THE INFLUENCE OF ELECTROCHEMICAL PARAMETERS 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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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

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>S</th>
<th>P</th>
<th>Ni</th>
<th>Al</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.11</td>
<td>1.45</td>
<td>0.30</td>
<td>0.001</td>
<td>0.020</td>
<td>0.42</td>
<td>0.030</td>
<td>0.011</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$\sigma_y$ (MPa)</th>
<th>U.T.S. (MPa)</th>
<th>Elong. (%)</th>
<th>R.A. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>540</td>
<td>20</td>
<td>75</td>
</tr>
</tbody>
</table>

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 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 distortion 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 $\Delta I$, 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 $\Delta V$ at the terminals of a shunt with a resistance of 10 or 100 $\Omega$.

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.

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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 $5.4 \times 10^{-3}$ mA.

In the plastic range, the amplitude of the cyclic variation increases to a much greater extent 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 $(I, \varepsilon)$ 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 $D_0$ and length $L_0$.

\[
S_0 = \pi D_0 L_0 \quad \text{initial surface area}
\]

\[
S = \pi D L \quad \text{surface area after distortion}
\]

\[
\frac{S}{S_0} = \frac{DL}{D_0 L_0}
\]

The longitudinal strain can be written:

\[
\varepsilon_1 = \log \frac{L}{L_0} \quad L = L_0 e^{\varepsilon_1}
\]

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The radial strain can be written:

$$
\varepsilon_2 = \varepsilon_3 = \log \frac{D}{D_0} = -\nu \varepsilon_1
$$

$$
D = D_0 \varepsilon^{\nu} 1
$$

If the strain is small, we can write:

$$
\frac{S}{S_0} = \varepsilon (1-\nu)^{\nu} 1 = (1-\nu) \varepsilon_1
$$

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 \( (S = K \varepsilon_0) \). Experimentally, it has been found that the variation of the \( (I,\varepsilon) \) 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 distortion.

For the same strain \( (0.5 \%) \) and a relatively low strain rate \( (\dot{\varepsilon} = 8 \times 10^{-4} \text{ s}^{-1}) \), the amplitude of the cyclic variation is 1.5 to 2 times lower than for a strain rate of \( \dot{\varepsilon} = 8 \times 10^{-3} \text{ s}^{-1} \). 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 \((I, \varepsilon)\) and \((\sigma, \varepsilon)\) 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 polarized.

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 \((R = \sigma_{\text{max}}/\sigma_{\text{min}} > 0)\), 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, \(R = \varepsilon_{\text{max}}/\varepsilon_{\text{min}} = -1\). At the moment when the loading becomes compressive, residual 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 \((I, \varepsilon)\) 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 \((I, \varepsilon)\) 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, \(S > 3 \text{ mm}^2\) and depth \(\geq 0.25 \text{ mm}\).
In these fatigue tests, the surface area of the test specimen 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 \( \Delta e / 2 \) 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:

\[
\frac{\Delta e_t}{2} = \frac{\Delta e_p}{2} + \frac{\Delta e_p}{2}
\]

hence:

\[
\frac{\Delta e_t}{2} = a'f \left( \frac{2N_A}{2} \right)^b + \varepsilon f \left( \frac{2N_A}{2} \right)^c
\]

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 initiation for the different environments are given in table 3.

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Table 3 - MANSON-COFFIN curves for the steel E355 in various environments.

<table>
<thead>
<tr>
<th>Environment</th>
<th>$\frac{\Delta\varepsilon_t}{2}$ (%)</th>
<th>$\Delta\varepsilon_p$ (%)</th>
<th>$\Delta\varepsilon_e$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\frac{\Delta\varepsilon_t}{2} = 0.604 \ (2N_A)^{-0.13}$ + $127.98 \ (2N_A)^{-0.61}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1000 mV/Ag/AgCl</td>
<td>$\frac{\Delta\varepsilon_t}{2} = 0.386 \ (2N_A)^{-0.09}$ + $15.73 \ (2N_A)^{-0.49}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 800 mV/Ag/AgCl</td>
<td>$\frac{\Delta\varepsilon_t}{2} = 0.620 \ (2N_A)^{-0.13}$ + $76.62 \ (2N_A)^{-0.64}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free corrosion</td>
<td>$\frac{\Delta\varepsilon_t}{2} = 0.636 \ (2N_A)^{-0.14}$ + $84.50 \ (2N_A)^{-0.56}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

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REFERENCES


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Figure 1 Corrosion cell

Figure 2 Effect of the polarisation time

Figure 3 Effect of the turbulence
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
Figure 7 MANSON-COFFIN curve for the steel E355 in different environmental conditions

Figure 8 Elastic and plastic contributions to the MANSON-COFFIN curves
Figure 9 The influence of the cathodic potential on the fatigue life

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