PRJ, Vol 1, (January 1989) ; P. 4–10, 10 FIGS.

SUSCEPTIBILITY OF WELDING JOINTS TO STRESS CORROSION CRACKING IN AERATED 3.5% NaCl WATER SOLUTION

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قابلية الوصلات الملحومة للتآكل الشرخى بالاجهاد عند تعرضها لمحلول من الماء وكلوريد الصوديوم بتركيز 3,5٪

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لم يتم بوضوح حتى الآن معرفة قابلية الوصلات الملحومه للفولاذ المنخفض الكربون للتآكل الشرخى بالاجهاد حيث يعتبر هذا النوع من الفولاذ عادة غير قابل للتآكل الشرخى . ولكن عدة انهيارات حدثت فى المناطق الملحومه . ويمكن أن يعزى ذلك نتيجة لنمو شروخ طفيفة تكون سببا لانتشار شرخى مفاجىء . تعرض هذه الدراسة نتائج الجزء الأول من الابحاث التى أنجزت على صفائح فولاذية مقطوعة وملحومه بسمك 40 مم تم تعرضها لمحلول من الماء وكلوريد الصوديوم بتركز 3,5٪ . تم وضع العينات المراد تحليلها فى منطقة الانصهار وعلى شكل رقم سبعة وأختبرت بطريقة الكتيفة المعلقة تحت ظروف الدائرة المفتوحة ، هذا وقد لوحظ أن انتشار الشروخ بالتآكل الشرخى بالاجهاد يتغير بوضوح عندما تنتقل الشروخ من منطقة الانصهار والمنطقة المتأثرة بالحرارة الى منطقة الفولاذ الأصيل . وقد وجد أن نسبة قابلية التآكل الشرخى بالاجهاد تساوى 0.72 حيث تنتمى هذه القيمة الى أعلى تصنيف لقابلية التآكل الشرخى بالاجهاد لهذا الفولاذ . ويعتقد هنا أن آلية انتشار الشروخ كان نتيجة مجتمعة بين قصافة الفولاذ بتأثير الهيدروجين بسبب وجود بنية المارتنسايت والبينايت والمسارات النشطة المتواجدة قديما اينما تواجدت بنية المارتنسايت والبينايت .

ABSTRACT

Susceptibility of welding joints of low-carbon steels to stress-corrosion cracking (SCC) is not clearly established. Such steels are generally not susceptible for that type of corrosion, but many failures have been observed in welding zones where subcritical crack growth was suspected to be a cause of catastrophical crack propagation. This work consists of the first set of research results performed on samples cut from welded 40 mm thick steel sheets exposed to a 3.5% NaCl water solution. The specimens with the tip of a V notch placed in a fusion zone were tested by the cantilever beam method in an open circuit condition. The mechanism of SCC susceptibility ratio K_{SCC} / K_C was 0.72. This value belongs to the highest class of susceptibility to SCC. The mechanism of crack propagation is believed to be a mixed mode of "hydrogen induced embrittlement" due to bainitic (or martensitic) structures and "pre-existing active path" where the pearlite and ferrite structures are present.

INTRODUCTION

Stress-corrosion exhibits a very specific mechanism involving a particular environment and tensile stresses applied to the metallic construction. There will be no fracture if only a stress or corrosive environment is present. For a particular environment the stress-corrosion cracking (SCC) will appear if the metallic construction is loaded by sufficiently high tensile stresses. Below some critical stress level, stress-corrosion cracks will not start to grow. Actually, the best measure of the material's sensitivity to stress-corrosion cracking is the ratio K_{ISCC} / K_{IC}. The value of K_{ISCC} represents a maximum of stress of fracture toughness, which can be safely applied to construction in a specific environment without producing a SCC during long periods of time. Usually the standard testing-time is 1000 hours. Although stress-corrosion is not the only type of material degradation but the form of such attacks are always dangerous. A very localized crack is often propagating thoughout

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the cross-section of the construction without alarming marks visible on the metals surface. Such a crack can be initiated on the metallic surface at the tip of a corrosion pit or at any of the sharply ended microdefects.

If applied loads are lower than yield limit but still higher than the critical stress (in terms of K_{ISCC}), the stress-corrosion crack grows slowly until it reaches a critical length and then propagates very fast (catastrophically) throughout the whole cross-section of the construction. Sometimes the period of slow-crack growth is very long. According to (1), a large number of pipe-lines and pressurized installations failed catastrophically only when five or more year of service-time passed. The routine corrosion inspections can hardly discover a stress-corrosion attack, especially if the surface of the steel member is covered by general corrosion products or other types of deposits.

High strength steels consisting of bainite and tempered martensite are generally highly susceptible to stress-corrosion cracking especially if the environment is cathodically promoting evolution of atomic hydrogen at the surface of steel. Therefore, it is believed that hydrogen induced stress-corrosion cracking is the leading mechanism of catastrophical trans-granular fractures of this steel grade. Weldable low-carbon steels are also susceptible to stress-corrosion but in very specific environonments such as highly concentrated caustics (2) and nitrate solutions (3), and anhydrous ammonia (4). The laboratory experiment on welded structures have indicated that the residual stress relief streatments can reduce the susceptibility of such steels to SCC in the above mentioned environments (5). According to the general opinion, weldable low carbon steels are not significantly susceptible to SCC in sea-water or in 3.5% NaCl water solutions. This implies that the rate of the other types of corrosion is higher than the rate of SCC. Such an opinion is based on the results obtained for steel sheets or bars that did not consider the experimental work conducted on welded joints. Internal stresses, segregations and other in homogenities and nonequilibrium structures like martensite and bainite are usually associated with welding joints, strongly promoting SCC in NaCl water solutions with a pH value lower than 7. In modern steel structures welding technology is commonly used. Such welding joints should have similar or better properties than the parent steel to be joined. Of the many failures that have been initiated in the welding areas, some of them had been of a purely mechanical (or metallurgical) origin, but a great many exhibited a typical appearance suggesting that the environment in combination with stresses produced catastrophical crack growth.

Assuming that the engineering calculations and material selection was correct and the safety margin properly applied, the welded construction should be safely used for decades. However, case histories provide many examples of serious failures of welded structures after quite a long period of service-time without characteristic traces of fatigue fracture or general corrosion action. Such long delayed fracture phenomenon should be connected with subcritical crack growth. That crack is nucleating in the areas of weldments characterized by detrimental factors such as mentioned above; chemical and structrual inhomogenities, discontinuities, etc. This is the reason why the results of SCC tests conducted on parent metals are not valid with respect to welding joints. Lack of well elaborated and published data concerning SCC of weldments has been the main reason of the experimental project performed by the Petroleum Research Centre in Tripoli. A part of this project was done with the cooperation of the al Fateh University (6).

MATERIAL

The material tested was a semi-killed steel of a chemical composition typical for SAE 1008 steel grade : 0.10% C max, 0.25 - 0.50% Mn, 0.10% Si max, 0.04% P max, and 0.05% S max. The hot rolled-steel sheet of 40mm thickness had mechanical characteristics as follows : tensile strength Rm = 303.4 MPa, yield strength Re = 168.9 MPa, elongation A5 = 30%, reduction in area Z = 55%, Vickers hardness HV = 170, critical stress-intensity factor (fracture toughness) K_{IC} = 95 − 110 MPam½. Grain-size accroding to ASTM scale was of No.5. The central zone of steel sheet contained a great number of elongated non-metallic inclusions (NMI) and inhomogeneities.

WELDING TECHNOLOGY

The two 40mm thick steel plates of 1000 mm × 1000 mm in size were horizontally welded together, using a manual arc-welding method. The expected heat-affected zone (HAZ) properties did not recommend preheating and postheating treatments. A 60° V- groove was cold machined. For the root-pass, the electrode E - 6018 was selected. For the first and following passes the E- 7018 electrodes have been used. Before welding, the electrodes were dried at an elevated temperature to avoid hydrogen (cold) cracking.

SAMPLING

Figure 1 shows the geometry of specimens cut off the welded steel sheet. They were mechanically grinded applying cooling water and then the mechanical notch of 40° and 5mm in depth was machined. The notch was cut parallel to the welding direction and perpendicularly to the rolling direction of steel sheet. At the notch tip, the narrow 1.5mm in length fissure was cut-in as a place where the stress-corrosion crack

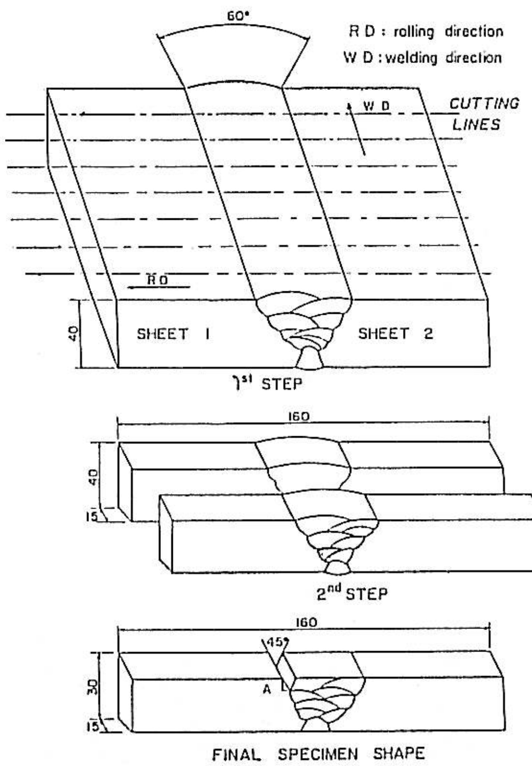

FIG. 1. Sampling and geometry of the specimens.

will nucleate. The welding and sampling processes were made at the Az-Zawiya Refinery.

METHODS

The Cantilever beam method was selected due to its great advantage over the other types of SCC tests that have been used . Such a method provides the following information :

i) Critical stress-intensity factor for SCC (K_{ISCC}),
ii) Stress-corrosion sensitivity ratio (K_{ISCC} / K_{IC}) . If this value is low, the sensitivity of the material to SCC is high .
iii) Time to failure of the steel structure of equal (or smaller) thickness to the tested specimen under known load and environment,
iv) Master-curve of stress-corrosion crack propagation can be derived .

Assuming that SCC are propagating by the brittle or quasi-brittle mode, the Brown's formula (7) for plain-strain conditions will not necessarily be fulfilled . A sketch of the cantilever beam stand is shown in Fig.2. Deflection of the beam was mechanically measured with an accuracy of 0.01 mm. This deflection is proportional to the SCC extension. Initial stress-intensity factor k_{Ii} was calculated according to the formula (8) :

$$K_{Ii} = (4.12\ M\ (\alpha^{-3} - \alpha^{3})^{1/2}) / B\ (W)^{3/2}$$

Where :

$M = Pd + (gd^2) / 2$
d = lever length, (m)
M = momentum, (MN m)
g = (lever weight (MN)) / (lever length (m))

B = specimen thickness, (m)
W = specimen width, (m)
P = Load applied, (MN)
a = crack length, (m)
$a = K_m + K_f$, (m)
K_m = length of mechanical notch, (m)
K_f = length of precrack, (m)
α = geometrical factor

$$\alpha = 1 - (a / W)$$

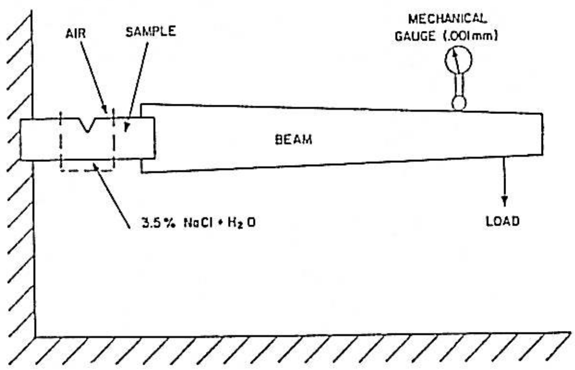

FIG. 2. Scheme of the cantilever beam test.

ENVIRONMENT

An atmosphere containing chloride ions is one of the most corrosive ones. The rate of pittting and general corrosion rate in such an atmosphere (pH below 7) for low-carbon steel is much higher than the rate of SCC. For a fully controlled, standard environment; a 3.5% NaCl water solution is very commonly used, however in some works (9), such a solution should not be considered as a standard one, but none the less a water solution of 3.5% NaCl can represent the atmosphere of marine and coastal areas as well as other environments of ahigh salinity level.

Some works performed on high strength steels gave evidences that the severity of such an enviroment is increased by its aeration (10). Therefore. in this experiment an aerated water solution of 3.5% NaCl has been used. The measured pH was about 6.5 The stress-corrosion cracking was tested in an open-circuit condition. The solution was exchanged for a fresh one every 24 hours.

RESULTS

A photomacrograph of welding joint cross-section is shown in Fig.3. Well done welding passes are visible there. Shaddowed area enveloping the weld-bead consists of a heat-affected zone. The quality of welding workmanship was very good. Elongated macrodiscontinuities due to chemical segregation and a great amount of NMI are expected in the central area of the base steel sheet which is marked by arrows. The presence of such inclusions was confirmed by microobservation of a cross-section taken from the central area of the tested sheet (Fig.4.) These defects vanished close to the fusion zone (FZ). Obviously, the elongated discontinuities should have a great influence on the corrosion crack propagation in the parent steel sheet. This suggestion leads to special attention payed during analysis of the mechanism of SCC propagation in tested specimens.

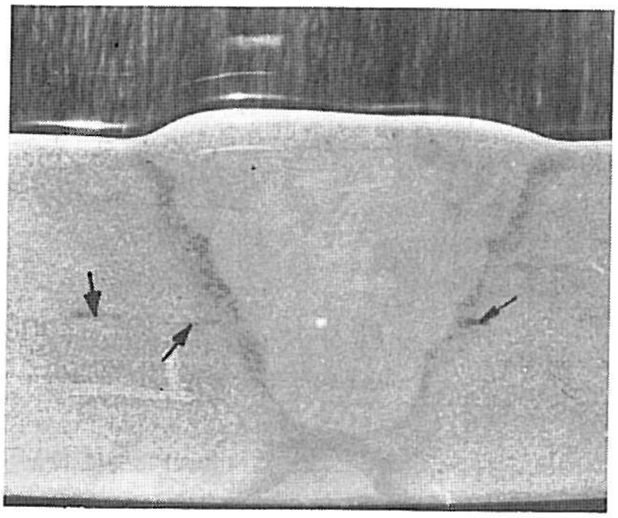

FIG. 3. Macrophotography of welding joint.

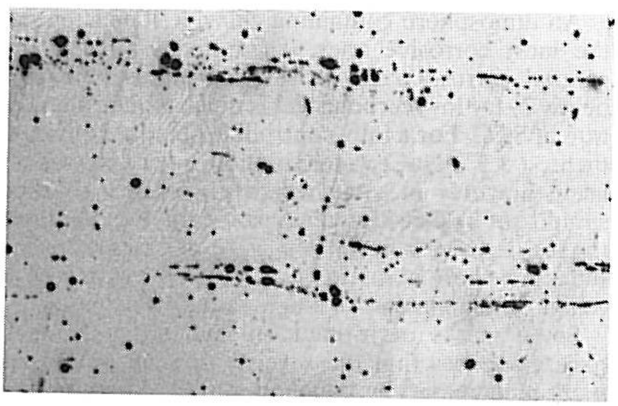

FIG. 4. Non-metallic inclusions in the mid-section of the steel sheet. Non-etched, magnification 100x

Optical microscopic observation revealed different structural constituents present in HAZ and in the parent steel. Figure 5. shows a typical ferrite-pearlite structure in the parent steel. It was possible to find out that the steel sheet was hot-rolled at the temperature well over A_{C3} and then slowly cooled through transition $A_{C3} - A_{C1}$ temperatures that produced the typical widemanstatten structure. HAZ consists of some amount of upper bainite (Fig.6) and ferrite of different shapes and sizes with some pearlitic structure distributed at the ferritic grain-boundaries.

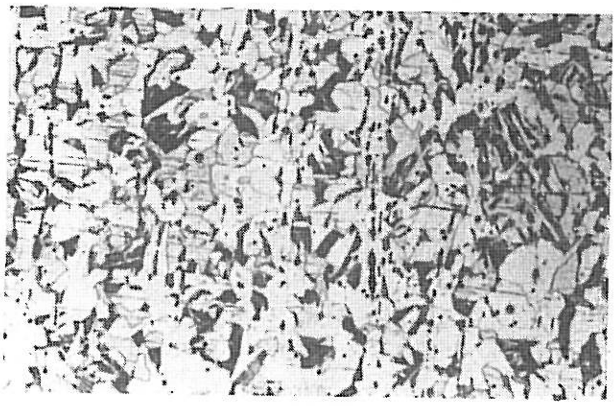

FIG. 5. Ferrite and pearlite structure in the parent steel nital etched, magnification 100x.

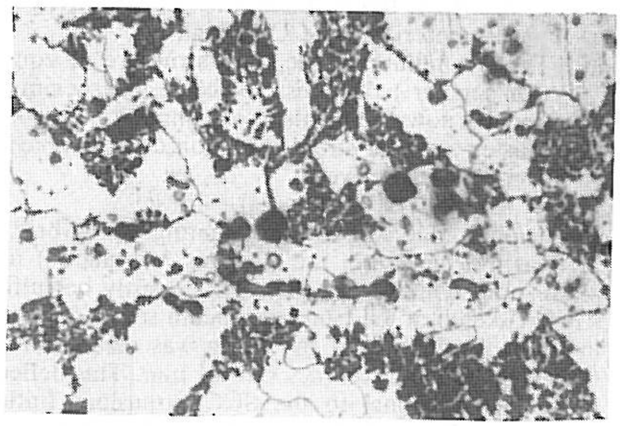

FIG. 6 Ferrite and upper bainite structure with some amount of pearlite in HAZ, nital etched, magnification 250x.

Figure 7 shows a graph of hardness distribution along the three different lines (a,b,c,) passing the weld, HAZ and parent steel. Hardness numbers were higher in HAZ and weld areas than in the parent steel. Some of the higher hardness numbers in parent steel were due to plastic deformation in the notch area produced by mechanical machining as well as by plastic zone developed during the crack propagation. Results of SCC tests are presented in

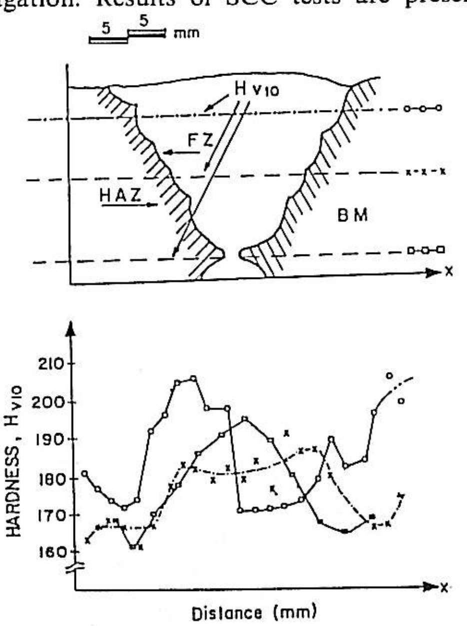

FIG. 7 Distribution of hardness numbers measured along the three lines across the weldbead, HAZ and fusion zone.

Fig. 8. The resultant K_{SCC} value is 68.4 MPa m ½ with an accuracy of ± 3.16 MPa m ½. The sensitivity of the tested joints to SCC (K_{SCC} / K_{IC}) was 0.723 (± 0.03) According to (10) such values belong to the highest class of susceptibility (0.78 – 0.62). It is important to note that K_{SCC} is the resultant value of SCC phenomenon performed in the three zones : fusion zone, HAZ and parent steel sheet. Assuming that low-carbon weldable steels (parent sheet) are not very sensitive to SCC in a 3.5% water solution of NaCl, the decrement of K_{IC} should be due to the stress-corrosion crack propagation in the fusion and heat-affected zones. Existence of such zones with bainitic and martensitic structures decreases the K_{SCC} / K_{IC} ratio proportionally to the fraction of the crack length passing those zones in comparison with the whole path of the SCC. The exact measure of the SCC crack path-length in particular zones gave results as follows : FZ – 4.8mm, HAZ – 2.4mm, parent steel – 5.2mm. Thus, the fraction of stress-corrosion crack propagated in the most sensitive zones (FZ and HAZ) is 0.58. The upper limit of the stress-corrosion sensitivity ratio is 0.95 (The lowest sensitivity of parent steel to SCC). If the whole SCC hypothetically propagated in FZ and HAZ, that expected sensitivity ratio would be 0.56. That is a very high sensitivity of such areas to SCC and any welded structure should be calculated taking into account this value. Microscopic observation revealed that the typical hydrogen induced mixture of trans and intergranular crack-path in FZ and HAZ, changed to a completely intergranular mode in the parent sheet steel where "preexisting active path"

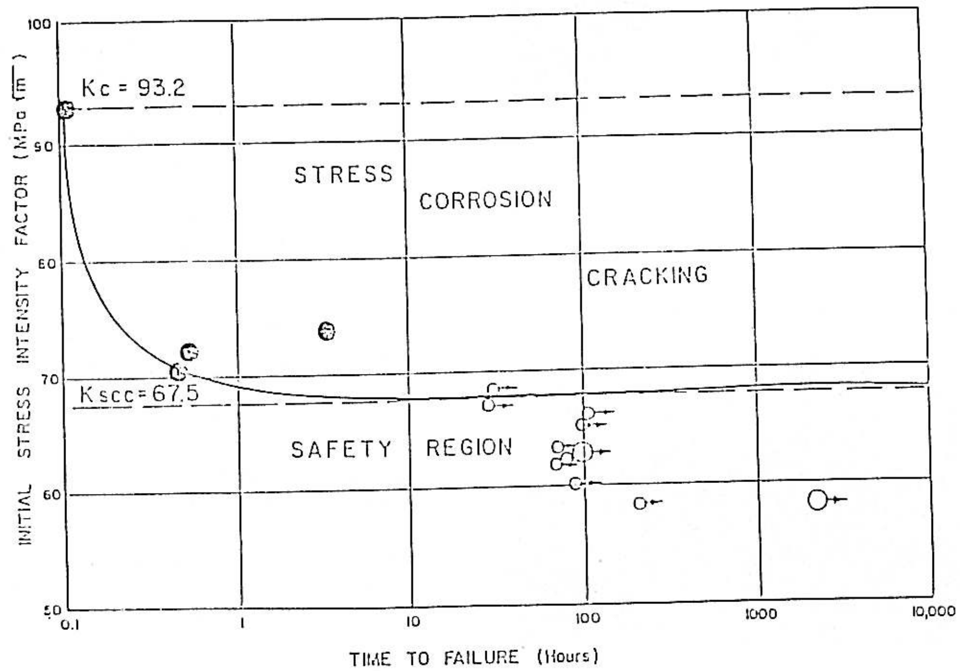

FIG. 8. Results of SCC measurement in form of graph : K_I against time to failure.

mechanism prevailed. As it was mentioned before, the NMI are playing a significant role in SCC propagation. Main crack terminates when meeting a sizable inclusion that sometimes deviates its direction or produces microbranches. Fig. 9 shows a micrograph of an unetched cross-section. The crack started at the point A according to the stress concentration concept (or K_{IC} concept) and stopped at point B where the crack met a segregation area, and started to develop a branch C by electrochemical model of dissolution. That process decreases the rate of crack propagation due to the blunting effects at the crack tip. As the stress concentration at the tip of the branch C decreased, the tensile stress component at point B increased, therefore the mechanical factor prevailed and the higher crack propagation rate in the branch D is observed. In branch D there was a lack of blunting processes. Fig. 10 shows the reaction between a main stress-corrosion crack and the NMI. The non-metallic inclusions usually are cathodic sites and surrounding areas are anodic ones. Therefore the dissolution process is advanced there. This process is strongly time-dependent involving transport phenomenon which needs contact with the environment through very clear visible tunnels.

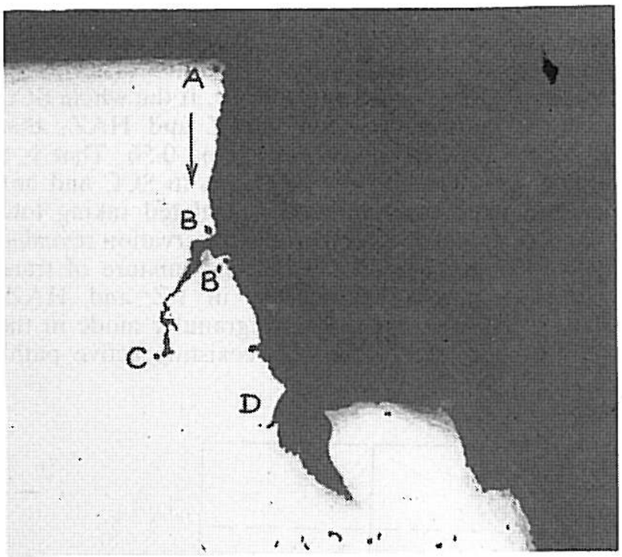

FIG. 9. Stress-corrosion crack passing the segregation area, non-etched, magnification 50x.

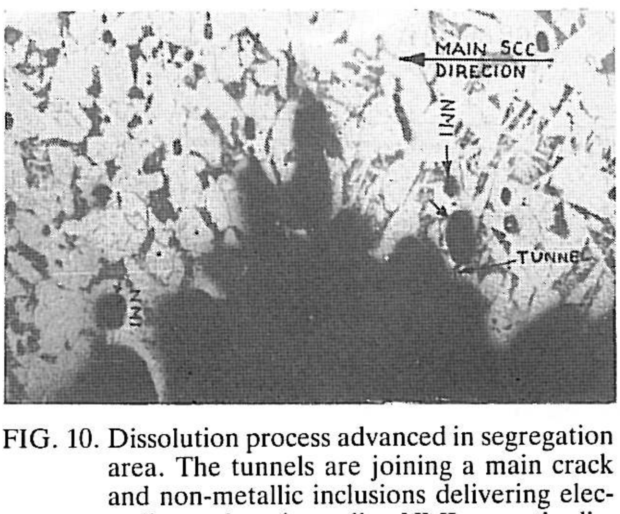

FIG. 10. Dissolution process advanced in segregation area. The tunnels are joining a main crack and non-metallic inclusions delivering electrolite to the microcells : NMI are cathodic, ferrite matrix is anodic. Nital etched, magnification 250x.

DISCUSSION

Many investigations were carried out on SCC of ferrite-pearlite low-strength steels exposed mostly to the environments of high pH values. A number of SCC tests made in NaCl solutions with a pH below 7 or in a marine atmosphere were limited to unnotched specimens. A general conclusion of these last results is that low-strength steels are not sensitive to SCC. It means that corrosion failures happened by the other types of corrosion as for instance pitting, crevice or general corrosion.

If the constructions (structures) made of low-strength weldable steels are considered as consisting of hundreds of welding joints, it is necessary to test such special areas (joints) for their susceptibility to SCC. The reason is that welding joints consist often of different structural constituents in the bead and HAZ (bainite, martensite) which have decidedly higher sensitivity to SCC than parent sheet steel with ferrite-pearlite structures. On top of that, welding joints are characterized by different types of segregation, differences in the grain-sizes, NMI distribution and a high level of internal stress. All these factors tend to accelerate stress-corrosion crack growth. The number of specimens tested by the cantilever beam method in the case of very inhomogeneous samples (weldment case) should be as much as possible. Such a method is a long-term one and for the first part of this project the number of experiments was very restricted just to realize that welding joints are very sensitive to SCC. Steel sheet chosen for welding has been produced from semi-killed grade steel and unfortunately the microstructure includes a large number of NMI concentrated mostly in the mid-section area. The majority of the NMI had an elongated shape due to the directionality of the hot-rolling process.

The trajectory of crack propagating from the mechanical notch was perpendicular to the above mentioned NMI direction Therefore if a stress-corrosion crack met a NMI, the local stress situation abruptly changed due to a) blunting effect which decreases stress concentration there (crack will be arrested), b) simultaneously the electrochemical reactions between NMI (cathode) and surrounded iron matrix (anode) will change the crack fissure, creating an elongated hole. That will additionally decrease the stress concentration at the crack tip. Both effects were observed. Sometimes at the arrested crack, the slow process of "branching" formation was noticed. The next step of crack propagation usually started from the tip of the one branch formed in some area, where due to the segregations, the electrochemical reactions produced a sharp pit. Such a pitend (tip) becomes a stress-riser enabling the crack to propagate again. The front of the crack passing throughout the cross-section does not have a straight line shape but depends upon local properties in the micro-areas of the structure and it changed due to the microstructural and chemical segregations, NMI volume fraction, their shape and distribution. Such structural and chemical segregations are very characteristic for welding joints, and also affects the hardness distribution there. A higher hardness is always associated with HAZ where harder structures are formed (bainite and martensite). There are also higher internal stresses which additionally accelarated the SCC processes. This means that if the crack front has reached HAZ, the SCC process has rapidly accelarated because of mechanical factors. Microscopic observations proved that the leading mechanism of SCC in tested steel is based on "preexisting active path" but hydrogen assisted craking in the HAZ can not be neglected because of the hard structural constituents formed there. In tested specimens, the HAZ was relatively thin and such mechanism had a small share in the total SCC processes in this steel. The specimens did not fulfill the Brown's, formula for plain-strain conditions but according to (10) SCC always produces brittle fracture. The estimated K_{SCC} value is valid for this steel if the thickness of the constructional member is smaller than 15mm. Such a value (K_{SCC}) marked in Fig. 8 should be considered as an obligatory limit for engineering calculations of allowable stresses when the welded constructions will be exposed to NaCl solutions or marine atmosphere.

CONCLUSIONS

Some important conclusions based on experimental and theoretical data are as follows :

1. In spite of the general opinion that low-carbon steels are not significantly susceptible to SCC in water environments containing NaCl with a pH below 7, the presented results show that in welded areas such steels are highly susceptible to this type of corrosion.

2. Susceptibility of welded joints to SCC exposed to aerated 3.5% NaCl water solution is of the range (K_{SCC} / K_{IC}) = 0.72 (± 0.03) which belongs to the class of the high susceptibility (10).

3. The leading mechanism of SCC in welding joints belongs to "preexisting active path" type.

4. The main reason for the high susceptibility of tested weldments to SCC is due to the high level of different inhomogeneities and internal stresses introduced by the welding process. Such high levels of detrimental factors (from a SCC point of view), do not exist in the parent steel per se, and such steel can exhibit low sensitivity to SCC exposed to NaCl solution, but in a welded structure such an opinion is not correct.

5. It is necessary to underline that such important experiments should be repeated for a greater number of welded specimens with different shapes of joints and welding technologies.

6. The projects of salt-water installations, offshore platforms etc, should be checked for allowable stresses which must not exceed K_{ISCC} value for welding joints.

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