Rupture and Fracture of Fastener by Embrittlement - Stress Corrosion Cracking (SCC)

by Wei-Ming Wang

1. Introduction

Stress corrosion cracking (SCC) is a fracture process that involves the combined and simultaneous action of a tensile stress and a corrosive environment. SCC occurs when the fastener supporting the tensile stress and a specific environment are able to cause failure by their combined action, but are insufficient to cause failure by either one acting alone. In fact, the tensile stresses are usually below the fastener's yield strength. Furthermore, the metal fastener would suffer only minimal corrosion in the absence of the applied stress.

There are three requirements for SCC to occur, please refer to **Figure 1**.

(1) A susceptible metal.
(2) Tensile stresses applied to the metal.
(3) A specific environment containing an aggressive species that promotes SCC.

The SCC key stages shall have been studied that the fracture mechanism should be similar to hydrogen-induced cracking (HIC) with external corrosion condition introduced. It may exist with or without Internal Hydrogen Embrittlement (IHE). The SCC should only combine with External Hydrogen Embrittlement (EHE) if there is no Internal Hydrogen Embrittlement (IHE). The SCC is often mistaken to be simple Hydrogen Embrittlement caused by the fastener manufacturing process.

The combined action of a tensile stress and a corrosive environment may have been ignored and neglected for the root cause and trigger factor of SCC.

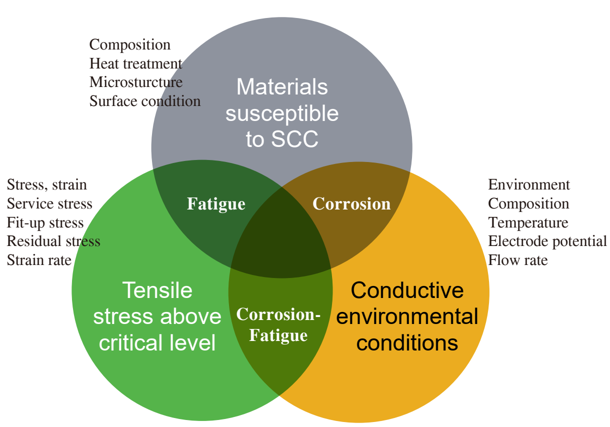


Figure 1. Three Requirements for SCC to Occur

Reference: https://www.ducorr.com/ducorr-blog/2018/5/13/causes-stress-corrosion-cracking-in-pipelines

2. SCC Mechanism

Stress corrosion cracking begins when small cracks develop on the external surface of fastener material. These cracks are not visible initially, but as time passes, these individual cracks may grow and form colonies, and many of them join together to form longer cracks. (See **Figure 2**)

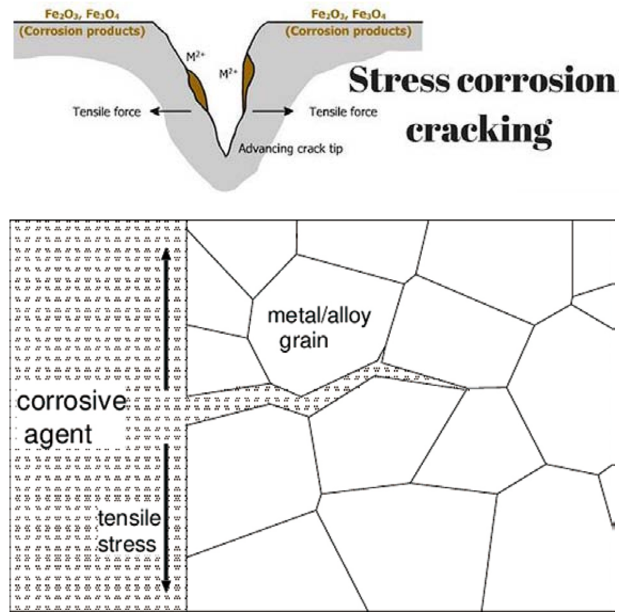


Figure 2. Stress Corrosion Cracking Begins When Small Cracks Develop

Stress plays an important role for crack initiation, growth and coalescence of crack. (See **Figure 3.1**) Corrosion is another important role for crack sources. (See **Figure 3.2**)

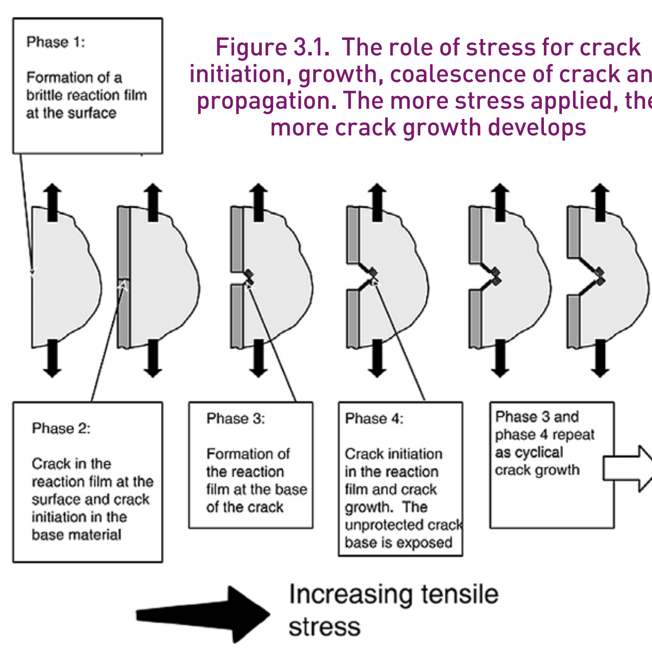


Figure 3.1. The role of stress for crack initiation, growth, coalescence of crack and propagation. The more stress applied, the more crack growth develops

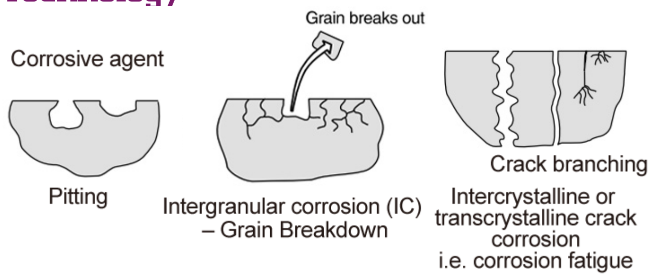


Figure 3.2. The Sources of Crack by Corrosion

The SCC phenomenon has four key stages:
(1) The initiation of stress corrosion cracks. (See **Figure 4**)
(2) The slow growth of cracks. (See **Figure 5**)
(3) The coalescence of cracks. (See **Figure 5**)
(4) Crack propagation (See **Figure 6**) and structural failure then. (See **Figure 7**)

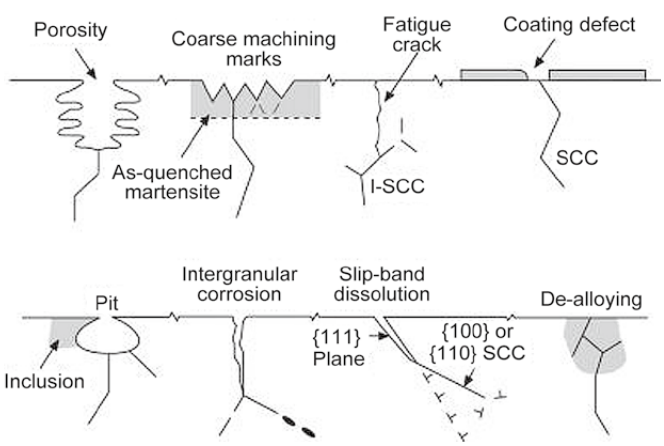


Figure 4. Mechanistic and Fractographic Aspects of Stress-corrosion Cracking Initiation

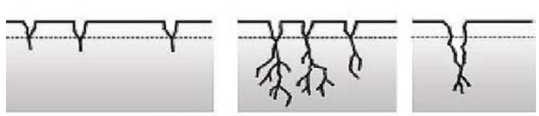


Figure 5. Slow Growth of Cracks and Coalescence of Cracks

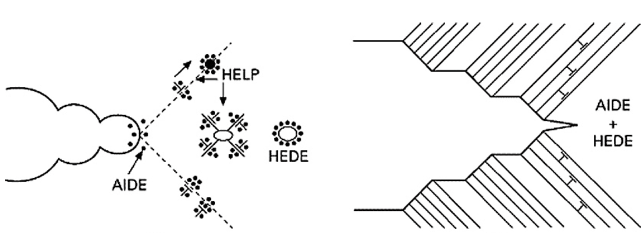
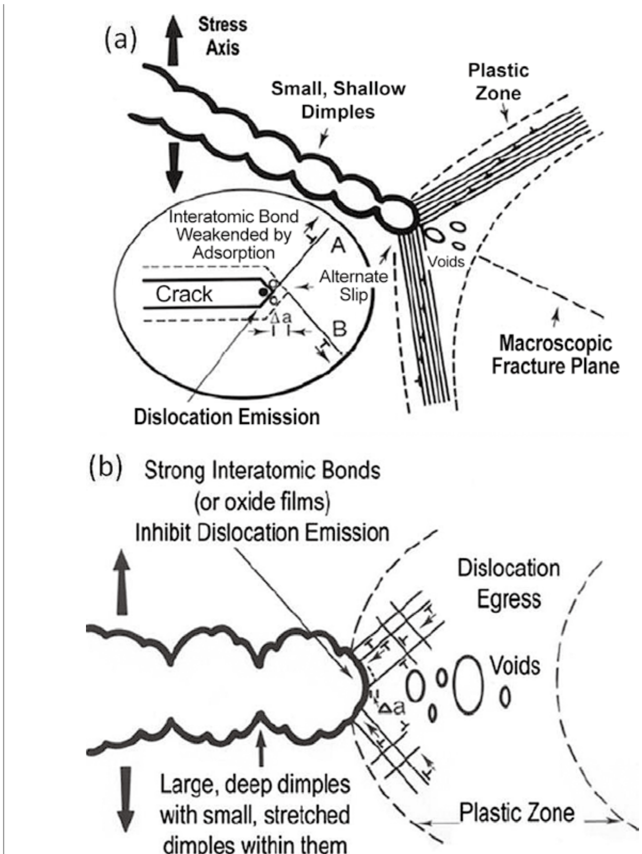


Figure 6. Stress Corrosion Crack Propagation with External Corrosion Environment Introduced

Adsorption-active media could affect deformation and fracture of solids due to decreases in the surface energy. Chemisorption of specific ions, e.g. complex Cu-NH3 ions for SCC of brass fastener or Chloride SCC or Sulphide SCC of Steel fasteners, weakened the strained interatomic bonds at crack tips, promoting crack growth by decohesion along a cleavage plane or a grain boundary. (See **Figure 8**)



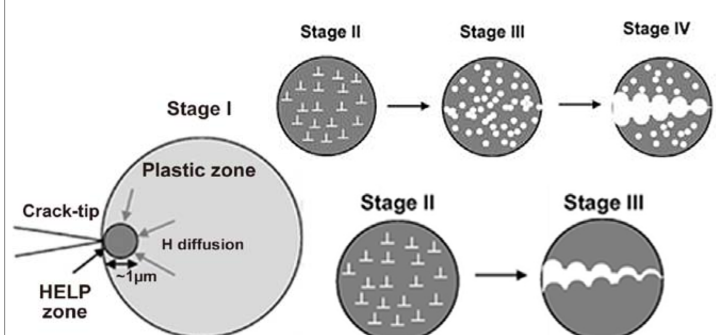


Figure 7. Crack Propagation and Structural Failure

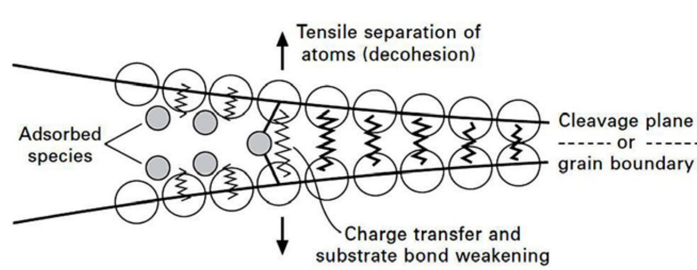


Figure 8. Adsorption-active media weakened the strained interatomic bonds at crack tips, promoting crack growth by decohesion along a cleavage plane or a grain boundary

The SCC four key stages shall have been studied that the fracture mechanism should be similar to hydrogen-induced cracking (HIC) with external corrosion condition introduced. The SCC should focus on the following mechanisms:

- hydrogen-induced decohesion (HID) or hydrogen enhanced decohesion (HEDE); or/and
- hydrogen-enhanced local plasticity (HELP); or/and
- hydrogen-induced phase transformation (HIPT); or/and
- hydrogen-enhanced strain-induced vacancy formation (HESIV).

A brief description of the adsorption-induced dislocation emission (AIDE) and hydrogen enhanced vacancy formation are also included. **Figure 9** shows the adsorption-induced dislocation-emission (AIDE) mechanism for SCC involving coalescence of cracks with nano-voids (or microvoids) in the plastic zone ahead of crack tips that adsorption-active media exists in corrosive agent.

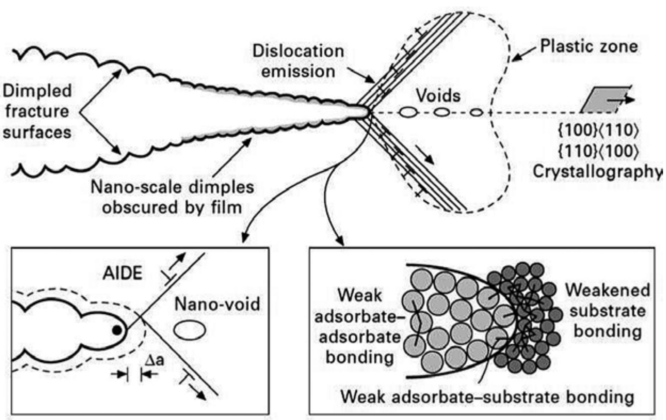


Figure 9. Adsorption-induced dislocation-emission (AIDE) mechanism for SCC involving coalescence of cracks with nano-voids (or microvoids) in the plastic zone ahead of crack tips

Fasteners made of copper alloys which contain oxygen can be embrittled if exposed to hot hydrogen rich atmosphere. The hydrogen diffuses through the copper and reacts with inclusions of Cu2O, forming H2O (water), which then forms pressurized bubbles at the grain boundaries. This process can cause the grains to literally be forced away from each other, and is known as steam embrittlement (because steam is produced, not because exposure to steam causes the problem). It is the typical SCC failure.

For fasteners made of Copper and Copper Alloys, such as brass, it may concern about SCC phenomenon in hydrous or anhydrous ammonia atmosphere. The residual stress of brass fastener should be the key factor of SCC without external serving load or stress. The stresses can be the result of the crevice loads due to stress concentration, or can be caused by the type of assembly or residual stresses itself from fabrication (e.g. cold working); the residual stresses can be relieved by annealing or other surface treatments.

3. Diagnosis of SCC for Fasteners

All threaded fasteners shall be taken the shape and geometry of thread area to be a crack notch or crack tip. It may exist micro-crack(s) within the crack notch or crack tip. (See **Figure 10**) The very useful measurement for diagnosis of fastener's SCC is the direction of the lateral crack and its fracture morphology of fastener. Under a microscope or macro visual measurement, the branched direction of the crack initiation, crack growth, and propagation can be seen and they are practically measured in the form of intercrystalline or transcrystalline corrosion.

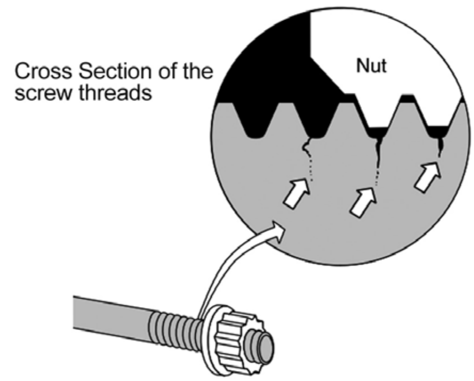


Figure 10. The shape and geometry of thread area should be taken to a crack notch or crack tip. It may exist micro-crack(s) within the crack notch or crack tip. Different cracks initiate at base of threads. The development of cracks depends on the stress differences.

Even in the absence of applied stress, residual stresses in a structure can often be of a sufficiently high sensitivity to cause SCC and failure in service. Stress corrosion cracking is not only highly localized but it can occur in environments that are only mildly corrosive to the fastener material. Stress corrosion cracking presents an especially difficult problem that the damaging concentration of the harmful ions in that corrosive agent or environment may be quite small and difficult to detect. One of the very useful ways for diagnosis of SCC is to measure the direction of the crack. The crack always follows the plane of maximum stress, and therefore, has branches in its form. These branched cracks are often visible without any other assistance. When the crack fracture is viewed under a microscope, the branched direction of the cracks can be seen and they are practically always intergranular or transgranular.

The concentration of stress at the tip of a sharp crack or flaw can be quantified in terms of the Stress Intensity Factor, K1. It determines the growth rate of SCC cracks for a specific alloy–environment combination. The exposure time of corrosion agent needed to cause SCC failure depends on the stress intensity at any pre-existing or developed crack tip. Stress-intensity factor is also called fracture toughness for a loading condition that displaces the crack faces in a direction normal to the crack plane (also known as the opening mode of deformation).

Kc is the symbol for Plane-stress fracture toughness and the value of stress intensity at which crack propagation becomes rapid in sections thinner than those in which plane-strain conditions prevail.

KIC is the symbol for Plane-strain fracture toughness and the minimum value of Kc for any given material and condition, which is attained when rapid crack propagation in the opening mode is governed by plane-strain conditions.

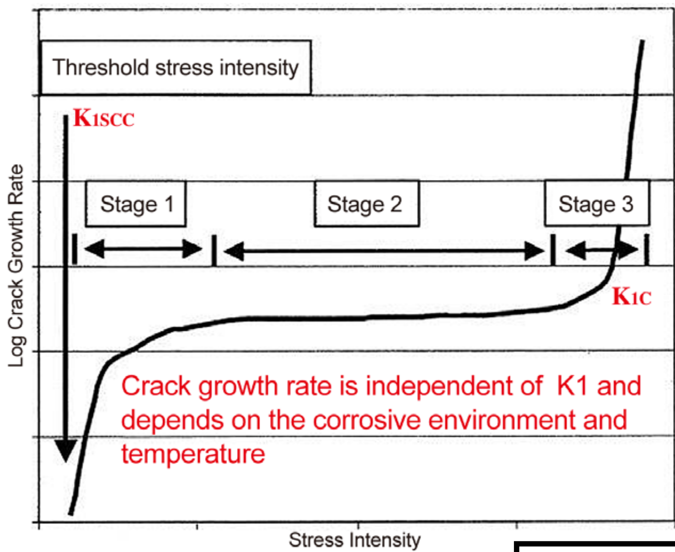


Figure 11. Typical three stages occur for stress corrosion cracking

Most stress corrosion cracking typically occurs in three stages (see **Figure 11**):

Stage 1 - Initiation, below a threshold value of K1, called K1SCC, growth of a crack by SCC is not expected. Above this value, the initial SCC growth rate climbs with increasing K1.

Stage 2 - Steady-state crack propagation, the crack growth rate is independent of K1 and depends instead on the corrosive environment and temperature. During stage 2 growth, K1 continues to increase and this leads to the rapid acceleration of the crack in stage 3, and

stage 3 - Rapid crack propagation or final fracture. final fast fracture when K1 reaches K1C which is the fracture toughness.

The higher the value of K1SCC under given conditions, then the greater the expected SCC resistance.

4. Controlling and Prevention of Stress Corrosion Cracking (SCC)

Underlying causes that trigger SCC, a susceptible material for fasteners, an environment for fastener application intended to use, and stress or stress intensity factor shall be taken into consideration for Controlling and Prevention of Stress Corrosion Cracking (SCC). There are a number of approaches that we can use to prevent SCC or give stress corrosion cracking control strategy. The design stage of fastener will focus on the selection of alloy material of fastener, the limitation of stress and the control of the environment for intended use.

Selection and control of fastener material is the first line of defense in controlling stress corrosion cracking. By choosing a fastener made in appropriate material that is not susceptible to SCC in the service environment, and by processing and fabricating it correctly, subsequent SCC problems can be avoided. The fastener in exact alloy composition, microstructure and heat-treatment can have a marked effect on SCC performance. It is not always simple. Some environments, such as high temperature water, are very aggressive especially where hydrogen embrittlement is involved, and will cause SCC of most steel fastener. A fastener with high strength mechanical property requirements can be very difficult to reconcile with SCC resistance when hydrogen induced cracking is involved.

The presence of stress in the fastener components is one of the factors for stress corrosion cracking to be triggered. One of the approach control methods is to eliminate that stress, or at least reduce it below the threshold stress or threshold fracture toughness value of K1SCC for SCC. Residual stresses is one of the stress sources retained in fastener for use. Residual stresses can be relieved by stress-relief annealing process. It is a proper way to eliminate the residual stress of fastener during working process.

Fasteners of austenitic stainless steels have a very low threshold stress for chloride SCC. Austenitic stainless fastener should be carried out with combined with the high annealing temperatures for stress relief that are necessary to avoid sensitization and sigma phase (σ Phase) embrittlement.

Stresses can also be relieved mechanically. A surface compressive stress are beneficial for the control of SCC. Fasteners should be similarly shot-peening or grit-blasting to introduce a compressive stress on fastener surface for the control of SCC.

The installation tightened force of fasteners shall be the stress source directly. The installation tightened force should be caused by driving torque on fasteners. The deformation effect and cracks shall occur on surface or crack-like thread area when a fastener is driven by over torque. The formation of cracks shall impair the resistance to SCC of fasteners. The suitable applied torque and service stress of fasteners shall be the important key to control the SCC.

Apparently, the most direct way of controlling SCC through control of the environment is to remove or replace the fastener component of the environment that is responsible for the SCC problem. But it is relatively rare for this approach to be applicable. If the active species is present in an environment, it is hard and difficult to remove the active species away. For example, chloride stress corrosion cracking of austenitic stainless steel fastener has been experienced in hot-water or sea-water, we can't easily change the fastener material, environment or the temperature. It cannot remove the chloride from the water by an ion exchange process or other successful proper control and monitoring approach. Adding corrosion inhibitors could be an alternative approach to reduce corrosion rate in order to prevent SCC. Corrosion inhibitors are chemicals that reduce the rate of a corrosive process. Inhibitors may be effective at controlling SCC.

Fastener protective coatings isolate the metal from the environment, and can prevent SCC, too. Zinc coating such as electroplating or galvanizing is a popular coating for carbon steel fasteners. The normal corrosion potential for zinc is relatively low, and if any of the underlying steel is exposed, this will be cathodically protected. But the low electrode potential will also encourage hydrogen evolution, and this may lead to external hydrogen embrittlement (EHE) and trigger the SCC which is shown in **Figure 12**. The single electroplating coating layer may be not sufficient against corrosion agent to fastener body. Fastener's basic coating system exists multi-coating layers should have better Controlling and Prevention of Stress Corrosion Cracking. The multi-coating layers may include sealant/top coat, conversion coating and protective metal coating according to ISO 4042:2018. Appropriate measures for prevention of IHE for quenched and tempered fastener depend on hardness specified in ISO 4042:2018. Since reducing the risk of IHE has been done and multi-coating layers of fasteners to be the corrosion barrier, it is better approach than single coating protection layers for Controlling and Prevention of Stress Corrosion Cracking. To reduce the risk of IHE should be important for fasteners to reduce the risk of embrittlement by Stress Corrosion Cracking. In presence of IHE, it will be complicated and confused to identify the root cause of the stress corrosion crack in order to control and prevent Stress Corrosion Cracking. Thus, the root cause of the stress corrosion crack shall be clearly identified to control and prevent it in absence of IHE. ■

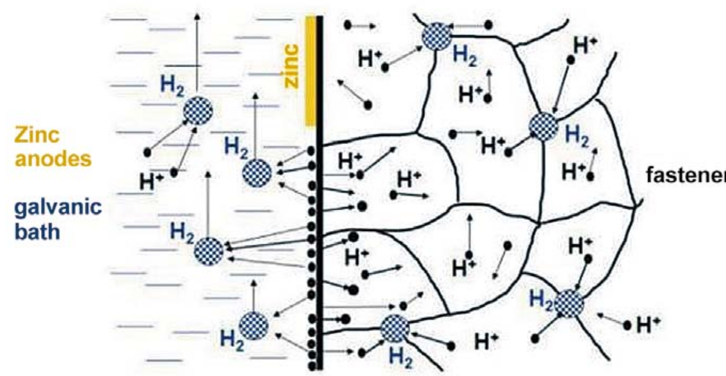


Figure 12.

Reference:

https://www.ducorr.com/ducorr-blog/2018/5/13/causes-stress-corrosion-cracking-in-pipelines

https://www.ducorr.com/ducorr-blog/2018/5/13/causes-stress-corrosion-cracking-in-pipelines,

https://www.researchgate.net/figure/Schematic-depiction-of-intergranular-stress-corrosion-cracking-A-corrosive-agent_fig2_7669934)

https://aeroenginesafety.tugraz.at/doku.php?id=5:54:542:5421:5421

https://www.sciencedirect.com/science/article/pii/B9781845696733500018?via%3Dihub

http://steelalloys.blogspot.com/2006/11/metallic-corrosion-stress-corrosion.html

https://www.sciencedirect.com/science/article/abs/pii/S1359645410007743,

https://www.sciencedirect.com/science/article/pii/B978184569673350002X

https://www.researchgate.net/figure/Figure-2-18-Schematic-diagrams-illustrating-a-the-adsorption-induced-dislocation_fig15_282003599,

https://www.semanticscholar.org/paper/Hydrogen-embrittlement-of-ferritic-steels%3A-on-and-Neeraj-Srinivasan/1a5111fb8b7bc1744238d23dcfe62850f32f0e27/figure/11

https://ashrafi.iut.ac.ir/sites/ashrafi.iut.ac.ir/files//files_course/stress_corrosion_cracking_02.pdf

https://ashrafi.iut.ac.ir/sites/ashrafi.iut.ac.ir/files//files_course/stress_corrosion_cracking_02.pdf

https://www.sciencedirect.com/topics/engineering/stress-corrosion-cracking

https://trends.directindustry.com/bossard-group/project-187952-157973.html