INFLUENCING FACTORS ON FATIGUE CRACK PROPAGATION RATE OF MILD STEELS CATHODICALLY POLARIZED IN SEAWATER

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Various factors influencing FCPR in mild steels were studied. These factors are : chemical composition, welded and heat affected zones (stress being relieved or not), cathodic polarization potential level, pH value, tidal and overload effects. Two enviromments are used ; air and synthetic seawater (ASTM D 1141). The results show that FCPR is lower when the crack propagates in welded or in heat affected zones than that observed in base metal. Cathodic protection in seawater enhances FCPR independently of potential (E_D to -1300 mV/SCE) and pH values. Tidal sollicitations decreases FCPR. The delayed effect immediately after the overload is more pronounced in air than in seawater.

INTRODUCTION

In seawater, cathodic protection of off-shore structures causes complex phenomena. Hence fatigue crack propagation rate is affected and many factors can inhibit or enhance this rate. The first important one is the chemical composition of the material used in these structures (1). To improve mechanical toughness of welded joints, carbon, sulphur, and phosphorus must be reduced to minimum values (1). Copper, aluminium and chromiun are known to improve the corrosion resistance in seawater (1).
This is only the case for homogeneous materials. If the crack propagates in the weld or heat affected zone (stress being relieved or not), crack propagation rate is different from that of base metal (2).

On the other hand, when steel is cathodically polarized in seawater, calcareous deposits are produced on metal surface (3). The properties of these deposits depend on chemical composition of seawater, electrochemical conditions such as cathodic potential level, pH of the solution, flow velocity, pressure and temperature of the seawater (3). These factors may also affect fatigue crack propagation rate. In addition to the previous factors, others as tidal action, overload (see wave impact), frequency, load amplitude, stress ratio R (σmin/σmax) and wave form, may change FCPR.

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In this work, we have studied in air and in seawater, four mild steels with different chemical compositions (Table I). For steel A, we have investigated the role of cathodic potential level (E_D = -750 to -1500 mV/SCE) and of pH (two values 4 and 7.7). The influence of welded and heat affected zones (stress being relieved or not) was studied on steel B. The overload effect was achieved on steel C and finally, tidal action was studied on steels A and D.

EXPERIMENTAL PROCEDURE

Steel A is a commercial one used in offshore structures. The three others were produced by CREUSOT-INDUSTRY Laboratory. The first one was studied as received, but the others were normalized at 900°C during one hour. Steel C was tempered at 700°C during one hour. Mechanical properties of steels A, B, C and D are presented in table II. The welding process was performed by the same laboratory using shielded metal arc (SMAW). Fatigue crack propagation rate was calculated for the four steels in the following conditions : frequency = 1 Hz, $R \simeq 0,1$ with a sine wave shape. Fatigue tests were carried out on two closed-loop electrohydraulic servocontrolled fatigue testing machines AMSLER (20 tons) and MTS (25 tons). All tests were almost doubled and carried out at room temperature. The seawater was unstirred. Single edge notched (SEN) specimen with 10 mm thick was used to measure FCPR in steel A, while CT specimen with 20 mm thick was employed for steels B, C and D. Half of the specimens relative to welded and heat affected zones were stress relieved at 550 °C during one hour.

RESULTS

A. Fatigue crack propagation rate in air

A.1 Chemical composition

Figure 1 shows that steels with low C, S and P contents have higher FCPR than that of commercial steel (steel A).

A.2 Microstructures

FCPR is higher when crack propagates parallel to the rolling directions (L) than perpendiculary to them T). The lower FCPR is obtained when crack propagates in welded and heat affected zones, figure 2. FCPR increases when these zones are stress relieved at 550°C/1hr.

B. Fatigue crack propagation rate in synthetic seawater

B.1. Chemical composition

The influence of the chemical composition on FCPR, when the steel is whether at corrosion potential or at E_C = -1000 mV/SCE in seawater, is shown in figures 3a and 3b. In spite of great dispersion in steel A, it is observed that steels containing 0,45% Cu have slightly slower FCPR than the others.

B.2. Microstructures

As we have seen in air (figure 2), the fatigue crack propagation rate is decreased in the welded and heat affected zone. When these zones are stress relieved FCPR increases but remains lower than that measured in base metal, as well as in seawater when cathodic protection (-1000 mV/SCE) is applied (figure 4). We can make two remarks relatively to those results :

1) the difference between minimum and maximum FCPR in seawater is smaller than that measured in air ;
2) in welded and heat affected zones, the crack is deflected and stopped and there is no further propagation during 10^6 cycles.

B.3. Cathodic polarization potential

Figure 5 shows that cathodic polarization potential in synthetic seawater from E_D to -1300 mV/SCE does not affect FCPR in steel A but remains higher than that measured in air. At E_C = -1500 mV/SCE, fatigue crack propagation rate is higher than that obtained at lower potentials. In unstirred seawater, we have observed that the pH decreases during fatigue life from 7.7 to 4. For this reason, we have also studied pH effect.

B.4. pH effect

Additioning HCl acid to synthetic seawater, we can reduce pH value from 7.7 to 4. Figure 6 shows that the pH value has no significant effect on FCPR (steel A, E_C = -1200 mV/SCE).

B.5 Tidal effect

When the cathodic protected structure is submitted to the tidal effect, fatigue crack tip is exposed alternatively to cathodic polarization and to air saturated seawater. The time of each exposure is about six hours. Figures 7a and 7b show that in absence of seawater (cathodic protection interrupted), crack length becomes immediatly either constant (figure 7a, steel A) or slightly increased (figure 7b, steel D). Plotting log da/dN versus ΔK (figure 8), it can be seen that the minimum value of FCPR measured after tide is lower than that in air and then increases again as ΔK increases. But when seawater is suppressed again, crack propagation rate is decreased. These results show that FCPR is very sensitive to the environment and also fatigue life is increased with tidal action.

B.6 Overload effect (steel C)

Sea waves may suddenly strike the cathodic protected offshore structure while ordinary waves are continuously acting This effect is simulated by increasing during one cycle ΔK to $2\Delta K$ and this is repeated twice at ΔK levels 19 and 23 $MPa\sqrt{m}$. The results are presented in figure 9 and show that the overload has two effects : that is an increase ΔN of fatigue life (ΔN is the retardation time), during which FCPR is decelerated over a length a*, (crack retardation). Theorytically $a^* = a_c^* = 2r_y = 1/3\pi\ (K_{OL}/\sigma_y)^2$, $2r_y$ plastic zone size, K_{OL} stress intensity factor at overload and σ_y flow stress. Table III presents the values of ΔN, a^*, $2r_y$ and K_{OL} for the two overloads applied as a function of environment.

The ratio $a^*/\Delta N$ gives the average value of crack propagation rate during overload process. The difference between the a^* values obtained under the two environments is equal to the shift in crack length at minimum FCPR for each overload (figures 10a and 10b). This shift is higher for the second overload. If we compare the fatigue crack propagation rate measured for the two environments (air and seawater) with constant ΔK,(V), with the minimum FCPR obtained due to the overload process (V_{OL}), we can deduce (figures 10a and 10b) that V/V_{OL} ratios in air are respectively about 16 and 14 for the first and the second overload and these ratios in seawater (at -1000 mV/SCE) are 7 and 4 for the same environment . We can deduce that cathodic protection in seawater reduces overload effect, though the values of a^* are not consistent with the plastic zone sizes, table II.

DISCUSSION

In air, fatigue crack propagation rate is sensitive to the chemical composition of the steel and to the microstructure. High carbon, sulphur and phosphorus contents may respectively lead to induce pearlite layers, MnS inclusions and phosphorus segregation at grain boundaries. Pearlite layers and inclusions deviate crack front and therefore measured FCPR at the surface is decreased. This finding is supported by the following results :

1) Steel A which contains MnS inclusions and pearlite layers exhibits lower FCPR than that of steel B which is purer than steel A (figure 1).
2) FCPR is low when crack front is perpendicular to the rolling direction, i.e. normal to pearlite layers.
3) Welded and heat affected zones which have bainitic-pearlite structures with stretched misoriented grains and having residual compressive stresses through the thickness (2) produce lower FCPR than that observed in the respective stress relieved zones, and also much lower than that measured in base metal (figure 2).

In seawater and at corrosion potential E_D, copper addition reduces slightly FCPR with respect to the other additions by formation of $FeCu_2$ film (4) at crack tip (figure 3a) especially when the crack opens at high ΔK level. On the other hand, corrosion products reduce crack opening by wedge effect (5) and then FCPR decreases. Addition to the wedge effect, interactions between protective film and kinetics of anodic dissolution at crack tip when crack is completely opened are responsible of FCPR level in these steels.

In seawater and at a potential value higher than E_D, i.e. when E_C > - 960 mV/SCE (6), calcareous deposits form on the metallic surface. The chemical composition, structures and thickness of deposits depend on many factors, especially cathodic potential value E_C, pH and time of polarization. At pH = 7.7, the increase of E_C and time, or one of them is followed by the increase of the deposit thickness. Furthermore, the crack tip opens during 1/2f (f frequency), i.e. 0.5 s here. The rate of displacement of hydrogen atoms to the crack tip is equal to 1/2 $(D/t)^{1/2}$, (7), with D diffusion coefficient of hydrogen in the metal and t = 1/2f. If we assume that D for these steels is equal to 10^{-7} cm^2s-1 at room temperature, the rate of displacement of hydrogen atoms is about 10^{-6} m/cycle. The highest FCPR obtained in this study is lower than this value. So, in our conditions, crack tip is always feeded by hydrogen atoms. Two processes may occur when cathodic protection is performed in sea water :

a) during crack opening, hydrogen atoms diffuse behind crack tip and hydrogen embrittlement is produced ;

b) crack closure may be hindered by deposits whose formation leads to the wedging of the crack tip.

If these two conditions are fulfilled, the cathodic polarization potential value will have no effect on FCPR (figure 5), except at high potential value (-1500 mV/SCE) at which hydrogen bubbles hinder the formation of deposits at crack tip (6). Up to now no attempt has been made to display the role of deposits in crack closure. Hydrogen embrittlement in metals occurs when its local concentration C_H exceeds the critical concentration C_K of the traps. The types of traps, their number, shape and distribution depend on chemical composition of the metal and heat treatments (9). Figure 3b shows that addition of copper with 0.45% produces traps more beneficial (steels A and D) than an addition of Al and Cr which forms oxides in steel C (Al_2O_3, Cr_2O_3). The steel B which has a small number of traps, has a low C_K in the matrix behind the crack tip, with respect to average hydrogen concentration. This is more evident in the welded and heat affected zones in which hydrogen increases FCPR by 6 times instead of twice for the base metal (figure 4) and in spite of the existence of residual compressive stresses through the thickness of the two zones. In the base metal cathodically polarized in seawater, crack advances straightforward perpendicular to load direction but in welded and heat affected zones, in the same electrochemical conditions, crack advances following zig-zag direction and then stops at grain boundaries which have greater misorientations with respect to others. This result is not consistent with that of VANDER VELDEN et al. (10) which shows that grain misorientation has no effect on crack retardation.

ENGELL and FORCHHAMMER (11) forward that the pH at the surface of cathodically protected steel in seawater would be 10.9. KOBAYASHI (12) measured a pH of 11.5 at a distance of 0.1 mm from the surface cathodically polarized at 0.938 $mA.cm^{-2}$ in an unstirred 3% NaCl of bulk pH = 8. Our results (13) also indicate that the pH is 10.5 at the surface polarized at -1350 mV/SCE when the bulk pH of the seawater varies from 3 to 7.7. We can then conclude that it is not surprising that FCPR for pH 4 and 7.7 is the same (figure 6).

Tidal tests are another examples which show that FCPR is very sensitive to wedge effect. When the crack tip is exposed to air saturated seawater in which oxygen content becomes high, corrosion products and consequently wedge effect are then more important than in the case of exposure to corrosion potential in unstirred seawater (figure 8). After tide and with cathodic protection, corrosion products are almost at crack tip and may reduce hydrogen permeation. At high ΔK level and during the second tide, crack tip is sufficiently blunted and the wedge effect is not efficient to reduce greetly FCPR.

The retardation due to overload is explained by many models : 1) residual compressive stresses at crack tip and its interactions with the associated plastic zone (14), 2) crack closure (15), 3) crack blunting (16), 4) work hardening elements behind crack front (17). The problem is complex,especially while cathodic protection is performed. The retardation mechanism in thick specimen is explained by the fact that crack advances in specimen mid-thickness either by ductile tearing, by cleavage or by mixture of them, and is stopped at specimen surface because of an important plastic deformation (plane stress) (18). Crack retardation is equivalent to the difference between crack extension in the center and at the surface. With cathodic protection in seawater, hydrogen increases embrittlement at crack tip and at the whole specimen surface. The amount of ductile tearing is increased at the center but crack may propagate, also at the surface. At low ΔK level, crack retardation is about the same in air and in seawater (table III), showing that the relative crack extension in center and on the surface is identical in the two environments. At high ΔK level, a^* is more important in the case of hydrogen than in air, displaying that the relative extension is higher in seawater than in air. This finding is due to the increase of hydrogen embrittlement when high triaxial stresses are present in mid-thickness of the specimen.

CONCLUSION

We have studied some factors influencing fatigue crack propagation rate in mild steels used in offshore structures. These factors are chemical composition, microstructures, welded and heat affected zones with stresses relieved or not, electrochemical conditions as cathodic potential and pH values, tidal and overload processes. The two environments used in this study are air and unstirred synthetic seawater (ASTMD 1141). The following conclusions are drawn.

1) Fatigue crack propagation rate measured in air depends on chemical compositions of mild steels and homogeneity of its microstructure. Low C, S and P contents increase FCPR in spite of addition of Cu, Cr and Al. Large pearlite bands or MnS inclusions which are crossed by crack front lead to low FCPR. Compressive stresses in mid-thickness generated by welding process decrease also FCPR ;
2) FCPR in seawater is controlled by the cathodic reaction during crack opening and the wedge effect during crack closure. At corrosion potential E_D, the wedge effect due to corrosion products governs FCPR, while at cathodic potential higher than E_D, there are two antagonist factors : firstly hydrogen embrittlment during crack opening ; this embrittlement increases with a higher cathodic potential level. Secondly the increase of cathodic potential improves calcareous deposits thickness and the crack closure is more and more wedged. FCPR is not sensitive to cathodic potential level in the range E_D to -1300 mV/SCE. FCPR does the same when pH of bulk seawater varies from 4 to 7.7. However, FCPR is lowered slightly when copper is added in mild steel. In addition, FCPR is lowered or stopped in welded or heat affected zones cathodically protected ;
3) Tidal and overload effects are beneficial because they lower FCPR and then increase fatigue life. The decay in FCPR during cathodic protection in seawater, due to overload action, is smaller than that measured in air.
4) This study must be completed by investigating other factors as seawater velocity, frequency, stress ratio and also $U = \Delta K_{eff}/\Delta K$ evolution due to calcareous deposits at crack tip as a function of electrochemical parameters.

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REFERENCES

(1) J.B. HARRISON - "Choix et propriétés du métal de base et des soudures pour les joints tubulaires". Conference international "l'acier dans les structures marines". Institut de Recherches de la Siderurgie Française - oct. 1981. Paris, France, P.S.3, p. 175.

(2) M. TRUCHON, H.P. LIEURADE, C. PUTOT. "Propagation des fissures de fatigues dans les joints soudés en acier E36". Ibid 1, 9.1.

(3) W.H. HARTT, C.H. CULBERSON, S.W. SMITH. Corrosion NACE, vol. 40, n°11. 1984, p. 609.

(4) T. TARAI, K. TSUKADA, Y. KOBAYASHI, H. INAGAKI, T. WATANABE. Corrosion, Vol. 37, N°1, 1981, p. 5.

(5) K. ENDO, K. KOMAI, T; SHIKIDA, ASTM-STP 801, 1983, p. 81.

(6) G. PHILIPPONNEAU. Thèse Docteur Ingénieur. 1982 - Ecole Centrale des Arts et Manufactures - Châtenay-Malabry, France.

(7) C.Q. BOWLES, J. SCHIJVE. ASTM - STP 801, 1983, p. 96.

(8) B.G. ATTAYA, H.W. PICKERING. J. Electrochem. Soc., 122, 1975, p. 1018.

(9) G.M. PRESSOUYRE "Current solutions to hydrogen problems in steel". First International Conference. "Current solutions to hydrogen problems in steel". Nov. 1982, p18, ASM, Washington, USA.

(10) R. VAN DER VELDEN, H. L. EWALDS, W.A. SCHULTZE, A. PUNTER. ASTM. STP 801; 1983, p. 64.

(11) H. ENGELL, P. FORCHHAMMER. Corros. Sci. Vol.5, 1965, p. 479.

(12) T. KOBAYASHI. "Effect of environmental factor on the protective potential of steel". 5th Int. Cong. Met. Corros., Tokyo, 1972, National Assocation of Corrosion Engineers, Houston, Texas, 1974, p. 629.

(13) M. HABASHI, M. PROD'HOMME, G. MENARD, J. GALLAND, N.Q. DAO. "Formation d'un dépôt calcomagnésien sous polarisation cathodique en milieu de type marin : rôle de la composition chimique et du pH ; conséquences sur les processus de fissuration". Congrès Européen de Corrosion, Nice, Nov. 85. Centre Français de la Corrosion, Société de Chimie Industrielle. Paris, France.

(14) J. SCHIJVE, D. BROEK. Aircraft Engineering, 34, 1962, p. 314.

(15) W. ELBER. ASTM. STP 486, 1971, p. 230.

(16) R.H. CHRISTIENSEN. Metal Fatigue (MCGRAW-HILL), 1959.

(17) R.E. JONES. Eng. Fract. Mech., 5, 1973, 585.

(18) C. BATHIAS "Mécanique et mécanismes de la fissuration par fatigue". La fatigue des métaux et des structures, p.163, 1980, par C. BATHIAS et J.P. BAILON.

STEEL								
A	C 0.16 Cr 0.029	Si 0.30 Mo 0.009	Mn 1.36 Cu 0.445	P 0.019 Sn 0.01	S 0.023 V 0.011	Al 0.047 Ti -	N 0.007 O -	Ni 0.048 Fe balance
B	C 0.058 Cr 0.154	Si 0.311 Mo 0.054	Mn 1.45 Cu 0.029	P 0.004 Sn 0.015	S 0.007 V -	Al 0.023 Ti 0.001	N 58/175 ppm O 25/5ppm	Ni 0.19 Fe balance
C	C 0.044 Cr 0.992	Si 0.372 Mo 0.061	Mn 1.56 Cu 0.031	P 0.006 Sn -	S 0.004 V -	Al 1.00 Ti -	N - O -	Ni 0.17 Fe balance
D	C 0.042 Cr 0.162	Si 0.338 Mo 0.056	Mn 1.51 Cu 0.456	P 0.0057 Sn 0.017	S 0.005 V -	Al 0.023 Ti 0.003	N 60/81 ppm O 19/23 ppm	Ni 0.176 Fe balance

Table I : Chemical composition (wt%) of mild steels A, B, C and D.

STEEL	Re MPa	Rm MPa	A %	Z %
A	445	707	33.7	70.6
B	253	469	38.0	81.1
C	365	485	37.2	80.7
D	254	483	37.2	76.5

Table II : Mechanical properties of steels A, B, C and D.

N° of overload	1st overload				2nd overload			
Parameters environments	ΔN cycles	a* mm	K_{OL} MPa$\sqrt{m}$	$2r_y$ mm	ΔN cycles	a* mm	K_{OL} MPa$\sqrt{m}$	$2r_y$ mm
Air	$6.45\ 10^4$	0.84	40.57	1.13	$1.95\ 10^4$	1.12	49.30	1.94
Seawater (-1000mV/SCE)	$9.30\ 10^3$	0.72	40.60	1.31	$6.4\ 10^3$	1.82	49.13	1.92

Table III : ΔN, a*, K_{OL} and $2r_y$ evolution with the number of overloads and environments. Steel C.

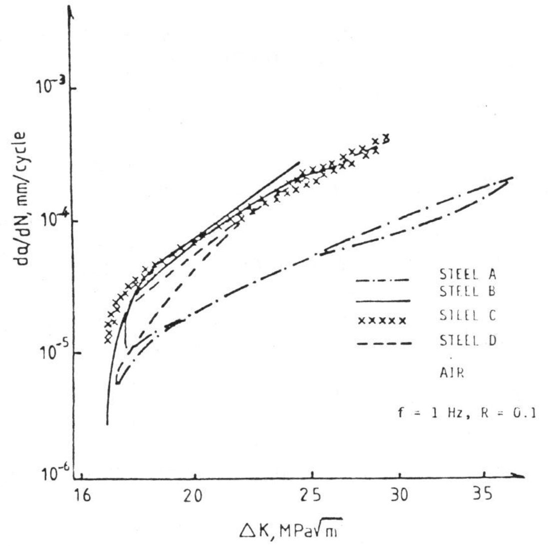

Figure 1. FCPR versus ΔK as a function of chemical compositions of mild steels A,B,C and D. Air environment.

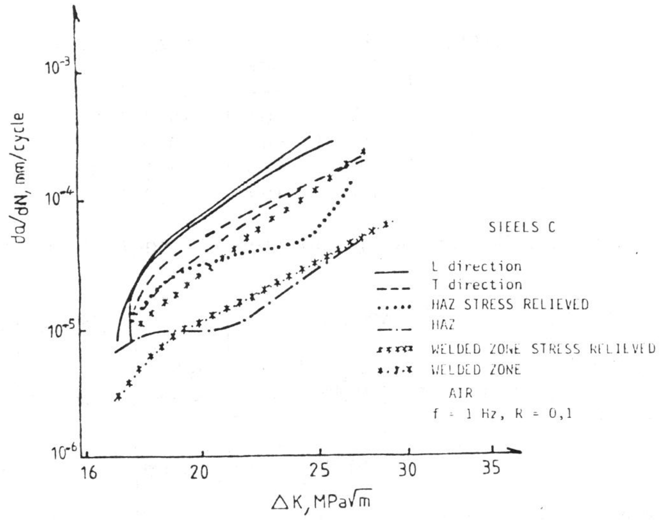

Figure 2. FCPR versus ΔK as a function of microstructures of mild steels B : base metal, welded and heat affected zone stress relieved or not. Air environment.

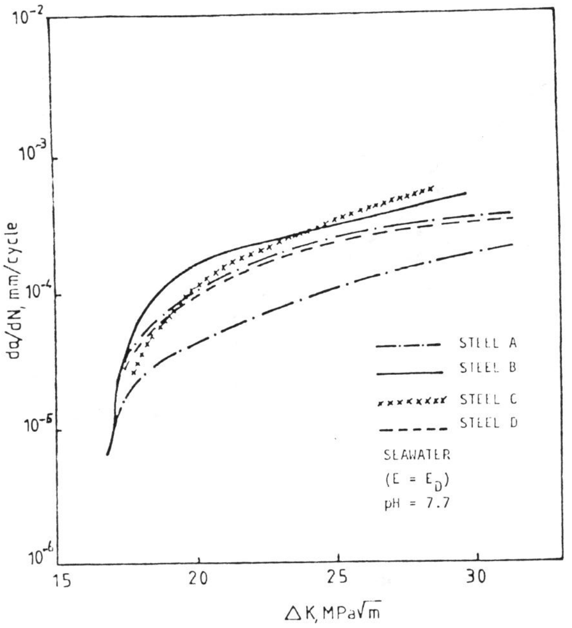

Figure 3a. FCPR versus ΔK as a function of chemical compositions of mild steels A,B,C and D. Seawater environment, $E = E_D$

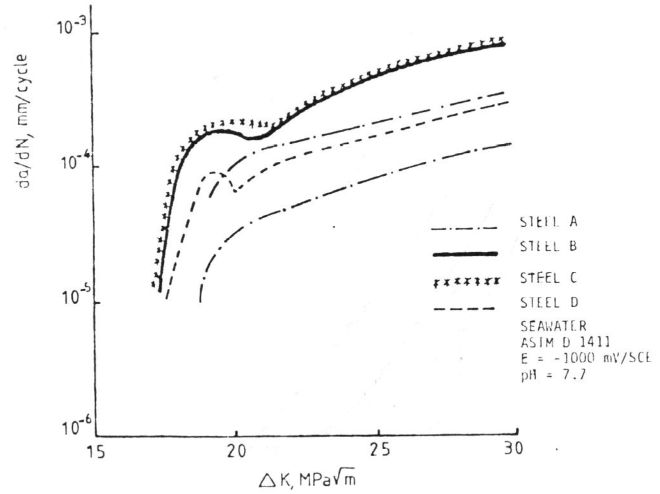

Figure 3b. FCPR versus ΔK as a function of chemical compositions of mild steels A,B,C and D. Seawater environment, E = - 1000m V/SCE.

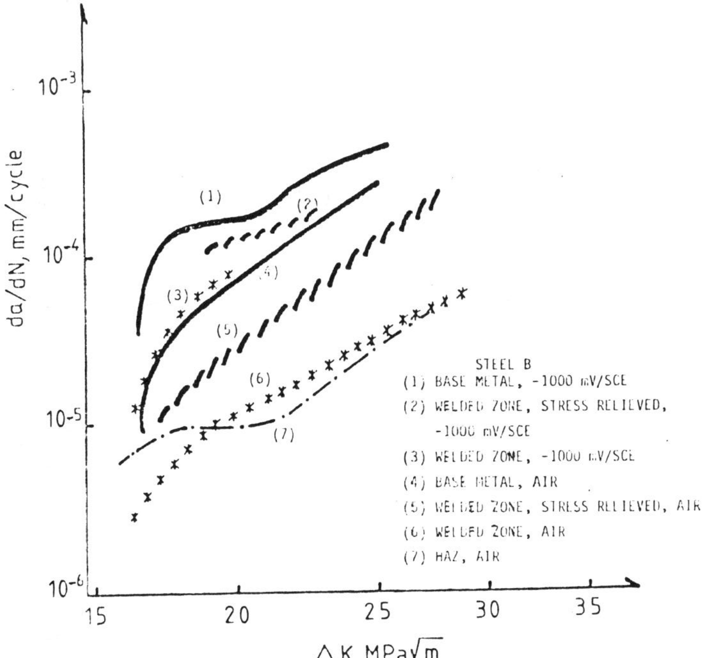

Figure 4. FCPR versus ΔK as a function of microstructures of mild steels B : base metal, welded and heat affected zone stress relieved or not. Seawater environment, E = - 1000m V/SCE.

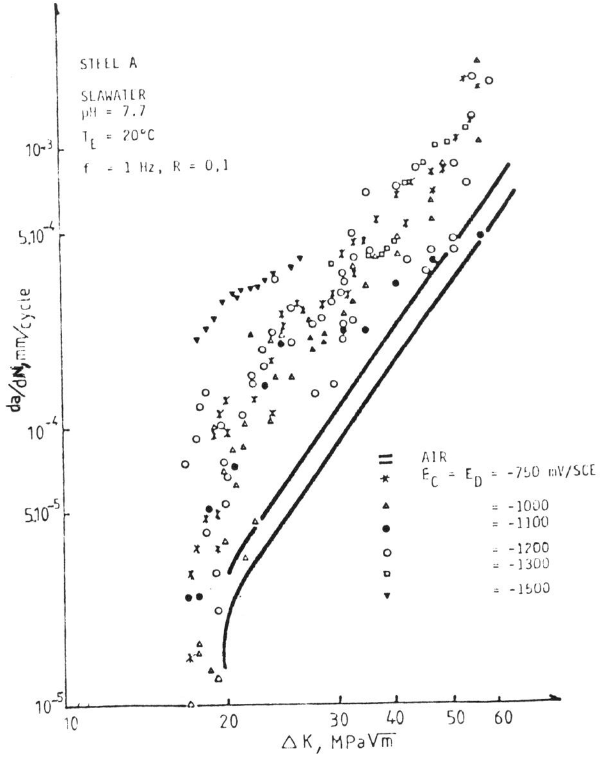

Figure 5. FCPR versus ΔK as a function of cathodic polarization level. Seawater environment, pH = 7.7, steel A.

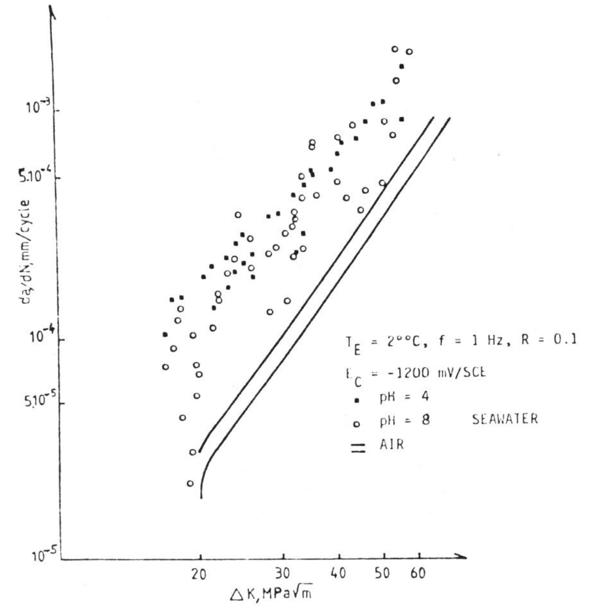

Figure 6. FCPR versus ΔK as a function of pH value: Seawater environment, E = - 1200m V/SCE, steel A.

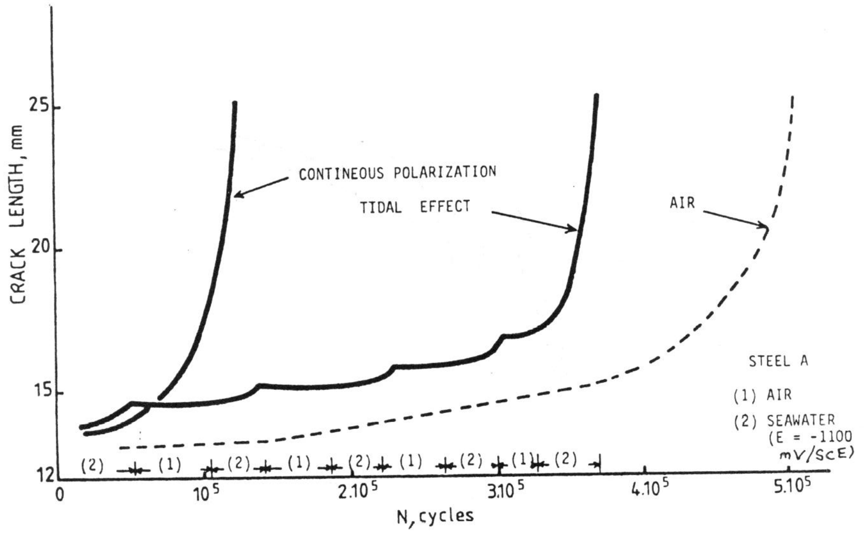

Figure 7. Crack length versus fatigue life as a function of environments: Air, continuous cathodic protection, and cathodic protection + four tidals : E = - 1100m V/SCE, steel A.

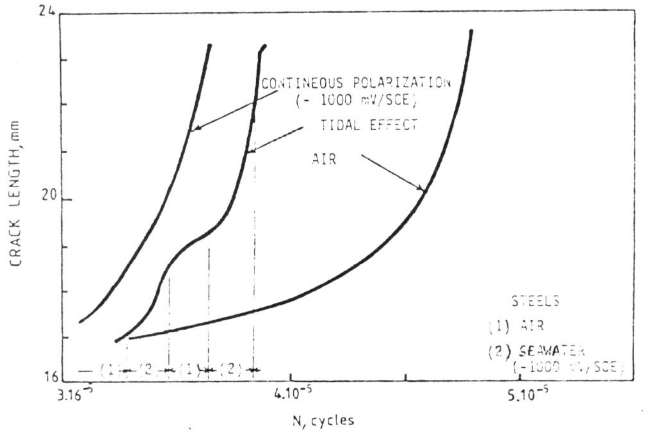

Figure 7b.Crack length versus fatigue life as a function of environments : Air, continuous cathodic protection + one tidal : E =-1000m V/SCE, steel D.

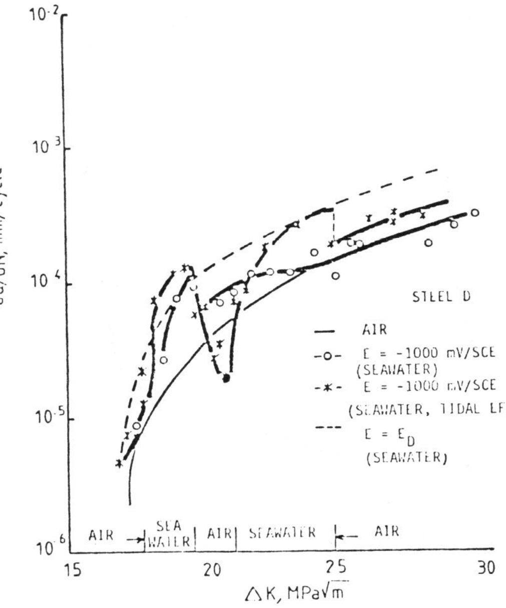

Figure 8. FCPR versus ΔK as a function of environments: Air, continuous cathodic protection (E=-100m V/SCE), corrosion potential E_D and continuous cathodic protection (E = - 1000m V/SCE) + one tidal.

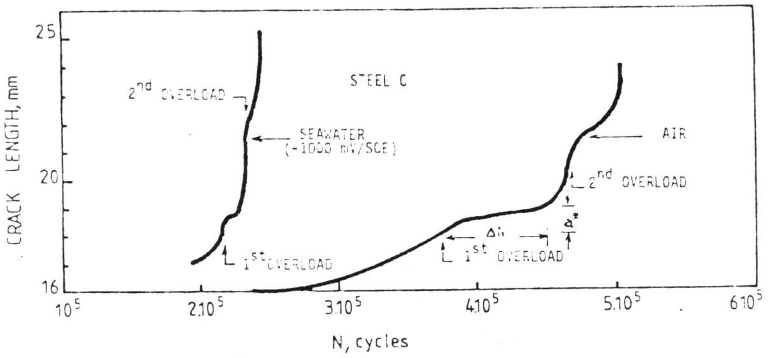

Figure 9. Crack length versus fatigue life as a function of overload actions : Air environment and seawater (E = - 1000m V/SCE, pH = 7.7).

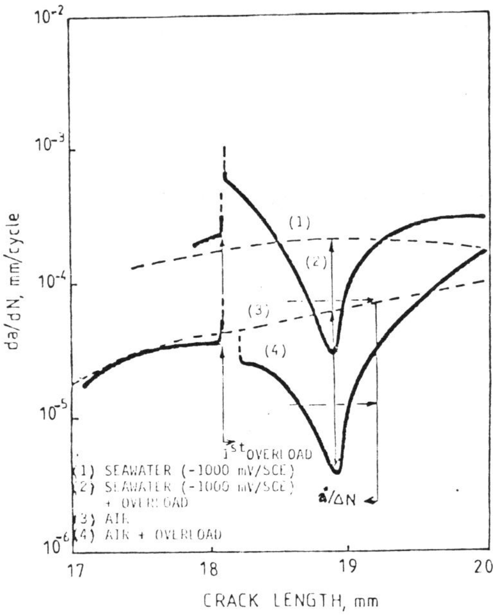

Figure 10a. FCPR versus crack length for four conditions: air, air with first overload, seawater (E = - 1000m V/SCE) and seawater (E = - 1000m V/SCE) with first overload.

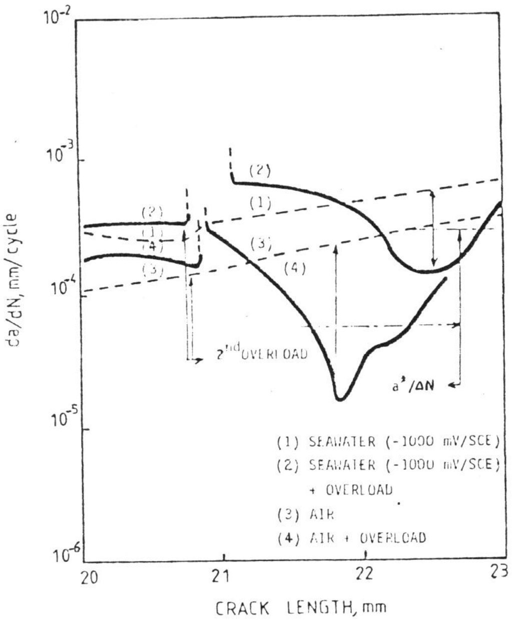

Figure 10b. As figure 10a but with second overload.