the tested material is constructed for comparison in an inert environment. As an example, Figure 4 shows the tensile stress-strain curves for 34CrMo steel with a strain rate of $\sim 1\times10^{-6}$ s^{-1}, obtained during tests in sodium chloride solution saturated with hydrogen sulfide or carbon dioxide, and, for comparison, in the air [86].

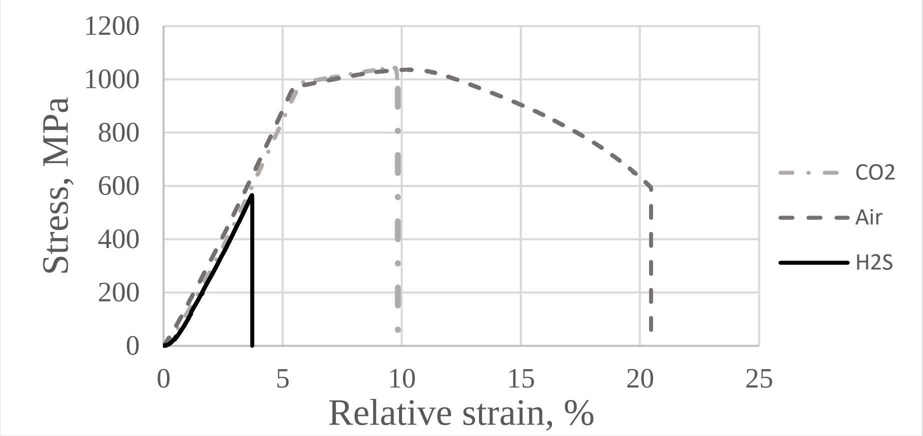

Fig. 4. Tensile stress-strain curves for 34CrMo steel in NaCl solution saturated with H_2S or CO_2 and in the air at room temperature [86]

One of the criteria characterizing the degree of corrosion susceptibility of material in SSRT is the relative strain at which specimen fracture starts in a corrosive environment (ε_{scc}). Another criterion is the stress at which crack propagation starts (σ_{scc}) [23,24]. The stress at which a crack initiates in a corrosive environment is determined from the point where the curves for the inert and the corrosive environment diverge. The ratios of ε_{scc} and σ_{scc} to the relative strain and the fracture stress, obtained during tests in the inert environment, can also be used. If the fracture occurs at stresses less than the yield stress of the material, it is convenient to determine the ratio of the fracture stress in the environment to the fracture stress in the air (or to the yield stress, which is customary for sulfide stress cracking tests under static loading with constant stress or strain applied).

According to [88], the strain criterion, which depends on the environment, temperature, and material properties, can characterize its state under static, quasi-static, and cyclic loading. Compared to the stress criterion, it more adequately reflects the physical nature of the fracture associated with stress corrosion cracking and how it is influenced by external and internal factors; the stress criterion is convenient as a direct characteristic in time-to-failure calculations of products and structures.

Initially, only smooth specimens, generally with circular cross-sections, were used in SSRT-SCC tests. Later tests were carried out with flat specimens, which are more convenient for determining the SCC sensitivity of thin-rolled steel sheets. Notched or fatigue pre-cracked specimens are convenient for testing welded joints with the fusion line metal and the heat-affected zone differing in structure and mechanical properties from the parent metal [90-92]. In such cases, the criterion for the steel's sensitivity to SCC can be the fracture stress in a corrosive environment or the corresponding threshold stress intensity factor. The latter criterion is used to determine the SCC resistance of high-strength low-alloy steels in hydrogen sulfide environments (K_{ISSC}) and is calculated by the formulas given in [92].

The methods aimed at finding the threshold value of K_{ISSC} have evolved over time: many present-day studies substantiate why nonlinear fracture mechanics methods should be applied for low-alloy steels with a yield stress of less than 1000 MPa [92]. Furthermore, the

SSRT method was proved to be effective in sulfide corrosion cracking tests with notched specimens (Fig. 5) [31], providing wider options for finding K_{ISSC} compared to static tests of specimens such as double cantilever beams (Method D NACE TM0177).

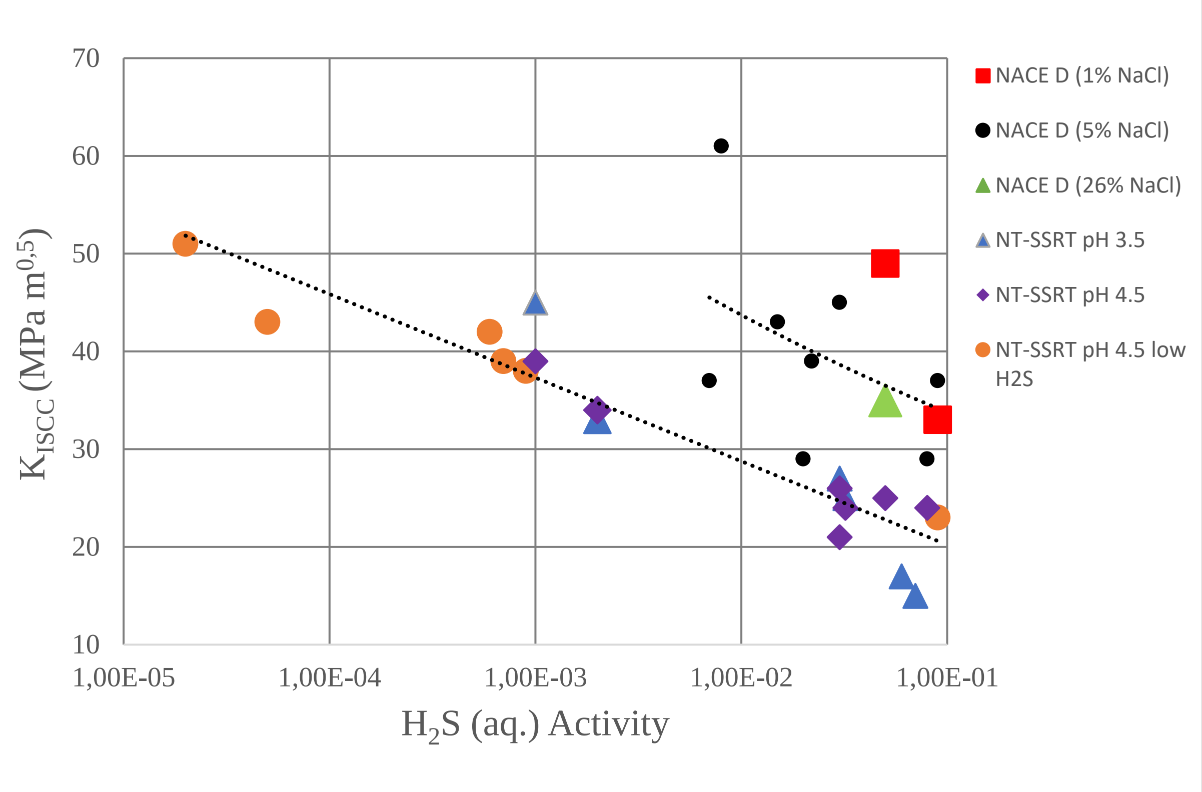

Fig. 5. Influence of hydrogen sulfide activity in sodium chloride solutions of different concentrations on K_{ISSC}, obtained by method D (NACE TM0177 standard) and SSRT for steel C-110 [31]

Apparently, the SSRT method is applicable for any concentration of hydrogen sulfide, yielding more rigorous results with a much smaller scatter.

SSRT allows obtaining results rather quickly, making the method the most convenient for studying the SCC mechanism, especially combined with analysis of fracture behavior in failed specimens and crack propagation trajectory, with simultaneous electrochemical studies. Analysis of the fracture surface of steel P110 after tests in solution A by the NACE TM0177 standard conducted in [93] established that the fracture structure bears a complex character resembling quasi-cleavage when ductile fracture regions alternate with brittle ones [93].

Ref. [62] studied the SCC mechanism in X52 steel by the SSRT method at various solution pH and applied potentials using polarization curves taken at different potential sweep rates. This allowed determining the electrochemical reactions leading to predominant HE or AD or their combined effect, ultimately governing the SCC mechanism [62].

Studies on SCC in low-alloy ferrite-pearlite steels by SSRT with cathodic polarization using metallographic analysis revealed that as the potential shifts to negative values, producing an increase in the hydrogen concentration in the solution, crack initiation and growth starts to be described by transgranular rather than intergranular mechanisms [93].

This paper does not consider the methods for SCC tests of low-alloy steels at high temperatures and pressures in the presence of corrosive gases (such as H_2S and CO_2), which requires separate consideration.

4. Conclusions

We have briefly reviewed the modern notions of the mechanism behind stress corrosion cracking in low-alloy steels, analyzing the methods for testing the tendency to SCC and drawing the following conclusions.

1. SCC in low-alloy steels is a complex multistage process combining electrochemical reactions of metal dissolution and oxidant reduction, diffusive penetration of atomic hydrogen into metal, and its accumulation in the zones with maximum stresses and local plastic strains, favoring the propagation of a corrosion crack.
2. The methods can be divided into several groups depending on the approach to generating the stressed state: constant loading tests; constant strain tests; tests with step loading and constant strain rate.
3. SCC tests with a constant tensile load or constant strain are generally aimed at finding the threshold stresses for which the specimen is not destroyed during the given testing period. While complex equipment is not necessary for such tests, a sufficiently large number of specimens is required.
4. SCC tests of high-strength steels involve fatigue-pre-cracked specimens, determining the threshold stress intensity factor or the J-integral. The main problem with the method is that producing specimens is very resource-consuming; furthermore, there are limitations to testing steels with a yield stress of less than 700 MPa. An accelerated method for SCC testing with a cantilever bend under step loading of cracked specimens is used to simplify the testing procedure and circumvent the limitations on steel strength.
5. The SSRT method is an accelerated type of SCC test, finding wide acceptance as it can greatly shorten the testing times, allowing to find the threshold stresses and strains with a small number of specimens. SSRT is most convenient for studying the SCC mechanism, particularly combined with the analysis of fracture behavior in failed specimens and crack propagation trajectories, with simultaneous electrochemical studies.

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