THE INFLUENCE OF ELECTROCHEMICAL PARAMATERS ON THE
LOW-CYCLE CORROSION FATIGUE OF A STRUCTURAL STEEL

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The influence of electrochemical parameters was
studied for a structural steel of the type E355,
when subjected to cyclic strains in the plastic
range. An original electrochemical method for the
detection of crack initiation was developed. The
resistance to low-cycle fatigue in the presence of
sea water was notably reduced. The application of a
cathodic potential accentuates this deterioration in
high strain range. Conversely, in the low strain
range, the application of a cathodic potential
results in the recovery of the fatigue life obtained
in air.

INTRODUCTION

The design of welded marine structures necessitates a knowledge
of the conditions for the initiation of fatigue cracks, under
mechanical and electrochemical conditions which are as close as
possible to those in practice. In particular, such structures can
possess areas of high stress and strain concentrations, due to
the simultaneous presence of stress concentrations around welded
joints (the weld toe) and of special loading conditions (storms).

The purpose of this work is to study the influence of
electrochemical parameters on a structural steel of the type
E355, when subjected to cyclic strains in the plastic range.

This study forms part of a wider activity undertaken to
determine the behaviour of welded marine structures with respect
to the initiation of fatigue cracks.

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1,227

EXPERIMENTAL METHODS

Material :

This was a structural steel, in the normalised condition, whose chemical composition is given in table 1. The mechanical properties are shown in table 2.

Table 1 - Chemical composition (% by wt.) of the steel E355

C	Mn	Si	S	P	Ni	Al	N
0.11	1.45	0.30	0.001	0.020	0.42	0.030	0.011

Table 2 - Mechanical properties of the steel E355
(transverse direction)

σ_y (MPa)	U.T.S.(MPa)	Elong. (%)	R.A. (%)
400	540	20	75

Test specimens :

The tests were carried out on cylindrical test specimens, 12 mm in diameter over the gauge length. The test specimens were loaded in tension and compression at a constant rate of strain. The tests were performed with the strain applied by an electro-hydraulically-controlled machine, through a strain gauge which measured the longitudinal distortion of the test specimen.

Corrosion and environmental cell :

The gauge length of the test specimen was immersed in sea water reconstituted in accordance with ASTM Standard D1141. The corrosion cell allowed potentiostatic tests to be carried out, and the side walls were flexible, to allow for the distortion of the the test specimen (figure 1).

The strain gauge was situated outside the cell.

An initial calibration was carried out, in order to relate the distortion of the test specimen in the waisted portion to the distorsion measured during the test.

Fatigue crack initiation detection :

Two methods were used simultaneously for detecting the initiation of fatigue cracks, one based on the variation in the load, the other on the change in the cathodic protection current. It is the latter that we will examine in greater detail.

CRACK INITIATION DETECTION BY AN ELECTROCHEMICAL METHOD

Variation of the polarisation current at zero load

If the electrochemical potential is maintained constant, the cathodic protection current gradually diminishes. This reduction is due to the formation of a magnesium calcium deposit which partially isolates the metal from its environment.

The effectiveness of this protection current is reduced by a noise level ΔI, which can be considerable at the beginning of the test ($\Delta I/I$ of 15 to 20 %). Both the protection current and the relative noise level diminish as the polarisation time is increased. The mean value of the current may be reduced by a factor of 4 or 5, while $\Delta I/I$ may fall to 0.5 % (figure 2).

The polarisation time to obtain a minimum value of the current and of the noise level, will depend on the applied potential and, to a lesser degree, on the temperature of the fluid. However, the noise component of the current is essentially linked to turbulence of the fluid. If, in fact, the circulation of the sea water is stopped, the protection current is greatly reduced and the noise disappears completely (figure 3).

In order to obtain sufficient sensitivity, the measurement of the current is obtained measuring the ΔV at the terminals of a shunt with a resistance of 10 or 100 Ω.

In the method for the detection of the initiation of corrosion fatigue cracks which we shall describe in the next paragraph, it is necessary, before the start of the test, for the noise level to be as low as possible.

1,229

Variation of the current during the fatigue test

Test specimens without cracks - If it has been possible to overcome the problem of noise level imposed on the cathodic protection current, it will be noted that the current varies with respect to the stress or strain of the test specimen.

Within the elastic range, this cyclic variation is very small and variation of its amplitude with respect to the applied strain is linear (figure 4). In general, the current is a maximum when the test specimen is in tension and a minimum when it is in compression. Curiously, in certain cases the opposite has been observed. To indicate the orders of magnitude - for a cyclic strain amplitude of 0.1 % at - 1 V/Ag/AgCl, the current I is 1.52 mA and the cyclic variation of this current is 5.4×10^{-3} mA.

In the plastic range, the amplitude of the cyclic variation increases to a much greater extend that in the elastic range. To indicate the orders of magnitude - for a cyclic strain amplitude of 2 % at - 1 V/Ag/AgCl, the current is 2.3 mA and the cyclic variation of this current is 0.1 mA. In general, the value of the current is a maximum when the test specimen is in tension and a minimum when it is in compression. The (I, ε) diagrams have considerable hysteresis compared to those obtained for the elastic strains (figure 4).

This phenomenon can be explained if it is considered that the surface of the test specimen in contact with the electrolyte increases when in tension and decreases when in compression. Let us consider a cylinder of diameter D_o and length L_o.

$S_o = \pi D_o L_o$ initial surface area

$S = \pi D L$ surface area after distortion $\dfrac{S}{S_o} = \dfrac{DL}{D_o L_o}$

The longitudinal strain can be written :

$$\varepsilon_1 = \log \frac{L}{L_o} \qquad\qquad L = L_o\, e^{\varepsilon_1}$$

1,230

The radial strain can be written :

$$\varepsilon_2 = \varepsilon_3 = \log \frac{D}{D_o} = -\nu\varepsilon_1 \qquad D = D_o \, e^{-\nu\varepsilon_1}$$

If the strain is small, we can write :

$$\frac{S}{S_o} = e^{(1-\nu)\varepsilon_1} \simeq (1-\nu)\varepsilon_1$$

in the elastic range $\nu = 0.3$
in the plastic range $\nu = 0.5$ (constant volume).

This theory describes the relative variation of the surface area with respect to the strain of the test specimen (figure 5).

In general, the current is proportional to the surface area to be protected ($S = KI_o$). Experimentally, it has been found that the variation of the (I, ε) current diagrams most frequently follows the example which has just been described, although the amplitude of the cyclic variation is much greater than the rule of proportionality would lead one to suppose. This can be explained in the following way : as the test specimens become cathodic, the densities of the protection current become lower than for the same test specimens when non-polarised (of the order of 4 to 5 times less). When the test specimen is distorted plastically, slip bands are formed which result in the creation of "fresh" (non-polarised) surfaces. These new surfaces to be protected necessitate locally higher current densities. The potential being maintained constant, it is not surprising that the amplitude of the cyclic variation of the current begins to increase more sharply during plastic distorsion.

For the same strain (0,5 %) and a relatively low strain rate ($\dot{\varepsilon} = 8 \times 10^{-4} \, s^{-1}$), the amplitude of the cyclic variation is 1,5 to 2 times lower than for a strain rate of $\dot{\varepsilon} = 8 \times 10^{-3} \, s^{-1}$. This suggests that these new "fresh" surfaces have the time during a cycle to become polarised, if the latter is long enough. The fact that these "fresh" surfaces are also created in compression would explain why we have found that, dependent on the case, the current is a maximum either in tension or in compression. (In the latter case, the increase in the current due to the creation of the "fresh" surfaces predominates over the reduction in the surface area in compression).

Test specimens with cracks - Figure 6a shows the simultaneous variation of the stress and of the protection current, with respect to the number of cycles.

Figure 6b gives the general shape of the (I, ε) and (σ, ε) diagrams with no cracks, and figure 6c shows how these diagrams develop when a crack is initiated.

In latter case, it will be noted that the amplitude of the cyclic variation of the current increases. Crack initiation results in an increase in the surface area of the metal in contact with the electrolyte. Since the potential is maintained constant, the amplitude of the current increases as the crack is propagated. Furthermore, the new surfaces exposed are also more reactive than the surface of the test specimen, which is polarised.

Also on figure 6c, it will be noted that the current increases sharply when the crack opens. It may seem surprising that this sudden increase in the current occurs while the test specimen is still in compression.

We therefore checked that, in this type of test, a crack does indeed begin to open, even though the test specimen is in compression.

One might be tempted to find a parallel with ELBER's theory (1), which showed that, for a cyclic loading in tension $(R = \sigma max/\sigma min > 0)$, a crack closes well before the load is completely removed. He attributed this closure effect to the presence, at the bottom of the crack, of residual tensile strains, left as the load increased to its maximum. In our case, $R = \varepsilon_{max}/\varepsilon_{min} = -1$. At the moment when the loading becomes compressive, resisual compressive strains are introduced, which cause the crack to open, although the loading is still compressive. In all the tests carried out, we noted that, whatever the shape of the (I, ε) diagrams, the appearance of a crack resulted in a sharp increase in the current shortly after the loading became compressive, at the moment when the crack opened.

Sensitivity of this method of crack initiation detection - This method is very sensitive with regard to the plotting of the $(I,)$ diagrams. The point where a "discontinuity" in the current in compression appears may be taken as the criterion for the initiation of the crack. Well before the load began to decrease, we were able to detect surface cracks, $S \geq 3$ mm2 and depth ≥ 0.25 mm.

In these fatigue tests, the surface area of the test speci-
men in contact with the electrolyte is relatively large (44 cm2).
If all the non-active area of the test specimen is marked, this
method gains in sensitivity.

INFLUENCE OF THE APPLIED POTENTIAL ON THE LIFE
TO CRACK INITIATION

The study of the low-cycle fatigue strength of the steel E355 was
carried out under different environmental conditions.

The MANSON-COFFIN curves of the relationship between the
amplitude of the strain $\Delta\varepsilon/2$ and the number of cycles to the
initiation of a crack were plotted for air, free corrosion, at
-800 and -1000 mV/Ag/AgCl, at 25°C.

The MANSON-COFFIN curve may be considered as a plastic
contribution and an elastic contribution, superimposed :

$$\frac{\Delta\varepsilon t}{2} = \frac{\Delta\varepsilon e}{2} + \frac{\Delta\varepsilon p}{2} \qquad \text{hence :} \qquad \frac{\Delta\varepsilon t}{2} = \frac{\sigma'f}{E} \ (2N_A)^b + \varepsilon'f \ (2N_A)^c$$

In the low strain range (high fatigue lives), the results
show the beneficial effect of cathodic protection compared to the
free corrosion condition (figure 7 and 8). The fatigue lives
encountered are close to those obtained in air, and sometimes
higher. In would seem that this favourable effect is due to the
presence of the magnesium calcium deposit, which tends to plug
incipient cracks (plugging of short cracks) (2). Conversely, in
the high strain range, the increase in the absolute value of the
potential results in a significant reduction in the life to crack
initiation.

Figure 8 shows that this phenomenon specifically affects the
plastic contribution, without affecting the elastic contribution.

The equations for the MANSON-COFFIN curves at crack initia-
tion for the different environments are given in table 3.

Table 3 - <u>MANSON-COFFIN curves for the steel E355 in various environments</u>.

Environment	$\frac{\Delta \varepsilon_t}{2}$ (%) =	$\frac{\Delta \varepsilon_e}{2}$ (%) +	$\frac{\Delta \varepsilon_p}{2}$ (%)
Air : $\frac{\Delta \varepsilon_t}{2}$	= 0,604 $(2N_A)^{-0,13}$	+	127,98 $(2N_A)^{-0,63}$
- 1000 mV/Ag/AgCl: $\frac{\Delta \varepsilon_t}{2}$	= 0,386 $(2N_A)^{-0,09}$	+	15,73 $(2N_A)^{-0,49}$
- 800 mV/Ag/AgCl : $\frac{\Delta \varepsilon_t}{2}$	= 0,620 $(2N_A)^{-0,13}$	+	76,42 $(2N_A)^{-0,64}$
Free corrosion : $\frac{\Delta \varepsilon_t}{2}$	= 0,636 $(2N_A)^{-0,14}$	+	84,50 $(2N_A)^{-0,66}$

The cyclic work-hardening curves remain sensibly identical, whatever the environmental conditions.

The effect of the cathodic potential on the life depends on the applied cyclic distortion, as shown by figure 9. The premature crack initiation in the high strain range for an electrochemical potential of - 1 V/Ag/AgCℓ is attributed to a hydrogen embrittlement mechanism.

In fact, the quantity of hydrogen increases as the potential becomes more cathodic, and the diffusion of the hydrogen in the form of atoms become easier as the cyclic plastic strain increases.

Internal micro-cracks were observed inside the metal, in the areas of greatest hardness (figure 10). The cracks are present only when the potential is - 1 V/Ag/AgCℓ, and for strains $\Delta \varepsilon_t/2 \geq 0.5$ %. Figure 11 shows that, in this case, the fracture surfaces have a brittle appearance.

CONCLUSION

This study shows the influence of sea water and of the electrochemical potential on the initiation of low-cycle fatigue cracks, for a structural steel of the type E355.

An electrochemical method was developed for the detection of crack initiation in the case of potentiostatic testing. This technique allows cracks less than 0.25 mm deep to be detected. The resolution of the detection method can be improved by minimising the area of metal in contact with the electrolyte.

The low-cycle fatigue strength of the steel E355 was studied for various environments: air, sea water, and various electrochemical conditions: free corrosion, - 800 and - 1000 mV/Ag/AgCl. For high values of strain, the fatigue life diminishes as the electrochemical potential becomes more cathodic. Hydrogen embrittlement, which is mainly responsible for this deterioration, was encountered when the potential was at its most negative values.

Conversely, in the low-strain range, although the fatigue strength under free corrosion is lower than in air, by the application of a cathodic potential the fatigue lives obtained in air can be recovered. This is attributable to the creation of magnesium calcium deposits, which plug the incipient cracks and considerably slow down their propagation.

Acknowledgements

REFERENCES

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      ASTM STP 486 - pp. 230-242.

(2)   HABASHI et Coll. - Interaction between fatigue crack growth rates and kinetics of magnesium calcium deposits formation at crack tip of mild steel cathodically polarized in seawater. Conf. NEW DELHI 84.
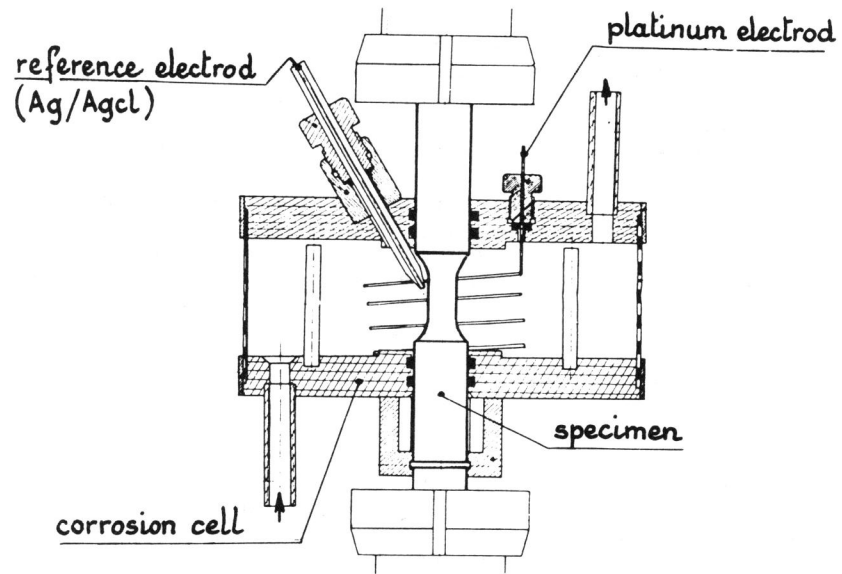   Proceed. ICF6, pp. 2521-2528, Pergamon Press, 1984.
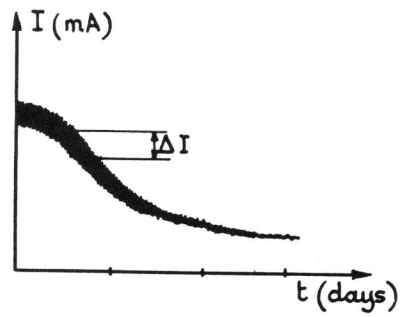
Figure 1 Corrosion cell
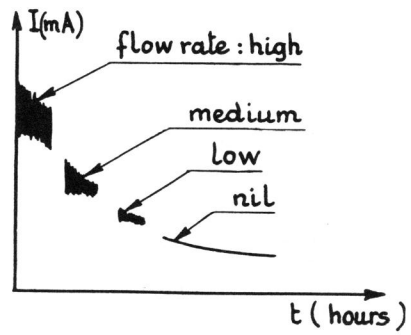

Figure 2 Effect of the polarisation time
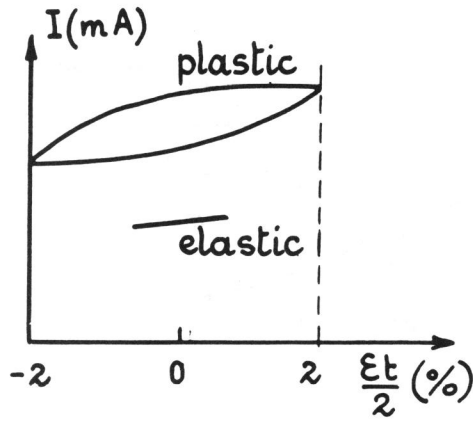

Figure 3 Effect of the turbulence

Figure 4 Variation of the protection current with respect to the strain of the test specimen
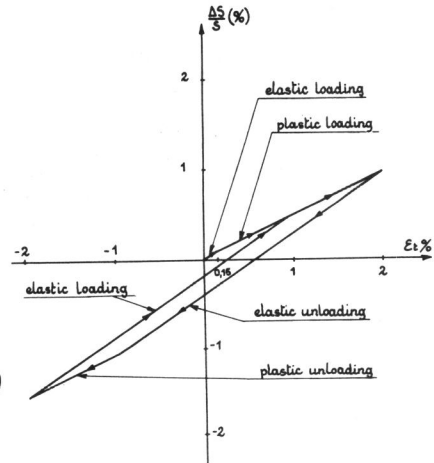

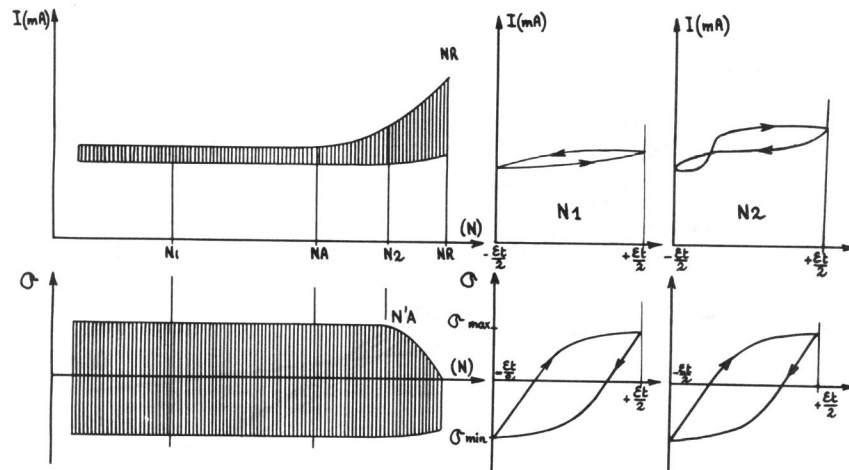Figure 5 Variation of the surface area of the test specimen with respect to the longitudinal strain

Figure 6a Variation of the current and the stress with respect to the number of cycles

Figure 6b Variation of the current and the stress with respect to the strain, with no cracks

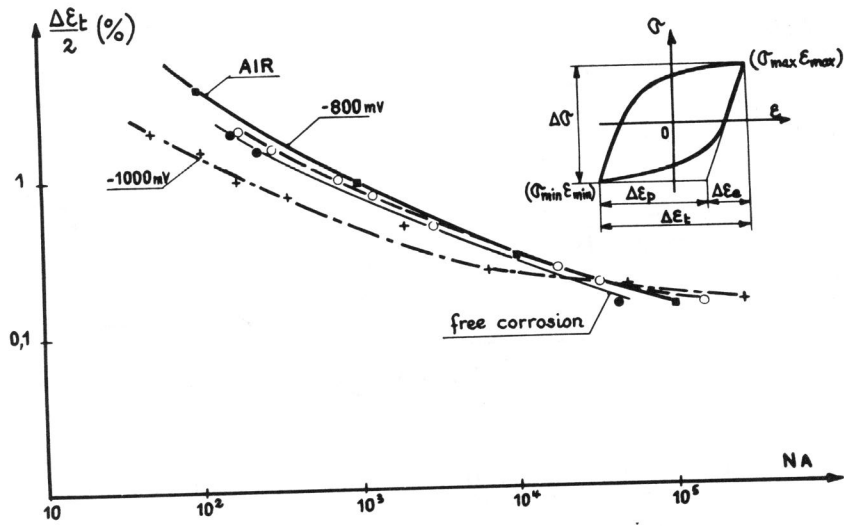Figure 6c Variation of the current and the stress with respect to the strain, with a crack

1,237

Figure 7 MANSON-COFFIN curve for the steel E355 in different environmental conditions
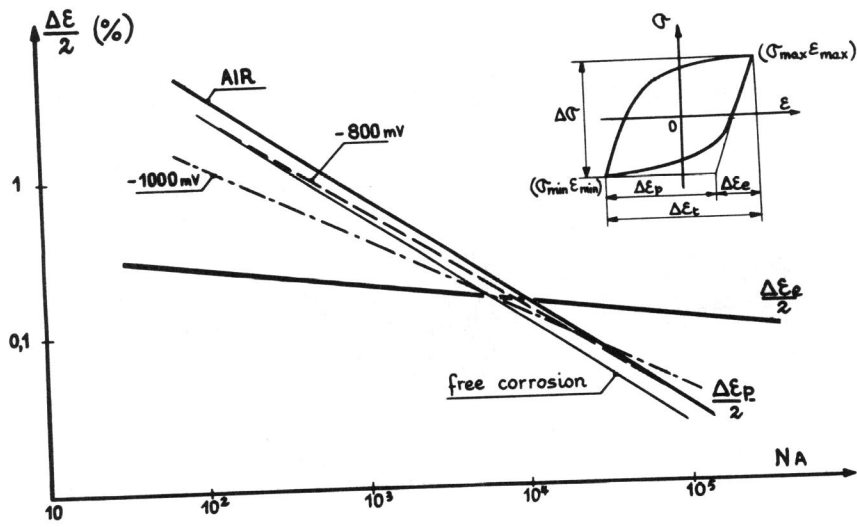

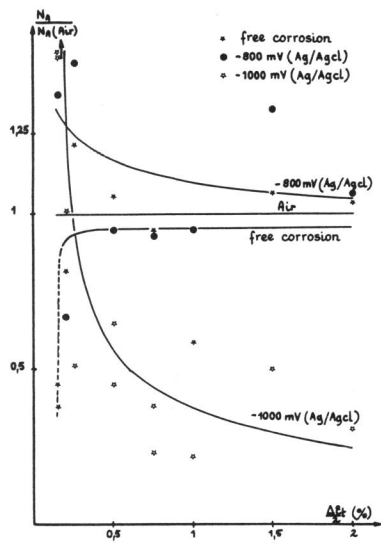Figure 8 Elastic and plastic contributions to the MANSON-COFFIN curves

1,238

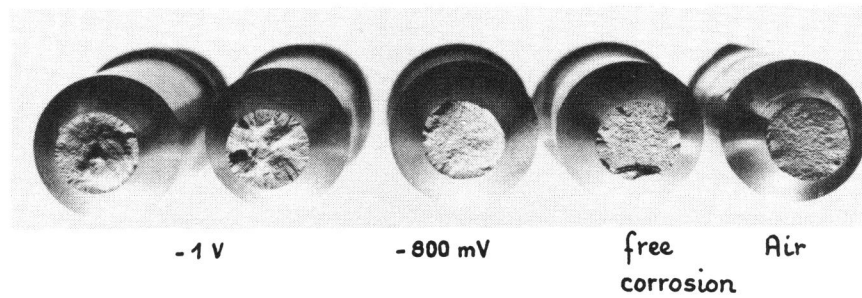Figure 9 The influence of the cathodic potential on the fatigue life

Figure 10 Fracture surfaces for $\dfrac{\Delta \varepsilon_t}{2}$ = 1.5 % in different environments