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FATIGUE CRACK GROWTH OF A HSLA STEEL IN SEAWATER

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ABSTRACT

The effect of seawater environment on fatigue behavior of a HSLA steel type API 5L X65 commonly used for offshore structures, has been investigated. Tests were carried out in air, in sinthetic seawater and in 3.2% NaCl solution, under conditions of both free corrosion and cathodic protection, with different values of frequency and stress ratio and with both increasing and decreasing values of stress intensity factor range. Conditions for environmental enhancement of crack growth rate, plateau formation, increase in threshold value of stress intensity factor range, etc., have been specified and discussed on the basis of recent models developed for corrosion fatigue.

IN A STRUCTURAL ELEMENT subjected to fluctuating stresses periodically repeated, fatigue cracks may initiate and propagate up to the failure of the same after a sufficient number of fluctuations, even when the stress level is lower than the one which produces the static failure. In the presence of an aggressive environment, the time to failure may become shorter; in fact the combined effect of corrosion and fatigue may be more and more greater than the one resulting from both actions separately considered.

In the case of offshore structures, the sea acts as an aggressive environment and at the same time produces, through the waves, a cyclic load. The main problems appear in the welded joints of the exploration or production platforms and in the sealines.

The exploitation of the first offshore oil wells in the Mexico Gulf, operating since the 1960s, led to the identification of the main causes for platforms failure, viz., the overloads which may occur during particularly violent sea storms on a structure already weakened by generalized corrosion, or simply a too heavy generalized corrosion. Therefore the design philosophy adopted was taking into consideration both the fulfilment of the maximum stress criterion so that the structures might support the maximum load like the one produced by the worst storm (100 year storm), and the application of an adequate cathodic protection against generalized corrosion.

In the 1970s the opening of Alaska and North Sea fields, revealed the appearance within a very short time of serious corrosion fatigue phenomena on structures similar to those already successfully operating in Mexico Gulf. Above phenomena particularly appeared in welded and non-stress relieved joints. The design philosphy was consequently modified considering that the most probable cause of failure is corrosion fatigue after a high number of stress cycles (1,2).

The sealines too, forming free spans on the irregular sea-ground, may be subjected to cyclic stresses due to oscillations caused by the sea currents when they trasversely cross the pipe, under particular conditions of motion and surface roughness of the pipe itself (vortex shedding) (3,4).

The above observations clearly indicate that the possibility of fatigue or corrosion fatigue appearance is always latent and represents the main difficulty and uncertainty for the safe design of the offshore structures.

The purpose of the research reported here, concerned the study of the effect of the seawater presence on the fatigue behavior of a HSLA steel commonly used for offshore structures, by means of methods and techniques peculiar to the linear elastic fracture mechanics. In particular, the effect of said environment on the fatigue crack growth rate under conditions of constant amplitude sinusoidal loading was investigated using precracked specimens.

Table 1 - Chemical Composition and Mechanical Properties of the Control Rolled Steel Type API 5L X65 under Study

C (wt%)	Mn (wt%)	Si (wt%)	P (wt%)	S (wt%)	Al (wt%)	Nb (wt%)	Cu (wt%)	Cr (wt%)	N (wt%)	O (wt%)
0.07	1.57	0.28	0.019	0.011	0.027	0.05	0.012	0.22	0.0086	0.001

Specimen	Yield Strength (0.2% Offset) (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)	Young's Modulus (GPa)	Brinell Hardness Number	Ductile-Brittle Transition Temp. (28J) (°C)
Longitudinal(1)	447	570	31	81	198	180	-80
Circumferential(1)	497	580		72			-60

(1) With respect to the axis of the pipe (rolling direction)

EXPERIMENTAL

The tests were carried out on a control rolled steel, type API 5L X65, commonly used in the offshore environment. The specimens were cut out from a commercial pipe manufactured by means of the UOE process, lenghtwise welded, 508 mm (20 in.) diameter and 20.62 mm wall thickness. The chemical composition of the tested steel is given in Table 1; it is a carbon-manganese steel, microalloyed with niobium. The metallurgical structure consists of ferrite grains and of pearlite nodules arranged in irregular bands. The grains, of different sizes, are lengthened in the rolling direction and have an average size of about 4.8 μm, ASTM index $12_{1.4,1.13}$. The inclusions, often aligned in the rolling direction, are rounded and this suggests that the inclusion shape has been controlled by adding rare earths and/or calcium. Table 1 also gives the values of the mechanical properties determined on the steel.

The constant amplitude tests were carried out by subjecting the specimens to a sinusoidal load with a 10÷20 Hz frequency for fatigue tests in air and with a 0.2 Hz frequency for corrosion fatigue tests. The last value was chosen at first because the effect of the aggressive environment on the fatigue becomes important for frequencies inferior to 1 Hz and secondly because it is typical of the real stress conditions in the offshore environment. The stress (load) ratio $R=\sigma_{min}/\sigma_{max}=P_{min}/P_{max}$ was chosen at 0.1 and 0.6 values. The 0.6 value is typical of conditions where the cyclic stress is added to a high tensile component due to applied constant loads or to residual internal stresses (for example non-relieved welded joints).

The specimens 200 mm by 70 mm by 17 mm Single Edge Notched-Three Point Bending type (SEN B3), were cut out with the length parallel to the pipe axis (L-C crack plain orientation, see ASTM E 616-82). They were fatigue precracked in order to obtain a crack of at least 3 mm length on both side surfaces of the specimen, with a 2 mm maximum difference. During precracking maximum load conditions lower or equal to those employed at the beginning of each fatigue test were adopted in order to avoid retardation effects in the crack growth, due to excessive plasticization at the tip of the crack. For tests carried out in water solution without cathodic protection, the specimens were covered by an acrilic paint with the exception of the crack growth area, thus reducing the total amount of corrosion products and the solution pollution.

For corrosion fatigue tests, a perspex and nylon cylindrical cell (20 l capacity) was prepared and connected to a solution recycling and filtering circuit (about 100 l/h flow rate). Two different solutions were used, both at 8.2 pH value:

- synthetic seawater (ASTM D 1141-75);
- 3.2% NaCl aqueous solution (said percentage equals the chlorides concentration of the synthetic seawater).

The free corrosion potential of the steel without cathodic protection remained within the range of -680 to -720 mV versus the Saturated Calomel Electrode (SCE). The cathodic protection was realized with sacrificial anodes in commercial zinc; by means of a variable resistance arranged between the anodes and the specimen, the potential value was regulated between -900 and -920 mV, that is at light overprotection values often verified on the protected offshore structures.

The crack length was determined by means of the method based on the measurement of the specimen compliance, defined as $\Delta v/\Delta P$, where Δv and ΔP are respectively the crack mouth opening displacement range $(v_{max}-v_{min})$ and the load range $(P_{max}-P_{min})$ during a load cycle. The crack length (a) is deduced from the compliance automatic measurement by means of the calibration relation hereunder given and obtained through specific fatigue tests (5):

$$a = 69.46-3.747(\Delta v/\Delta P)^{-1/2}+0.07113(\Delta v/\Delta P)^{-1}-$$
$$-0.0003379(\Delta v/\Delta P)^{-3/2}$$

where a is in mm and the compliance in mm/kN.

The fatigue and corrosion fatigue tests were carried out with both increasing and decreasing ΔK values of the stress intensity factor range $(K_{max}-K_{min})$. In the first case, after having chosen the initial ΔK value and consequently the ΔP value (which remains constant during the test), the ΔK progressively increases due to the crack growth, up to the failure of the specimen. On the contrary, during a test with decreasing ΔK values, the imposed progressive ΔP decrease is such to overcome the effect of the crack length increase. The test with decreasing ΔK values were carried out under strain control with constant Δv value, imposed by the testing machine; consequently, with the growth of the crack, the load acting on the specimen decreased (the average value of the crack mouth opening displacement was periodically modified in order to restore the stress ratio initial conditions). After having got a sufficiently low crack growth rate, the tests with decreasing ΔK values were stopped and by maintaining the same load values of the terminal cycle, new tests under load control with constant ΔP value were carried out, thus obtaining tests with increasing ΔK values (5).

The crack growth rate (da/dN) and the stress intensity factor range (ΔK) data were deduced processing the crack length (a) data and the corresponding number of elapsed cycles (N) obtained during the tests. ΔK was calculated as a function of the crack length according to ASTM E 399-83. The crack growth rate and the crack length used to calculate the ΔK associated with this crack growth rate were obtained from the a and N experimental data through reduction by the Seven Point Incremental Second Order Polynomial technique, recommended in ASTM E 647-83.

The da/dN vs ΔK curves obtained with both increasing and decreasing ΔK values exactly overlap, thus proving that the load has been decreased gradually, without inducing retardation effects.

RESULTS AND DISCUSSION

Figure 1 shows the da/dN vs ΔK curves obtained in air and in synthetic seawater under free corrosion or cathodic protection conditions.

The results of fatigue tests in air fall on a typical curve divisible in three pieces. The intermediate piece, in double logarithmic scale, is interpolable by a straight line (Paris law, see Table 2). At higher ΔK values, when K_{max} is approaching the critical value for crack instability (K_c), there is a sharp increase in the crack growth rate due to the appearance of extensive phenomena of static fracture together with the ones of cyclic fracture associated with fatigue, as pointed out by SEM fractographic

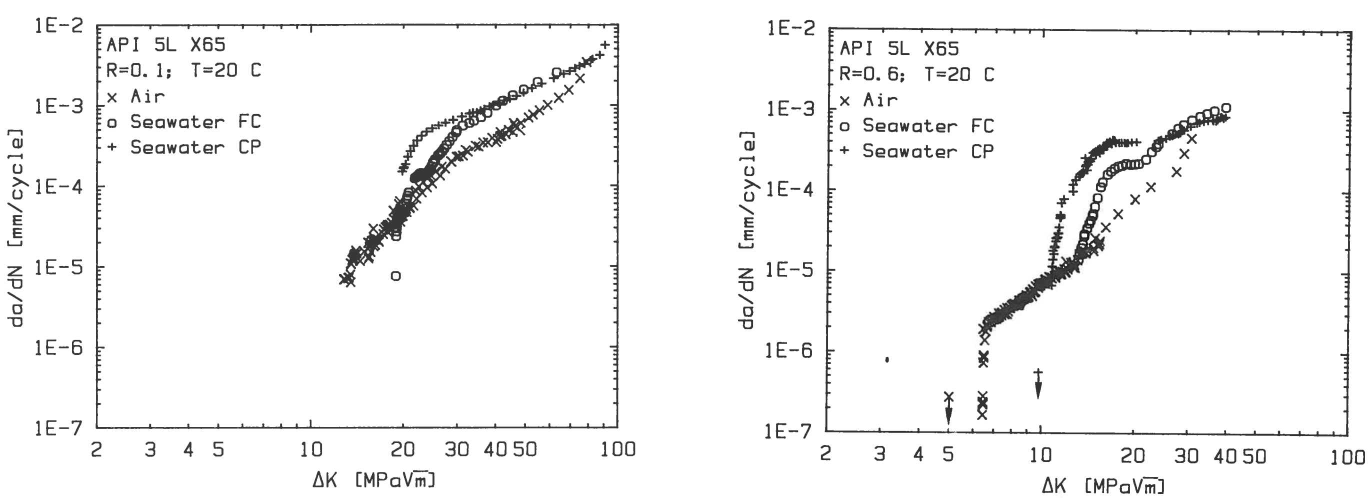

Fig. 1 - da/dN vs ΔK curves for the tested steel in air and in synthetic seawater under different conditions. FC = Free Corrosion. CP = Cathodic Protection at -900 mV vs SCE

Table 2 - Results of Fatigue Tests in Air: Paris Law for the Steel under Study $da/dN = C\Delta K^n$ (1)

R	ΔK	C	n
0.1	13÷33	3.2 E-9	3.2
0.6	7÷30	6.52 E-9	3.0
0.1&0.6	7÷60	7.95 E-9	2.9

(1) Where a is in mm and ΔK in $MPa\sqrt{m}$

examination. At low ΔK values, on the contrary, there is a sharp decrease in the crack growth rate when approaching the threshold ΔK_{th} value under which no fatigue phenomena appear. During the tests with $R=0.6$, crack growth rates as low as 2×10^{-7} mm/cycle were reached in correspondence with a ΔK value equal to 6.4 $MPa\sqrt{m}$, which can reasonably be taken as ΔK_{th} value in air for the tested steel. In confirmation of this, during a test at $\Delta K=5$ $MPa\sqrt{m}$, no growth after 3.7×10^{6} cycles was observed.

The R effect at intermediate ΔK values is negligible in air and the curves at R=0.1 and $R=0.6$ partially overlap; the critical conditions are however reached at different ΔK values when K_{max} exceeds K_c and consequently ΔK exceeds K_c (1-R). The Paris law coefficients at $R=0.1$ have values similar to those at R=0.6 (Table 2); however the results of tests at $R=0.1$ better fall on a piecewise-linear curve. (The change in slope appears in correspondence of the passing from plane strain conditions to plane stress ones at the tip of the crack, due to the unsufficient thickness of the specimen; this effect however has not been observed during the R=0.6 tests). As a whole, the linear pieces relative to all the tests (both at $R=0.1$ and at R=0.6) can be disposed, with a good approximation, on a straight line of $C=7.95\times10^{-9}$ and $n=2.9$ coefficients (Table 2).

The presence of the aggressive environment during the fatigue tests leads to an alteration of the da/dN vs ΔK curve (Figure 1). At intermediate ΔK values there is a considerable increase in the crack growth rate and the formation of a plateau; both phenomena are particularly evident under cathodic protection conditions. The presence of an aggressive environment has on the contrary a negligible effect when approaching the crack instability critical conditions where the mechanical factors prevail; so the fatigue and corrosion fatigue curves tend to come closer together. As far as low ΔK values, a test in synthetic seawater under cathodic protection was carried out at $\Delta K=9.8$ $MPa\sqrt{m}$ and R=0.6; no crack propagation occurred after 174,000 cycles. By supposing a minimum detectability limit of crack extension equal to 0.1 mm, that corresponds to a crack growth rate inferior to 5.7×10^{-7} mm/cycle; this value is clearly lower than the crack growth rate in air under the same load conditions. This confirms the hypothesis (not shared by everybody) that there is a ΔK_{th} increase when passing from the air to the synthetic seawater, at least under cathodic protection.

In synthetic seawater the crack growth rate increases when passing from $R=0.1$ to R=0.6 (Figure 1). The accelerating effect of the aggressive environment on the fatigue phenomena results to be more evident at high R values; in fact it appears at lower ΔK values when increasing R. The R effect on the corrosion fatigue decreases when ΔK increases, as the aggressive environment influence is decreasing in comparison with fatigue. Under cathodic protection conditions, the plateau rate does not seem to change when passing from R=0.1 to R=0.6, but plateau forms at lower ΔK values.

The fracture surfaces examination shows that the crack growth in air is of transgranular type and occurs along planes joined by tear ridges. Ductile tearing is mainly present at high ΔK values where, close to the critical conditions for crack instability, also splits and dimples appear. The presence of the aggressive environment during the fatigue test leads to the appearance of transgranular brittle zones (looking similar to the quasi-cleavage fracture) which are separated by ductile tearing and where fatigue striations are sometimes visible. The cathodic protection leads to an increasing extension of such brittle zones. As far as specimens subjected to cathodic protection, the EDS (Energy Dispersive Spectrometry) analysis of the deposits on the fracture surface pointed out the presence of calcium due to the carbonates precipitation even inside the crack and not only on the outside surface of the specimen.

The results of tests in 3.2% NaCl aqueous solution are shown in Figure 2. These tests were carried out in order to estimate the effect of carbonates, by comparison with the corresponding tests in synthetic seawater.

The experimental results reported and shortly discussed, can be explained as follows.

As far as the tested steel and more generally the low-alloy carbon steels, the increase in the crack growth rate at intermediate ΔK values in the presence of synthetic seawater, seems to be due to the occurrence of hydrogen embrittlement phenomena localized at the tip of the crack (6-10). This is confirmed by both the morphology of the fracture surfaces and the detrimental effect of the potential decrease

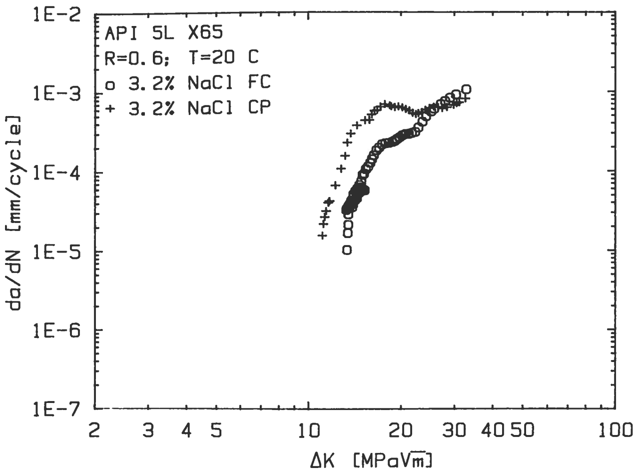

Fig. 2 - da/dN vs ΔK curves for the tested steel in 3.2% NaCl aqueous solution under different conditions. FC = Free Corrosion. CP = Cathodic Protection at -900 mv vs SCE

when passing from free corrosion to cathodic protection conditions.

During a load cycle, owing to the stress, an active surface forms at the tip of the crack in contact with the aggressive environment inside the crack itself. Mechanically, the crack progresses in every cycle by alternating slip accompanied by plastic deformation, so as to create a striation effect. Electrochemically, the presence of such an active surface leads to the anodic dissolution of iron and to the complementary cathodic reaction with the formation of atomic hydrogen. The first reaction blunts the tip of the crack and consequently reduces the growth rate, because the effective stress intensity factor results to be lower than the nominal one (6). The second reaction, owing to the diffusion process of the hydrogen atoms also supported by the dislocations movement, embrittles the zone adjacent the tip of the crack, where high internal stresses are present; this leads to microcrack formation and to the presence of a brittle striation on the fracture surface.

The microcrack nucleation depends on the hydrogen concentration and on the stress level; the higher are said variables, the shorter is the nucleation. The brittle zone extent is given by the distance to which the critical hydrogen concentration in the material in still reached, dependently on the hydrogen amount and on the time available for the diffusion process (said time being connected with the cyclic loading frequency). Thus, the crack growth rate is not depending on the ΔK and this explains the plateau formation. The lower is the frequency, the higher is the hydrogen penetration distance, since the time available for the diffusion increases; the growth rate corresponding with the plateau is higher, according to several experimental results (3,9). The crack growth rate due to hydrogen embrittlement, has however a limit (8) given by the maximum extent of the critical zone for microcrack formation; this maximum extent (which is a function of material and stress level) corresponds to a portion of the plastic zone at the tip of the crack. Finally, the hydrogen effect on the corrosion fatigue acts only above a minimum ΔK value (8), even if this value has not been well defined.

The crack tip blunting was also studied (6,10) and considered in the model for True Corrosion Fatigue together with the hydrogen embrittlement. The retardation effect, which should act on the whole curve, could cause a lower crack growth rate in comparison with fatigue in air at low ΔK values, since no embrittlement phenomena occur. This effect should be greater when decreasing the frequency and increasing the potential in anodic direction (for example, when passing from cathodic protection to free corrosion conditions). Until now no experimental data are available to clearly establish the importance of the crack tip blunting due to the environment effect in the corrosion fatigue in synthetic seawater. Furthermore, the access of the aggressive environment to the crack tip would be restricted because the mode I component of crack opening is reduced at low ΔK values (8) and therefore low corrosion rates only would be possible with a consequent small retardation effect.

The ΔK_{th} increase found out in synthetic seawater tests under cathodic protection in comparison with the ones in air, could also be explained on the basis of the carbonates wedge effect. The carbonates precipitation inside the crack can hinder the closing of the crack itself during tests under load control and determine a decrease in the effective ΔK value (11,12). The comparison between tests carried out in synthetic seawater and those in 3.2% NaCl aqueous solution, does not point out a clear influence of carbonates on the crack growth rate. In fact, the curves are almost coincident under free corrosion conditions, where no carbonates precipitation occurs, whilst under cathodic protection conditions the crack growth rate in 3.2% NaCl solution is lightly higher in correspondence with the plateau only. The lowest crack growth rate values in synthetic seawater, however, were reached in tests with ΔK decreasing value, that is under strain control. The effect of carbonates cannot be excluded in the practice. The results obtained are depending on the test conditions, as for example the test duration. Longer times of exposure to synthetic seawater under cathodic protection could lead to a larger deposit amount and to a higher difference between the two said environments. So the carbonates precipitation could play an important role in the offshore structures where, during the most part of the structure life, low deep cracks are present which grow very slowly.

The observations reported above are based on models and mechanisms not explicitly considering the occurrence of stress corrosion phenomena. In fact, the tested steel is commonly considered non-susceptible to constant load stress corrosion in synthetic seawater, even under cathodic protection conditions. Therefore it is not possible to apply the Process Competition Model (6,13,14), which is able to predict the corrosion fatigue behavior of materials susceptible to stress corrosion in the tested environment (for example high yield strength steels). However, as also shown by some tests carried out by us (15), the API 5L X65 steel seems susceptible to stress corrosion in synthetic seawater, when subjected to slow strain rate techniques. This is probably due to a complex interaction, similar to the one before reported, among deformation, dislocation movement, hydrogen diffusion and embrittlement phenomena. Under these conditions it is difficult to discriminate between Stress Corrosion Fatigue and True Corrosion Fatigue.

The models under consideration are able to predict, both from a qualitative and from a quantitative point of view, the fatigue behavior of the tested steel in synthetic seawater, but at the same time they are always inadequate at low ΔK values. As already said, literature data are often incomplete and sometimes contradictory in low ΔK range (16); this is due both to objective testing difficulties and to a complicated phenomenology, where an important role is played by mechanical and electrochemical variables such as stress ratio and potential (for example cathodic protection level), besides defect shape, etc.

From all the results obtained during the corrosion fatigue tests carried out with constant load amplitude, a detrimental effect of cathodic protection can be pointed out; nevertheless, it would be wrong to consider the cathodic protection as absolutely harmful on the steel behavior. Together with the crack growth rate, it is necessary to take into consideration the initiation of corrosion fatigue phenomena, on which the cathodic protection has a beneficial influence and which is prevailing when no sharp defects are present. In the presence of defects, the importance of the initiation stage compared with the crack growth rate one, depends on the environment characteristics and on the crack geometry, in particular the crack tip radius. Therefore a primary importance has the problem of the characterization of possible defects in the structures, in relation to their shape, since in an offshore structure always subjected to cathodic protection, the growth of such defects can occur at a higher rate than the one predicted on the basis of data for fatigue in air.

SUMMARY AND CONCLUSIONS

On the basis of the results obtained during the tests, the following conclusions can be pointed out:

1. The presence of seawater affects the fatigue crack growth rate. In particular, it causes a more rapid growth of the crack at intermediate values of ΔK, as compared with the behavior in air. This is mainly due to the hydrogen embrittlement phenomena at the tip of the crack.
2. Cathodic protection at -900 mV vs SCE leads to a further increase in the crack growth rate, as well as to a decrease in the ΔK value at which the effect of the aggressive environment appears. A plateau forms where the crack growth rate does not depend on ΔK.
3. The increase in the stress ratio R from 0.1 to 0.6 leads to a higher environmental effect; the ΔK value at which the effect of the aggressive environment appears, decreases and the crack growth rate increases. Under cathodic protection conditions, the plateau growth rate seems not to be affected; however the plateau forms at lower values of ΔK. In air and at intermediate ΔK values the stress ratio influence is negligible.
4. At low ΔK values, the presence of seawater seems to cause an increase in the threshold value ΔK_{th}, under cathodic protection conditions, as compared with the behavior in air. This fact may be explained with the wedge effect of carbonates precipitated inside the crack and with the crack tip blunting.
5. At high ΔK values, the environmental effect on the da/dN vs ΔK curves becomes negligible.

Experiments have shown how it is important to characterize possible sharp defects present in an offshore structure always subjected to cathodic protection. In fact, the growth of above defects may occur at a rate which is much higher than the one predictable on the basis of data for fatigue in air.

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