

Review

Effects of Different Parameters on Initiation and Propagation of Stress Corrosion Cracks in Pipeline Steels: A Review

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Abstract: The demand for pipeline steels has increased in the last several decades since they were able to provide an immune and economical way to carry oil and natural gas over long distances. There are two important damage modes in pipeline steels including stress corrosion cracking (SCC) and hydrogen induced cracking (HIC). The SCC cracks are those cracks which are induced due to the combined effects of a corrosive environment and sustained tensile stress. The present review article is an attempt to highlight important factors affecting the SCC in pipeline steels. Based on a literature survey, it is concluded that many factors, such as microstructure of steel, residual stresses, chemical composition of steel, applied load, alternating current (AC) current and texture, and grain boundary character affect the SCC crack initiation and propagation in pipeline steels. It is also found that crystallographic texture plays a key role in crack propagation. Grain boundaries associated with {111}||rolling plane, {110}||rolling plane, coincidence site lattice boundaries and low angle grain boundaries are recognized as crack resistant paths while grains with high angle grain boundaries provide easy path for the SCC intergranular crack propagation. Finally, the SCC resistance in pipeline steels is improved by modifying the microstructure of steel or controlling the texture and grain boundary character.

Keywords: stress corrosion cracking; residual stress; AC current density; crystallographic texture; intergranular and transgranular cracks

1. Introduction

The demand for energy has increased in recent decades which forced the industry to develop high resistance pipeline steels [1–3]. Such steels show better mechanical properties and a higher corrosion resistance compared with normal carbon steels. However, these steels still suffer from two important failure modes including hydrogen induced cracking (HIC) and stress corrosion cracking (SCC) [4–6]. There are numerous studies in the literature focused on these failure modes. The SCC has been recognized as one of the main important failure modes in humid environments and causes a huge amount of economical loss and environmental disasters all around the world. The SCC susceptibility in pipeline steels depends on various factors such as the microstructure of steel, distribution of inclusions and precipitates inside the steel, texture and micro-texture of steel, chemical composition of steel, pH of the oil and gas which is transported, the pH of soil and environment where the pipeline steel is buried, and many other factors. Importance of the SCC in pipeline failure motivated us to write this review paper. This paper concentrates on different factors affecting the SCC crack nucleation and propagation in pipeline steel and looks for new ways to increase the resistance of pipeline steels to the SCC. Tables 1 and 2 show the chemical composition and mechanical properties of common used pipeline steels (API X60, API X65, API X70, API X80 and L360NS).

Table 1. Chemical composition of API X60, X65, X70, X80 and L360NS pipeline steel (wt. %) [7–9].

Pipeline Steel	C	Mn	Si	Nb	Mo	Ti	Cr	Cu	Ni	V
X60	0.052	1.50	0.15	0.067	0.096	0.022	0.07	0.18	0.19	0.001
X65	0.081	1.54	0.33	0.04	-	0.002	-	0.18	-	0.001
X70	0.025	1.65	0.26	0.068	0.175	0.015	0.07	0.21	0.08	0.001
X80	0.056	1.90	0.31	0.046	0.213	0.018	-	0.044	0.221	-
L360NS	0.12	1.50	0.25	-	0.02	-	0.07	0.08	0.04	-

Table 2. Mechanical properties of API X60, X65, X70, X80 and L360NS pipeline steels [8–10].

Pipeline Steel	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
X60	520	610	33
X65	568	650	32
X70	615	720	29
X80	640	780	25
L360NS	380	510	41

The microstructure of API X60 and X70 pipeline steels has been mainly composed of polygonal and acicular ferrite. Moreover, there are some particles of martensite in the microstructure of both steels [7]. The microstructure of X65 steel includes mostly ferrite and some pearlite [10]. When the strength of pipeline steel increases, the microstructure becomes different from other types of steels. For example, the microstructure of X80 and X100 pipeline steels is mainly formed from ferrite and bainite [11,12]. There are also some martensite particles in the microstructure of both X80 and X100 steels. The microstructure of L360NS pipeline steel has been composed of white blocky polygonal ferrite, gray irregular blocky quasi-polygonal ferrite and black blocky pearlite colony [10].

2. Explanation of SCC and HIC

The HIC and the SCC are categorized as two types of corrosion that occur in pipeline steels. Since they have a close correlation, it is necessary to define both. In order to have an accurate definition of the HIC and the SCC, it would be better to explain the corrosion concept. Corrosion is the material degradation due to environmental effects. During the corrosion process, electrons are released due to the metal dissolution at anodic site [13]. Such electrons transfer to the cathode, where oxygenated water is reduced to hydrogel ions. The following overall reactions occur during the metal corrosion.

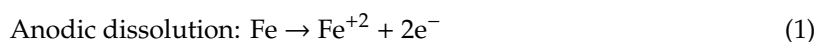
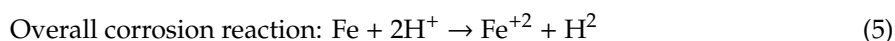
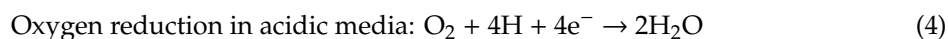
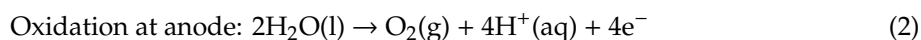


Figure 1 shows how a rust begins with the oxidation of iron to ferrous ions. The rust formation is a very complicated process, which begins with the oxidation of iron.



The SCC cracks are cracks that are induced due to the combined effect of the corrosive environment and sustained tensile stress. The tensile stress can be directly applied inside the pipeline or can be in the form of residual tensile stress. Therefore, three parameters including, a susceptible material (pipeline steel), a specific chemical species (environment), and tensile stress are required for crack nucleation and propagation. Therefore, the SCC is a type of environmentally assisted cracking (EAC), which is of great interest to the oil and gas pipeline manufactures. Recently, thousands of colonies of

the SCC cracks have been observed in pipeline steels. Such cracks usually become dormant at depth of 1 mm. However, sometimes these cracks result in failure of pipeline by crack propagation [14]. Figure 2 shows effective factors influencing SCC crack initiation in pipeline steels.

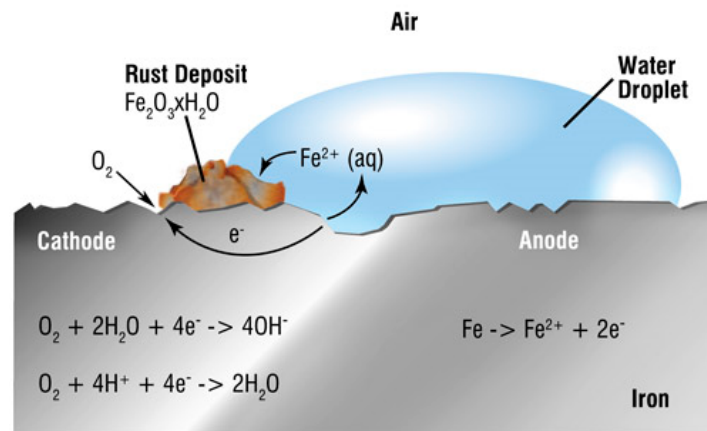


Figure 1. Formation of rust by the oxidation of iron to ferrous ions [13]. Reproduced with permission from [13], Noria Corporation and Machinery Lubrication, 2018.

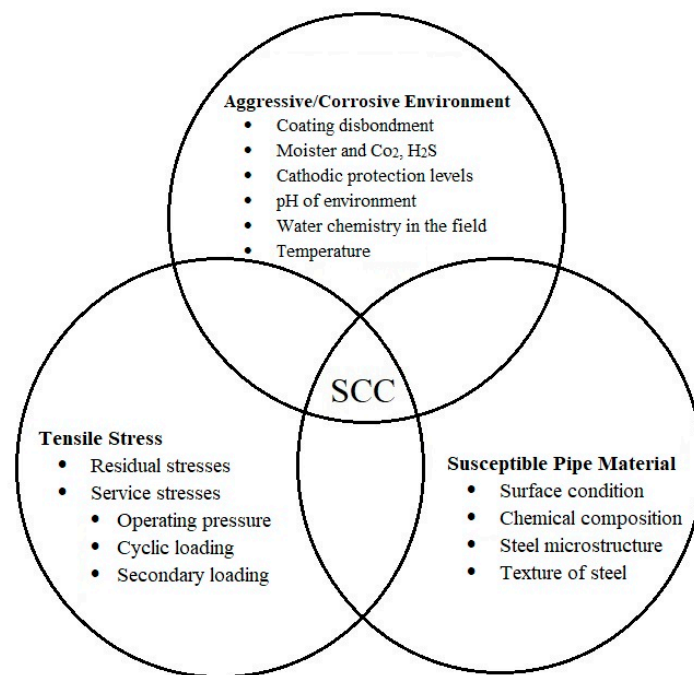
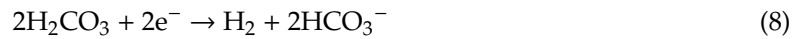


Figure 2. Effective factors for the stress corrosion cracking (SCC) crack initiation in pipeline steels.

Several factors such as microstructure, chemical composition, residual stress, texture of steel, water chemistry in the field, applied stress, pH of environment and AC current density may affect the SCC crack nucleation and propagation in pipeline steels, see Figure 2 [15–20]. Two types of corrosion happen in pipeline steels [21]. The first one is the sweet corrosion, which happens due to the presence of CO_2 . The sweet corrosion [21] in carbon steels is formed in an acidic solution by mixing the CO_2 and water. The corrodant material is H^+ which is derived from H_2CO_3 . The CO_2 gas is entered during some processes such as injection of CO_2 gas into the steel during the recovery operation. The sweet corrosion starts with the reaction of Fe and CO_2 . This reaction can be written as follows:



The reaction between the adsorbed surface complex with water produces Fe^{2+} (aq) and H_2CO_3 . This reaction provides the cathodic reactant H^+ during dissociation. The cathodic reaction can be written as follows:



The dissociation of H_2CO_3 in solution creates hydrogen ion for cathodic reaction.



Several studies have been focused on sweet corrosion [21], however, the mechanism of a cathodic reaction has not been fully understood. It was shown that when a pH value is lower than 4, the hydrogen reduction is the dominant mode for the corrosion. However, when the pH value varies between 4 and 7, the adsorbed H_2CO_3 reduction is considerable. This type of corrosion is called sweet corrosion since it occurs with the absence of hydrogen sulphide or high levels of hydrogen sulphide. Carbon dioxide or carbonic acid are the main causes of sweet corrosion.

The second type and more common type of corrosion occurs owing to the presence of hydrogen sulphide (H_2S). Hydrogen sulphide which is present in oil and natural gas is decomposed to H^+ and HS^- . HS^- ion acts as a hydrogen recombination poison and avoid hydrogen molecule formation [7]. The following reactions occur:



Hydrogen atoms in the forms of protons get electrons from the iron and converted to the hydrogen atoms based on the following equations:



It is worth mentioning that the hydrogen atoms are accumulated at microstructural defects such as empty spaces between inclusions and precipitates and metal matrix. The hydrogen atoms are combined at these regions and create a high amount of pressure. When this pressure reaches a critical value, the cracks initiate. Such cracks are known as hydrogen-induced cracks. The cavities or empty spaces are formed between inclusions and the metal matrix due to the difference between their thermal expansion coefficients. These cavities are formed during solidification of slabs or hot rolling process and can capture hydrogen atoms due to their small sizes. When the hydrogen atoms are accumulated in these areas, they combine to make hydrogen molecules, which make a high amount of pressure. The following equation shows the Gibbs free energy for hydrogen atoms combination.

$$\Delta_r G_H = \Delta_r G_H^\ominus + RT \ln \frac{p_{\text{H}_2}/p^\ominus}{C_H^2} \quad (14)$$

In the above equation, $\Delta_r G_H^\ominus$ is the reaction standard Gibbs free energy, T and R are the reaction temperature and gas constant and C_H and p^\ominus are the concentration of hydrogen atoms near the inclusion and standard atmospheric pressure. When the concentration of H atoms around the inclusions reach a certain value, the reaction will occur and hydrogen molecules are formed. Based on the above equation, the increase of C_H at the reaction interface will decrease the reaction Gibbs free energy and further leads to the production of H_2 molecules. Hydrogen molecule formation creates a high amount of pressure and this results in hydrogen-induced cracks.

3. Role of Microstructure on the SCC Cracks

Microstructure of pipeline steel plays an important role in the SCC crack propagation. In general, hard and brittle phases ease the SCC crack propagation. There are a few papers in the literature focused on the role of microstructure on the SCC crack propagation. Most of the papers have discussed the role of microstructure on the nature of crack. For instance, Zhu et al. [22] investigated the mechanism of failure by the SCC in X80 pipeline steel in high pH carbonate and bicarbonate solution. These authors concluded that the nature of the SCC cracks mainly depends on the microstructure of steel. They observed that when the local microstructure of steel has been formed from bulky polygonal ferrite and granular bainite in a high pH solution, the nature of the crack is intergranular. However, when the local microstructure changes to the fine acicular ferrite and granular bainite, both intergranular and transgranular types of the SCC cracks are observed. Moreover, they implied that the microstructure of steel has a decisive role in transgranular SCC cracking and the probability of transgranular crack propagation increases with a decrease of pH solution. As seen in Figure 3a,b, both types of cracks are seen in the cross section of X80 pipeline steel after slow strain rate tensile (SSRT) test in high pH solution. At the crack initiation stage, the crack type is intergranular; however, both types of cracks are observed at the later stage.

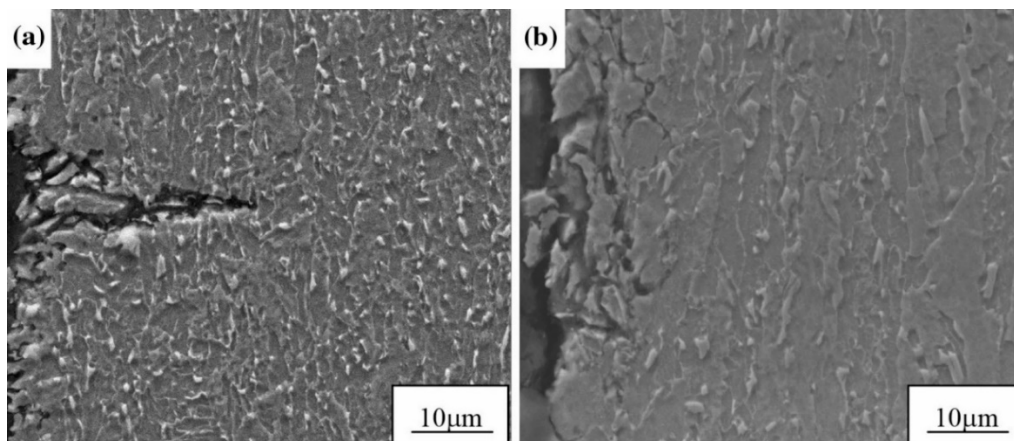


Figure 3. (a,b) SCC cracks in the cross section of X80 pipeline steel after SSRT test in high pH solution [22]. Reproduced with permission from [22], Springer Nature, 2014.

In another study, Gonzalez et al. [23] studied the effects of microstructure on the SCC behavior in HSLA steel. Their results documented that the microstructure of steel play a key role in the SCC behavior. Based on their findings, the type of microstructure is very important in transgranular crack propagation, while other metallurgical parameters including grain size and grain boundary character become determinative factors during intergranular cracking. It has been reported that the SSC susceptibility directly depends on the hardness, microstructure and chemical composition of steel [24]. Typically, the SSC cracks are internally propagated in intergranular manner and show little crack branching; however, some cracks have been also reported in transgranular mode [25]. Roffey et al. [26] investigated the SCC in an austenitic stainless steel hydrocarbon gas pipeline and concluded that transgranular SCC cracks initiate from corrosion pits from the internal and external surfaces and are divided to some branches, see Figure 4a,b.

Elboujdaini et al. [27] carried out research on the role of metallurgical factors on the SCC susceptibility. They found that the SCC cracks usually initiate from corrosion pits and pits nucleate from sulfides. Therefore, sulfide precipitates, inclusions and stringers can affect the SCC susceptibility in pipeline steel. Figure 5a–c shows a SCC crack initiating from a corrosion pit in X65 pipeline steel.

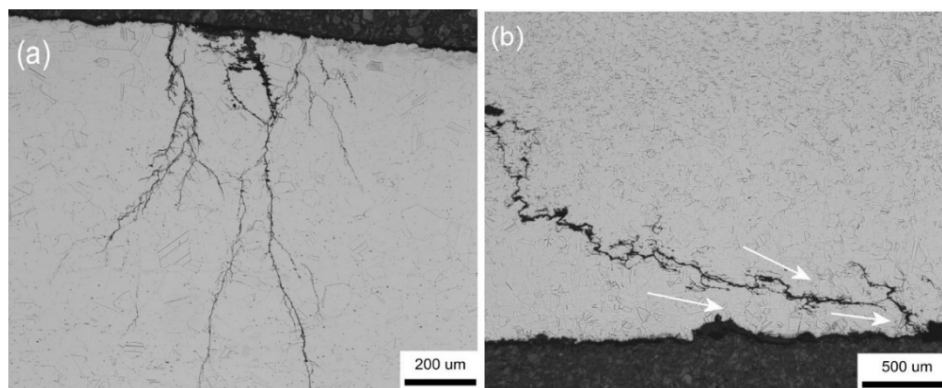


Figure 4. Transgranular type of cracks from corrosion pits on (a) internal surface, and (b) external surface [26]. Reproduced with permission from [26], Elsevier, 2014.

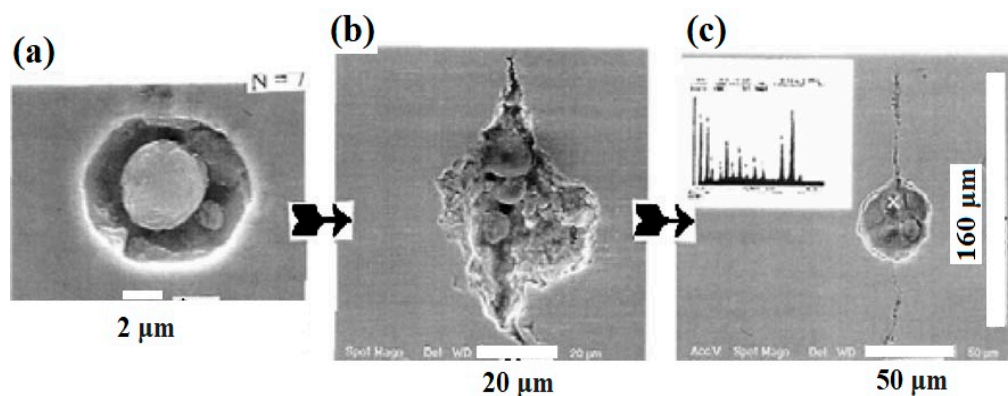


Figure 5. (a) Pit formation from an inclusion in X65 pipeline steel, (b) SCC crack initiation from a pit and (c) EDS analysis on the inclusion showing the existence of Na, Mg, Al, Si, P, S, Cl, K, and Ca elements [27]. Reproduced with permission from [27], Springer Nature, 2009.

4. Role of Stress Intensity Factor (SIF) in SCC and HIC Crack Propagation

SCC crack initiation and propagation in pipeline steel occur in three stages, see Figure 6 [28]. In the first step, small SCC cracks continuously initiate and coalesce. Initiation of these small cracks occurs in a large proportion of lifetime of pipeline steel. In the second step, the initiated small cracks propagate rapidly. This step is characterized by a function of stress intensity factor (SIF). SIF which is used in materials with small scale yielding at a crack tip represents the state of stress near the crack tip. In linear elastic fracture mechanics, it is used to explain the intensification of applied stress at the crack tip and is an important factor in characterizing the driving force and the crack propagation rate [29]. It basically depends on the geometry of the crack, location of the crack and applied load. In the third step, the material fails by rapid crack growth. Crack branching is one of the main characteristics of SCC cracks in pipeline steels. Two types of branching including micro-branching and macro-branching are observed in pipeline steels. In macro-branching, the main crack is divided to two running cracks and crack growth rate is independent from the crack length. The critical SIF for crack branching should exceed $\sqrt{2}$ two times of SIF for the crack propagation. In micro-branching, a main SCC crack splits into several small cracks at intervals of the order of one grain diameter. This phenomenon occurs when the critical SIF reaches at least $\sqrt{2}$ times of the subcritical value of the stress intensity [30]. The lifetime of pipeline steel is clearly determined by the second step. In fatigue corrosion, according to figure below, one process of fast crack propagation in step two is started when the maximum SIF at the crack tip exceeds the threshold SIF for SCC (K_{ISCC}). Another process of fast crack propagation occurs when the maximum stress intensity range (ΔK) exceeds the fatigue threshold (ΔK_{th}).

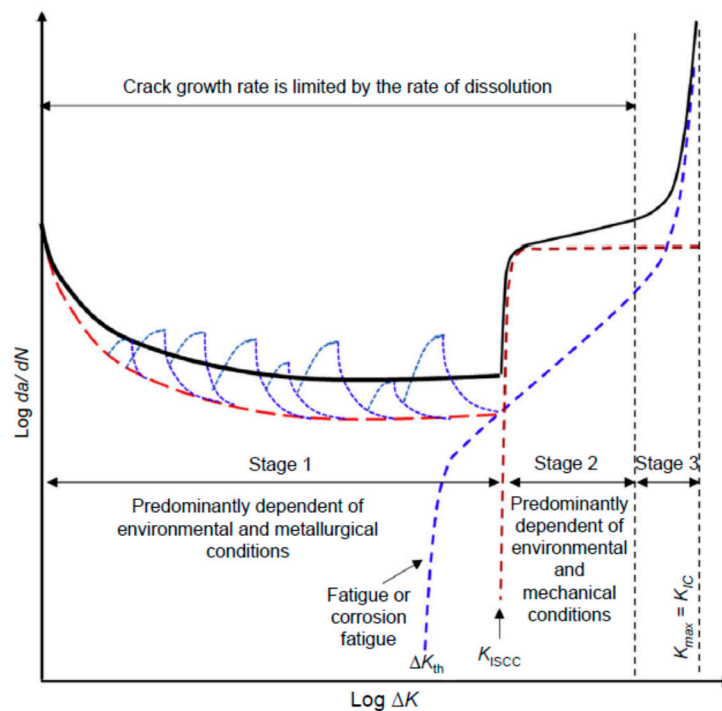


Figure 6. Effect of ΔK upon SCC velocity of pipeline steel exposed to carbonate, bicarbonate solution [28]. Reproduced with permission from [28], Elsevier, 2017.

Besides the SCC phenomenon, the SIF plays a key role in HIC crack propagation in pipeline steels. Costin et al. [31] reported that the threshold SIF (K_{th}) range for crack propagation is between $1.56 \text{ MPa} \sqrt{m}$ and $4.36 \text{ MPa} \sqrt{m}$. This range is lower than the K_{th} value which is calculated for ferrous alloys. This shows that subcritical HIC cracks propagate at micro-scale at lower SIFs.

5. Role of Surface Films in SCC

One of the important factors affecting SCC in pipeline steels is surface films. During the corrosion reaction, metallic iron is oxidized to the Fe^{2+} due to the electrochemical potential. There are some cracks at this oxide layer and at the interface between the oxide and the steel [32]. Figure 7 shows that SCC cracks initiated from the oxide film. The nature of these cracks is from transgranular. When the oxide films are cracked, the SCC cracks penetrated into the steel in transgranular manner. Therefore, two types of SIFs can be considered for SCC cracks in pipeline steels [28]. The first one is related to the external load while the oxide film induces the SIF in the second type. When the critical condition for film-induced SIF, the crack initiation and propagation will occur. The film-induced SIF can be considered as a driving force for SCC crack propagation.

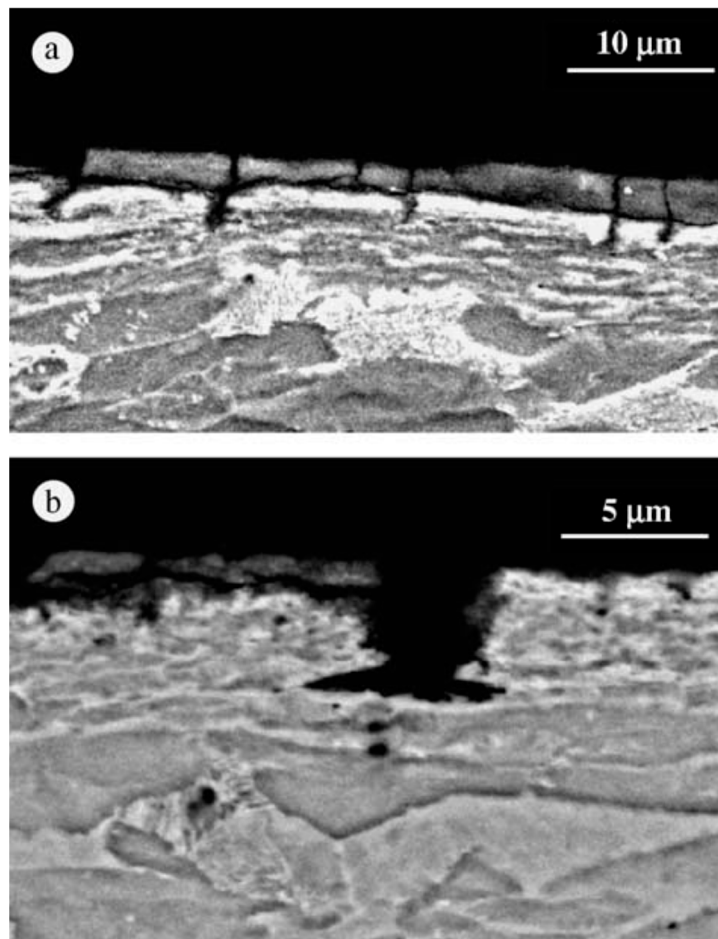


Figure 7. Initiation of transgranular SCC cracks from the surface oxide: (a) region 1, and (b) region 2 [32]. Reproduced with permission from [32], Elsevier, 2003.

6. Effect of Residual Stress on the SCC Crack Propagation

Beside the role of microstructure of pipeline steel on the SCC crack propagation in pipeline steel, the effect of tensile and compressive residual stresses on the SCC crack propagation is undeniable. Residual stresses are mainly developed during the manufacturing of forming and welding process in pipeline steels. Such stresses are high and sometimes reach yield stress of steel. Tensile residual stresses provide a driving for the SCC crack propagation while the compressive residual stresses have an opposite effect. In this field of study, Chen et al. [33] investigated the role of residual stresses on the SCC susceptibility in pipeline steel in neutral pH solution. These authors found that tensile residual stress gives a high amount of mechanical driving force for crack initiation and short crack propagation. These authors also showed that the SCC cracks are blunted by plastic deformation when the crack is propagated in a 45° where the shear stress for the plastic deformation is highest, see Figure 8a,b.

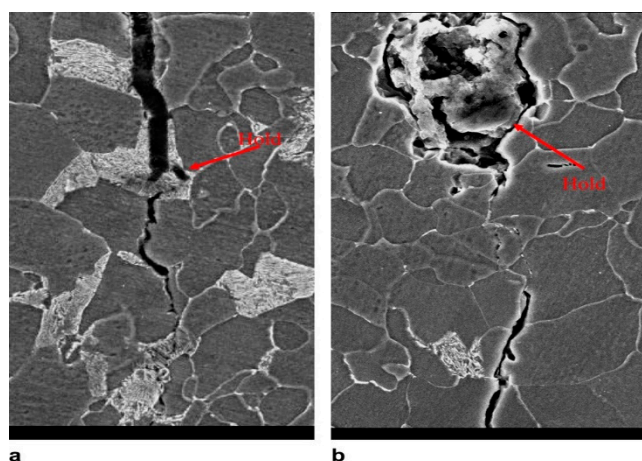


Figure 8. (a,b) Crack tip morphology after the pipeline specimens subjected to constant load for 7 days in different soil solutions [33]. Reproduced with permission from [33], Elsevier, 2007.

7. Role of AC Current on the SCC Susceptibility

Nowadays, pipeline steels are usually buried parallel with the electric power lines or electrified railways due to the limitation space [34]. Therefore, there is a possibility for the flowing of the AC current to the soil encompassed pipeline. Such AC flow results in AC corrosion of a pipeline where the coating is disbonded [35]. There are some investigations showing that AC interference increases the corrosion rate in metal alloys [36–38]. It has also been reported that AC current may break down the insulation layer of pipeline steel and destroy the cathodic protection system [39–41]. Zhu et al. [34] studied the role of AC current on the SCC susceptibility in carbonate/bicarbonate solution in X80 pipeline steel using SSRT experiment. They concluded that AC current plays a significant role on the SCC behavior. They observed that when there is no AC current, the SCC cracks propagate in intergranular manner and its mechanism is from the anodic dissolution. However, with the presence of AC current, the SCC susceptibility is increased and the SCC cracks propagate in transgranular manner at high AC current densities. In another study, Wan et al. [42] investigated the effect of alternating current on the SCC mechanism in X80 pipeline steel in near-neutral solution. The results of their research showed that crack propagation in X80 steel does not depend on the AC current and its mechanism shows a transgranular fracture feature. However, they observed that the depth of crack propagation is enhanced with the increase of AC current. Figure 7 depicts the fracture surfaces of X80 steel after SSRT experiment. As shown in the Figure 9a, there is no crack in the specimen tested in the air. However, there are small cracks in specimens tested in NS₄ solution without AC current indicating SCC susceptibility, as shown in the Figure 9b. NS₄ solution or near-neutral soil solution (pH = 7) is used as a test solution for SCC experiment. It is prepared by mixing distilled water and pure chemical reagent. The chemical composition of NS₄ solution is shown in Table 3.

It is important to note that the number and the length of the secondary cracks increase with the increase of AC current density see the Figure 9c,d. When the AC current density reaches 30 and 50 A/m², as shown in the Figure 9e,f, the secondary cracks become wide signifying an increased SCC susceptibility. As seen in these figures, some cracks nucleated from pitting illustrating that anodic dissolution affected the SCC in X80 steel [42].

Table 3. NS₄ solution composition (g/L) [43].

NS ₄ solution	KCl	NaHCO ₃	CaCl ₂ ·2H ₂ O	MgSO ₄ ·7H ₂ O
-	0.122	0.483	0.181	0.131

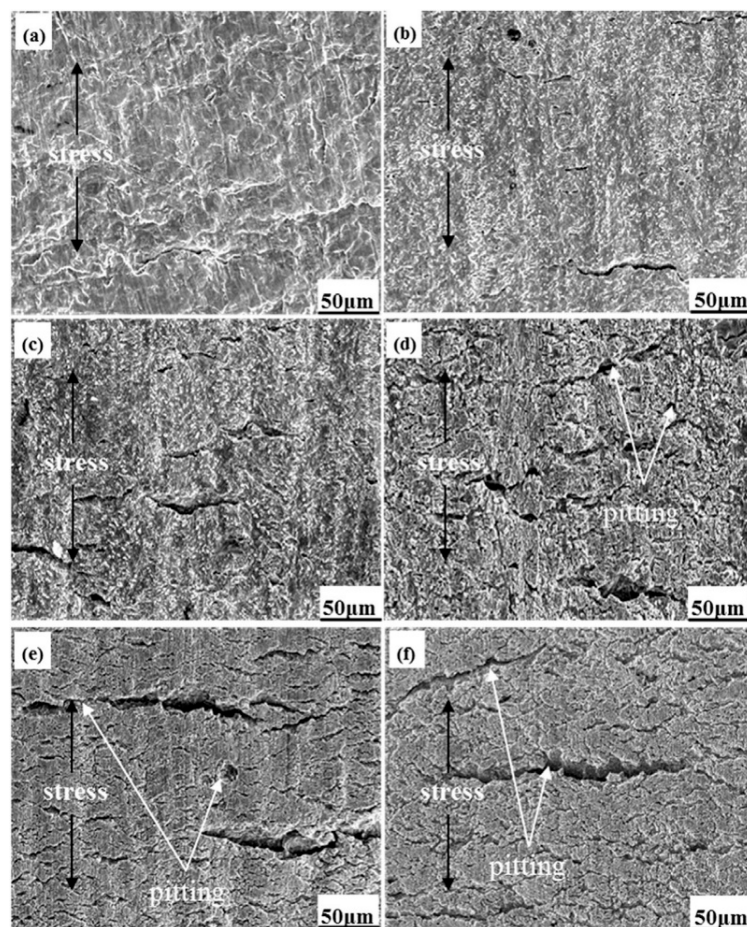


Figure 9. SEM image of fracture surfaces of X80 pipeline steel in air and NS4 solution in (a) in air, (b) 0 A/m², (c) 5 A/m², (d) 10 A/m², (e) 30 A/m² and (f) 50 A/m² [42]. Reproduced with permission from [42], Elsevier, 2017.

It is worth mentioning that the mechanism of AC current on SCC has not been fully understood. However, AC current transfers between pipeline steels and soil when there is a coating defect on pipeline surface and this leads to the AC corrosion [44]. The corrosion potential is negatively shifted by AC current and this phenomenon degrades the steel passivity in carbonate/bicarbonate solution. When the AC current increases, the corrosion type will change from uniform to pitting. Zhu et al. [45] studied the effect of short term AC current on SCC susceptibility in pipeline steel and observed several intergranular SCC cracks and the anodic dissolution of steel was the main mechanism for SCC. They concluded that when the AC current increases, the rate of intergranular crack nucleation from corrosion pits will increase as well.

8. Type of Environment on the SCC Behavior

Pipeline steels are usually used in various environments. For example, API 5L X60, X65 and X70 pipeline steels carry oil and natural gas in sour environments having a high amount of H₂S and CO₂ with low pH value. An acidic environment, containing H₂S, CO₂, and water, promotes corrosion and the H₂S enhances the absorption of hydrogen into the pipeline steel by the corrosion reaction as well. Some types of pipeline steels pass from sea water which has salt. Chloride ions are considered as one of the common atmospheric corrosive agent [46,47]. One of the environments is the deep sea water which applies a hydrostatic pressure to the pipeline steel. Even though there are few papers focused in this field, the deep sea water has a crucial effect on SCC susceptibility in pipeline steel. It has been reported that the SCC in land soil are divided into two types. The first type happens due to the effect

of anodic dissolution in high pH solution among the grain boundaries [11,48,49]. The second one, however, occurs due to the combination effect of anodic dissolution and hydrogen embrittlement in near neutral pH solution [50,51]. In subsea environments, when the coating on the pipeline surface is destroyed, the permeation of seawater in the gaps will promote the peeling of the coating resulting in a complicated and more severe corrosion in pipeline steel [52].

Sun et al. [53] carried out an interesting study on SCC susceptibility in deep and shallow sea water on X70 pipeline steel. They showed that the SCC susceptibility first decreased, reached minimum amount at 15 MPa and then increased with the increase of hydrostatic pressure. In other word, the SCC susceptibility is the lowest at 1500 m deep sea environment; however, it reaches the its highest amount at 3000 m.

Moreover, the electrolyte has a considerable effect on SCC susceptibility in pipeline steels. It has been reported that the electrolyte pH has a key role in determining the nature of SCC crack in pipeline steels [54]. The type of SCC crack is intergranular when concentrated carbonate electrolytes with high pH is present as a composition of environment. It is worth-mentioning that transgranular type of SCC crack occurs in pipeline steels with dilute electrolytes [55]. One should consider that the main components of ground electrolytes contain carbonate/bicarbonate, sulfate, chloride and nitrate anions. Moreover, some soils are acidic with different types of compositions and concentrations. The effect of each on SCC should be considered separately.

One of the factors affecting the SCC susceptibility is the produced hydrogen inside the pipeline steel. The correlation between the hydrogen effect and anodic dissolution has not been completely recognized. However, it appears that hydrogen may have a destructive effect on SCC susceptibility due to the hydrogen embrittlement phenomenon. Lu et al. [56,57] studied the effect of hydrogen on SCC susceptibility and reported that hydrogen restricts pipeline steel dissolution in near-neutral pH water. However, unexpected results were proposed by Liu et al. [58]. These authors investigated the SCC susceptibility in X70 steel under cathodic protection in an acidic and near-neutral solution by using SSRT experiment. The results of their findings proved that hydrogen induced plasticity has a positive impact on SCC susceptibility by releasing the stress concentration at the crack nucleation sites and reducing the stress intensity. However, they reported that in order to postpone the crack initiation and propagation, the applied potential should be within the high SCC susceptibility potential range.

The sulphur element has a key role on SCC susceptibility in pipeline steels. One can consider its effect in two different ways. First, it plays an important role inside the microstructure of steel. It has been reported that the sulfur element has a detrimental effect on HIC susceptibility by creating MnS inclusion [8,59,60]. This type of inclusion usually has an elongated shape and provides regions with high stress concentration. Therefore, this inclusion is considered as the HIC crack initiation site. From the second viewpoint, sulphur element provides a corrosive environment for pipeline steel. Fan et al. [9] investigated the SCC susceptibility in L360NS pipeline steel in sulfur environment and concluded that the existence of sulfur element considerably increases the SCC susceptibility. As shown in Figure 10, these authors modeled the SCC behavior in L360NS pipeline steel in sulfur melting cladding condition and observed that H^+ ion permeates into the substrate in region with high stress concentration. This permeation breaks the corrosion product film and the surface of pipe steel is corroded continuously. The combined effects of corrosion and hydrogen diffusion degrade the mechanical properties of steel and the pipeline steel fractures under the stress.

Moreover, an applied load plays an important role during crack initiation and propagation on the SCC phenomenon. Three types of stress may affect the SCC susceptibility in pipeline steel. The first one is the constant load such as the pressure inside the pipe. The second one is the preload and the last one is the fluctuating loads such as wind or ground movements. Pipe bending or welding process can apply preload as a residual stress in pipeline steel. There is stress fluctuation in pipeline steel and the effect of such stress on crack initiation and propagation should not be neglected. It is reported that the SCC crack propagation near-neutral pH solution does not occur under constant loading and fluctuation loading is required to initiate and propagate the cracks [61–64]. Jia. et al. [65] studied the effect of

constant loading and preloading on the SCC in X80 pipeline steel in near-neutral pH environment. They observed that preload do not change the SCC behavior in X80 steel near-neutral solution. However, the time of crack initiation near-neutral environment under constant load is decreased when preload is applied.

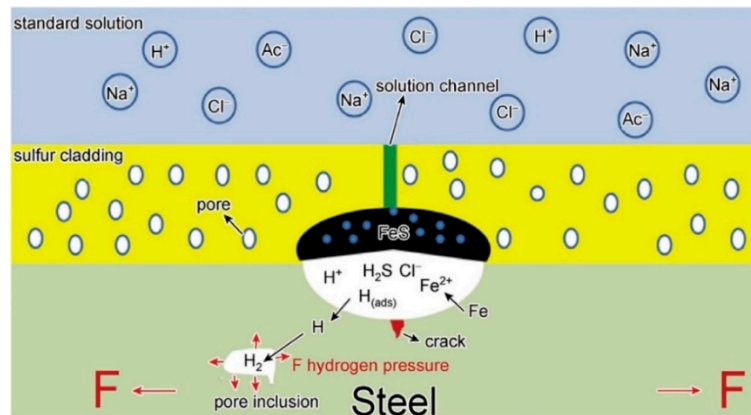


Figure 10. The SCC model for L360NS pipeline steel in sulfur melting cladding condition [9]. Reproduced with permission from [9], Elsevier, 2017.

9. Effect of Different Elements on SCC Susceptibility

There are several studies focused on the effects of different elements on the HIC and the SCC susceptibility in pipeline steel. No doubt, different elements play different roles on the SCC and the HIC susceptibility. The main elements playing a key role on SCC susceptibility are carbon, manganese, and phosphorus elements. These elements are recognized as segregation elements during solidification of steels such as pipeline steels. The mentioned elements are segregated at the center of thickness of pipeline slabs and create some hard phases and structures such as bainite and martensite. It has been reported that the manganese segregation ratio depends on carbon content [66]. It is important to note that low strength carbon steels can tolerate higher phosphorus segregation than high strength alloy steels [67]. Calcium element is usually added to pipeline steel due to its role on controlling the sulphur element [68,69]. Calcium element is combined with the sulphur and makes sulphide based inclusion which has a spherical shape. Therefore, the sulphur element is consumed by combining with the calcium and this phenomenon avoids the formation of more manganese sulphide inclusions. It is notable that manganese sulphide inclusion has an elongated shape and is considered as crack nucleation site [10,70].

It has been reported that copper has a beneficial effect on both increasing the strength of steel and HIC resistance by producing Cu-enriched fine precipitates [71]. Copper also makes a protective layer on the surface of steel and decrease the hydrogen diffusion inside the steel. Baba et al. [72] investigated the effect of copper addition on the prevention of hydrogen permeation in sour environment in pipeline steel. These authors concluded that copper creates an inner layer of corrosion product with 100 nm on the surface of steel preventing hydrogen entry inside the microstructure of steel.

10. Effect of Crystallographic Texture and Meso-Texture on SCC Susceptibility

There are several traditional methods, such as using micro-alloying elements, adding some elements, using some special heat treatments and reducing number of inclusions, to increase the SCC susceptibility in pipeline steels. However, most of such methods are not effective enough to increase the SCC susceptibility. Crystallographic texture has been recently considered as a novel technique which can reduce the SCC susceptibility in pipeline steels. There are a few studies focused on the role of texture on the SCC susceptibility in pipeline steel [60–62]. Arafin et al. [12] investigated the role of grain boundary character and crystallographic texture on the SCC susceptibility in X65 pipeline

steel by electron backscatter diffraction (EBSD) and X-ray texture measurements. Figure 11 shows one SCC crack in X65 pipeline steel. As shown in this figure, the SCC crack gets two branches when it approaches to grains number 7 and 8. It is important to note that the misorientation angle between grains (7, 13) and (7, 10) are higher than 15° falling in the classification of high angle grain boundaries. Therefore, the boundaries between these grains with high energies provide an easy path for crack propagation. As shown with red circle, the SCC crack is deflected about 45° when it reaches grain number 30. Calculation of misorientation between grains number (30, 31) and (31, 32) proves that the misorientation angles between them are 12.3° and 36.1° , respectively. This proves why the SCC crack deflects when it reaches grain number 30. Coincidence site lattice boundaries are categorized as low angle boundaries having a low energy. Therefore, such boundaries are not favorable for the SCC crack propagation. One should expect that the crack follows the grain boundary between grains number 37 and 38; however, the EBSD analysis shows that such boundary is from $\Sigma 11$ type boundary with a low energy. An interesting result was observed when the SCC crack reaches the grain number 39. The grain boundaries between grains number (39, 40), and (40, 41) are from low angle grain boundary (LAGB) and high angle grain boundary (HAGB), respectively. Surprisingly, the SCC crack has propagated through the grain boundary between grains number 39 and 40 which has a low energy. The EBSD analysis indicates that these grains have orientations close to the $\{110\}$ ||rolling plane with $\langle 110 \rangle$ boundary rotation axis. This might be the main reason for resisting of mentioned path for crack propagation.

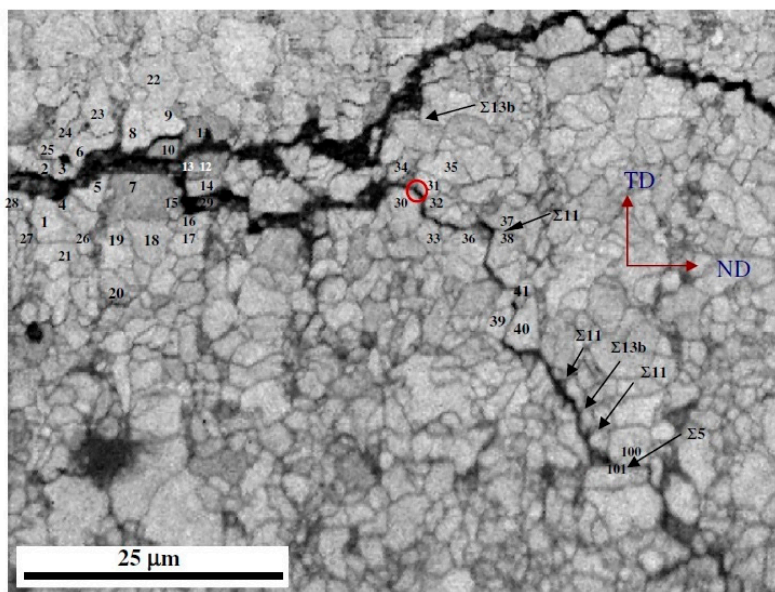


Figure 11. Electron backscatter diffraction (EBSD) map of the SCC crack propagation in X65 pipeline steel [12]. Reproduced with permission from [12], Elsevier, 2009.

The results of Arafin et al. [12] illustrated that the grain boundary character plays an important role in intergranular SCC. They also observed that CSL boundaries beyond the $\Sigma 13b$ do not provide the resistance path for the crack propagation. Finally, they showed that the macro and micro-texture significantly affect the intergranular SCC. It is worth-mentioning that the study of texture on the SCC crack propagation is a novel method and there are a few researches in the literature. Control of texture and grain boundary character may be used to produce new pipeline steels with a higher resistance to the HIC and the SCC in the near future.

11. Improvement of SCC Resistance

There are some methods that can be considered as new ways to improve the pipeline steel performance against SCC cracking. Crystallographic texture and grain boundary engineering have a

key role in increasing the SCC resistance in pipeline steel. Arafin et al. [12] investigated the role of texture on X65 pipeline steel and concluded that a new understanding of texture and grain boundary character will help to produce new pipeline steels with superior intergranular SCC resistance. They concluded that a large amount of CSL boundaries and LAGBs can avoid intergranular SCC crack propagation in pipeline steels. Such boundaries are provided by modifying the surface texture. It has been reported that some phases and microstructures have a better SCC resistance in pipeline steels. Bulger et al. [73] investigated the effect of microstructure in pipeline steels on SCC resistance in near-neutral pH and concluded that there is a possibility to improve the SCC resistance by providing the fine-grained bainite and ferrite microstructure. These authors also documented that the pipeline steels with ferrite and pearlite microstructure have a poor SCC resistance. Moreover, the role of inclusions on SCC crack initiation is considerable. Wang et al. [74] investigated role of inclusions on pitting corrosion and SCC in X70 pipeline steels in near-neutral pH environment. They concluded that oxide and silicon enriched inclusions are considered as SCC micro-crack initiation sites. Based on their observations, most of SCC micro-cracks propagated through ferrite grains in transgranular manner. Therefore, manufacturing a pipeline steel with low number of inclusions or with uniform distribution of inclusions would be desirable for a high SCC resistance in pipeline steels.

12. Conclusions

Based on the above-discussion, several factors playing a significant role on the SCC susceptibility in pipeline steels are as follow:

- (1) Microstructure of steel plays a key role on the SCC crack initiation and propagation. Nature of the SCC cracks, specially transgranular crack propagation, highly depends on the microstructure of steel. Other metallurgical factors including grain size and grain boundaries become determinative factors during intergranular cracking.
- (2) The effect of residual stresses in crack initiation and propagation should not be neglected. Tensile residual stress gives a high amount of mechanical driving force for crack initiation and short crack propagation.
- (3) AC current density may affect the crack propagation by two ways. First, AC current may break down the insulation layer of pipeline steel and destroy the cathodic protection system. Secondly, AC current density affects the nature of the SCC crack. When there is no AC current, the SCC cracks propagate through intergranular manner and its mechanism is the anodic dissolution. However, with the presence of AC current, the SCC susceptibility is increased and the SCC cracks propagate through transgranular manner at high current densities.
- (4) In a subsea environment, the permeation of sea water in the gaps will promote the peeling of the coating resulting in a complicated and more severe corrosion in pipeline steel by destroying the coating of pipeline steel.
- (5) Addition of some elements to the pipeline steel have a substantial effect on the SCC susceptibility. For instance, Carbon, manganese and phosphorus elements are segregated at the center of thickness of pipeline slabs and make some hard phases and structures such as bainite and martensite. Copper also makes a protective layer on the surface of steel and decrease the hydrogen diffusion inside the steel.
- (6) The SCC crack propagation near-neutral pH solution does not occur under constant loading and fluctuation loading is required to initiate and propagate the cracks. The time of crack initiation near-neutral environment under constant loading is decreased when preload is applied.
- (7) Crystallographic texture plays a key role in SCC crack propagation. Grains with $\{111\}$ ||rolling plane and $\{110\}$ ||rolling plane, coincidence site lattice boundaries and low angle grain boundaries are recognized as crack resistant paths while grains with high angle grain boundaries provides easy path for intergranular SCC crack propagation.

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