STRESS CORROSION CRACKING AND CORROSION FATIGUE IN SEAWATER OF A 2.25Cr1Mo STEEL

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The stress corrosion cracking and corrosion fatigue behaviour in seawater of a 2.25Cr1Mo steel have been studied as a function of its mechanical properties. A modified Slow Strain Rate testing technique was set up and utilized to evaluate the stress corrosion cracking behaviour. By means of this technique it was possible to establish the maximum degree of mechanical properties utilizable for offshore structures without risks of stress corrosion.

INTRODUCTION

In the past, the environmental embrittlement of the materials has been studied separating the stress corrosion cracking phenomenology from that of corrosion fatigue. The huge amount of data accumulated during the last years makes this distinction difficult. It is our opinion that these phenomena must be interpreted under a more general theory able to deal with those experiences that are not covered by the traditional definitions of stress corrosion cracking and corrosion fatigue.

The aim of this work is the study of the susceptibility to stress corrosion cracking and corrosion fatigue of a low-alloy steel as a function of its mechanical properties. This subject is also of great interest in relation with the construction of new offshore structures in deep seas, where steels with greater yield strength than those currently used are needed.

EXPERIMENTAL

Tests were carried out on a Chromium-Molibdenum low-alloy steel with yield

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strength ranging from 486 to 845 MPa. (Table 1) They were performed at room temperature in synthetic seawater (prepared following ASTM D1141-78) under cathodic protection realized using zinc sacrificial anodes at -1050 mV versus standard calomel electrode (SCE).

Two different types of stress corrosion tests were carried out on notched specimens: Slow Strain Rate tests (slow strain rate) (Parkins (1)) and Interrupted Slow Strain Rate tests (interrupted slow strain rate) (Cigada et al (2)). Both tests consist in a tensile test conducted in an aggressive environment imposing a constant displacement rate to the clevis of the testing machine. During interrupted slow strain rate the clevis displacement was stopped at 80% of the maximum load and the specimen was maintained under constant deformation conditions until rupture or as long as to exclude any crack propagation due to stress corrosion (at least 500 hours). The clevis displacement velocity was selected on the basis of preliminary tests so that a marked environmental effect occurs in a reasonable test time. Selected rate was equal to 10^{-5}mm/s.

Notched axial specimens with square section (Fig.1.a) were utilized. The notch was obtained by mechanical working and subsequently by electron discharging machine. The notch radius is about 50 μm.

The fatigue behaviour of the steel was studied using fatigue precracked compact tension specimens (Fig.1.b) through Linear Elastic Fracture Mechanic tests performed following ASTM E647-83. The crack propagation rate was evaluated as a function of the stress intensity factor range ΔK, by means of the constant load amplitude technique (ΔK increasing test). Fatigue tests in air and in synthetic seawater were performed with sinusoidal waveform, 0.6 stress ratio R and frequency equal to 10-20 Hz for tests in air and 0.2 Hz for corrosion fatigue tests in synthetic seawater.

TABLE 1 - <u>Chemical composition and mechanical properties of the steel.</u>

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al	Sn	V	Co
.09	.30	.53	.021	.004	2.26	.90	.14	.22	.33	.011	.012	.01

Material	Heat Treatment	σ_{TS} (MPa)	σ_{TS} (MPa)	Elong. (%)	R.A. (%)	HB
YS 70	Normalized[1]	611	486	30.6	74	196
YS 100	Quenched and tempered[2]	809	718	19.2	-	240
YS 110	Quenched and tempered[3]	872	764	15.0	73	272
YS 120	Quenched and tempered[4]	990	845	20.4	62	316

1 As received
2 970°C 2h/oil quenched + 600°C 2h + 620°C 2h
3 970°C 2h/oil quenched + 600°C 2h + 610°C 2h
4 970°C 2h/oil quenched + 600°C 2h

If no appreciable crack propagation was observed during corrosion fatigue tests, these tests were stopped after 100000 cycles and then continued at 10% greater load. The length of the crack was evaluated by means of an automatic compliance (C) measuring technique described in previous papers (Cigada et al (3)). The crack length (a) was correlated to apparent compliance by means of the following relation:

$$a = 51.04 - 4.058\ C^{-1/2} + 0.05\ C^{-1}$$

where apparent compliance is defined as CMOD/DP and CMOD and DP respectively are crack-mouth opening displacement during a cycle and load range. Experimental data obtained during tests (the length of the crack and the number of cycles) were processed in order to calculate the crack growth rate (da/dN) as a function of ΔK, by means of the "Incremental Second Order Polynomial Technique". ΔK value was calculated according to the relation contained in the ASTM E647-83.

RESULTS

Slow Strain Rate Tests

Fig.2 shows the results of the slow strain rate tests in air and in seawater. It can be clearly noted that the curves in aggressive environment are remarkably different from those in air. Both the maximum load and the energy required to fracture the specimen (proportional to the surface subtended to the curve) decrease in synthetic seawater compared to tests performed in air. This is due to stress corrosion cracking phenomena clearly shown by scanning electron microscope fracture analysis.

Load/displacement curves obtained in aggressive environment become different from those in air well before reaching the maximum load, as stress corrosion cracking crack initiation and propagation takes place in correspondence of the notch. The specimen fracture occurs without a marked plastic deformation. Whereas in air, the specimen starts to crack after a marked generalized plastic deformation.

The stress corrosion crack initiation has been evaluated using: maximum load (P_{max}) and the load P_i obtained drawing a secant line through the origin of the test record with slope equal to 95% of the tangent to initial linear part of the record. Then, stress corrosion cracking susceptibility of the material is expressed dividing the values by the maximum load measured in the test carried out in air. These two parameters show an increase of susceptibility of the steel with yield strength (Fig.3). Moreover the two parameters are substantially equivalent.

The results of slow strain rate tests point out the stress corrosion cracking susceptibility of the material under particular strain conditions (dynamic conditions) in all the different metallurgical states. On the other hand, field experience proves that low alloy or carbon steels with yield strength lower than 500 MPa (like the normalized steel considered) are not subject to stress corrosion cracking in marine environment. Using slow strain rate tests to assess materials behaviour in marine environment may be an excessively conservative approach.

Interrupted Slow Strain Rate Tests

Fig.4 reports the curves obtained during interrupted slow strain rate tests; the trend of the load after the interruption of the clevis motion is drawn as a function of time by dashed line. After the clevis displacement was stopped, the load remained almost constant during tests on YS70, YS100 and YS110 steels, whereas YS120 steel exhibited a reduction of applied load due to crack propagation by stress corrosion till failure of the specimens. This happened regardless whether the interruption occurred before or after reaching the maximum load.

However, also on YS110, YS100 and YS70 steel specimens the crack initiation occurred during the first part of the test but no propagation was observed after the clevis displacement was stopped. It can be concluded that 2.25Cr1Mo low-alloyed steel is not susceptible to stress corrosion cracking under static load, if heat treated up to 764 MPa yield strength but it is susceptible if heat treated to 845 MPa yield strength. Furthermore, the material which in interrupted slow strain rate tests failed in few hours showed no crack propagation when the specimen was quickly loaded (even if dipped in the solution). This confirms that the strain rate is a very important factor in stress corrosion, sometimes determinant for the behaviour of the material.

The interrupted slow strain rate technique tests allow to quickly evaluate whether a crack is able to propagate under constant loading. This is very important for engineering approach, permitting the evaluation of the susceptibility of the material without taking into account the initiation time, supposing the presence of defects prone to stress corrosion cracking propagation. Whereas, in traditional tests the time required for stress corrosion cracking crack initiation may be very long, and sometime longer than the test time usually used.

Corrosion Fatigue Tests

Fig.5 shows the results of the fatigue tests. During tests performed in synthetic seawater on the material with lower mechanical properties (YS 70) a five-fold increase in the crack growth rate can be noted in correspondence of intermediate ΔK values as well as a slight increase in the curve slope. Moreover, a change in the curve slope with plateau formation was observed at high ΔK values, exceeding 30 $\text{MPa}\sqrt{\text{m}}$.

Fatigue crack growth rate in air of YS 120 steel is greater than that measured on YS 70 steel with lower mechanical properties. In seawater, plateau formation is observed at ΔK value above 15 $\text{MPa}\sqrt{\text{m}}$ with crack growth rate about ten fold that in air. The behaviour of the two materials is quite different in synthetic seawater, mainly at low ΔK values where the incidence of environmental embrittlement in fatigue phenomena is very important.

During fatigue tests in seawater, an increase in the threshold ΔK can be noted compared to tests in air. This is probably due to the calcareous deposits precipitated inside the crack that hinder crack closure and reduce the effective ΔK value.

DISCUSSION

The environmental embrittlement examined in this work can be attributed to two different phenomena mainly linked to the type of applied stress, that is static or dynamic. The former includes all phenomena traditionally known as stress corrosion. The latter includes both phenomena occurring under cyclic loading (corrosion fatigue) and in presence of a continuously increasing deformation (stress corrosion during slow strain rate tests). In both cases, the mechanism of embrittlement can be the same. In sea water and for carbon or low-alloy steels, it should be attributed to hydrogen embrittlement at the tip of the fatigue or stress corrosion crack.

Depending to the degree of susceptibility of the materials, the environmental assisted fracture can occur only under dynamic stresses (corrosion fatigue or slow strain rate conditions) or even under static conditions. For example, it is well known that low alloy or carbon steels are not subject to stress corrosion under static conditions in seawater, provided that the yield strength is sufficiently low; whereas, as pointed out during our tests, they are susceptible under dynamic conditions during both fatigue and slow strain rate tests. On the contrary, high strength steels can undergo stress corrosion cracking even under static conditions (Carter and Hyatt (4)) and the presence of dynamic stresses, though not necessary, can enhance this phenomenon.

The phenomenology exhibited by low strength steels has to be attributed, it is our opinion, to the fact that only progressive strain (such as in fatigue and slow strain rate tests) and the consequent movement of dislocations inside the material can permit hydrogen penetration in such a quantity as to embrittle the plastically strained zone at the crack tip. During traditional constant load or constant deformation tests, no slipping is practically present to facilitate hydrogen penetration and diffusion. Therefore, this kind of test is not suitable to evaluate the behaviour of the material where slow load variations, with frequency and amplitude insufficient to cause fatigue, are applied. It is well known that these load conditions very often can give rise to stress corrosion phenomena (as in buried gas pipelines (Parkins (5)). Not even traditional slow strain rate tests provide fully satisfactory results, as they are excessively severe for the evaluation of the material application. However, although the correlation between the results of the slow strain rate tests and corrosion fatigue behaviour needs specific studies, it could be possible to estimate the occurrence of environmental embrittlement under dynamic conditions, hence the possibility of corrosion fatigue too.

The interrupted slow strain rate test permits to achieve a more accurate discrimination of the material behaviour as a function of mechanical properties and, in our opinion, such differentiation may be related to foreseeable material behaviour. If in these tests the material behaviour in aggressive environment is quite different from that in air during straining of the material and if after strain interruption there is no crack propagation, environmental embrittlement can be expected under dynamic conditions only. Thus, in offshore conditions, where essentially corrosion fatigue occurs, the material is utilizable if the structure is correctly designed to resist fatigue. Instead, if the crack propagates even after strain interruption, stress corrosion can occur under static conditions and the use of this material is not recommended.

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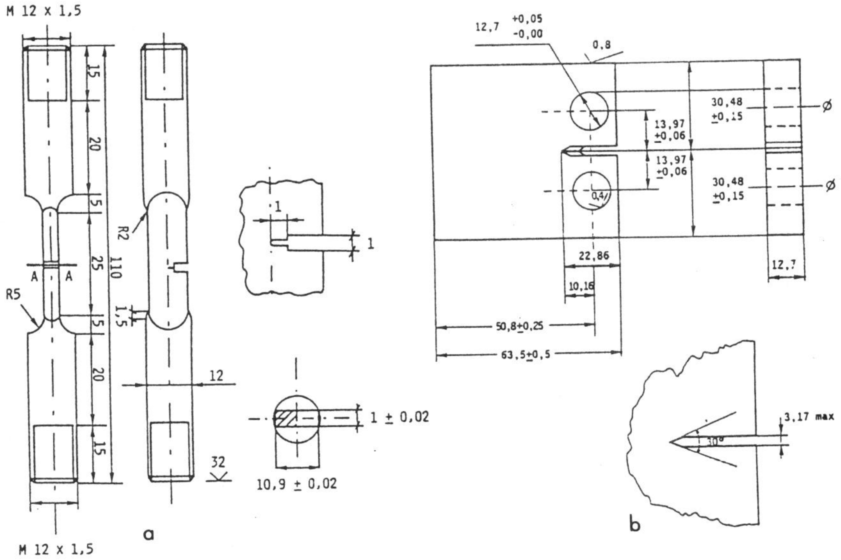

Figure 1 - Specimen for a) stress corrosion cracking tests and b) fatigue tests.

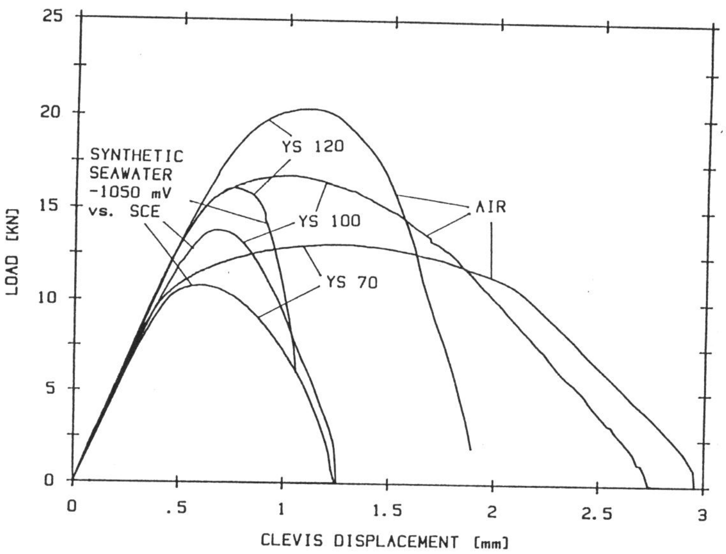

Figure 2 - Load-clevis displacement curves obtained during the slow strain rate tests.

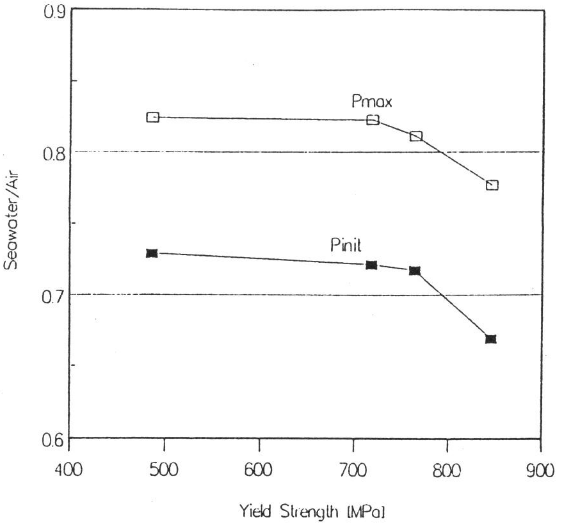

Figure 3 - Maximum load (P_{max}) and initiation load (P_{init}) in seawater at -1050 mV vs. SCE divided by the maximum load in air as a function of yield strength.

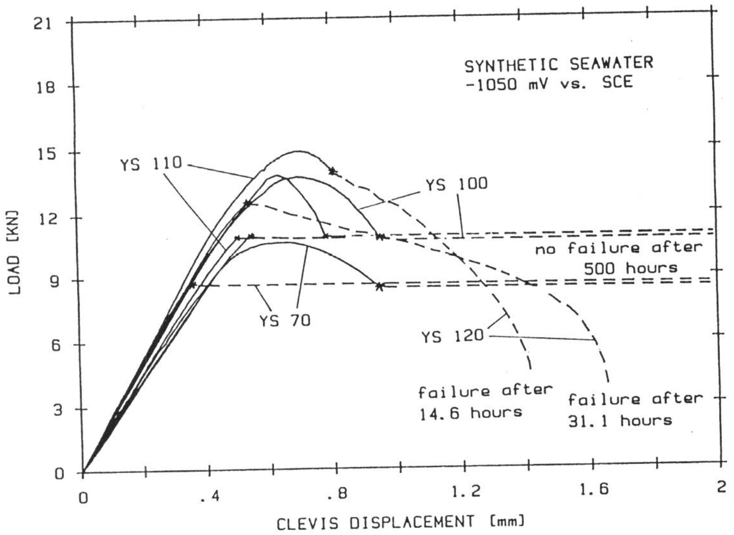

Figure 4 - Load-clevis displacement curves obtained during the interrupted slow strain rate tests (dashed lines describe the load versus time after interruption).

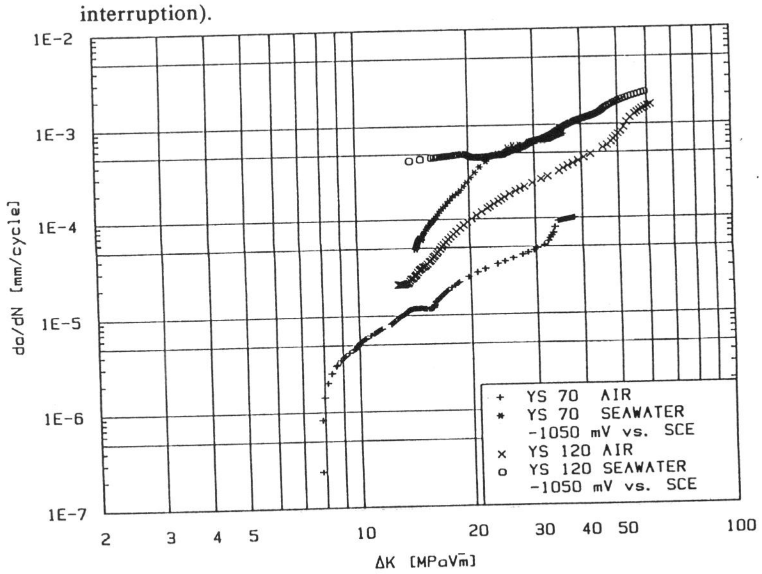

Figure 5 - Fatigue crack growth plots.