ON FATIGUE CRACK PROPAGATION IN HSLA STEELS

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ABSTRACT

Corrosion fatigue crack growth rates in 3.5% NaCl water solution have been investigated on high tensile low alloy steel used for mining chains. The aim of this study is to show the effect of a corrosive environment on the relationship between the Paris-Erdogan (C and n). It is found that a linear behavior is obtained in air and corrosive environment. Meanwhile the fatigue corrosion process results in increasing values of C by a factor of 10 for the same value of n in air. This finding is confirmed using data from literature for 35 NCD 16, SAE 51100 steels.

Keywords: high tensile steel, fatigue, corrosion, crack propagation, K_{Iscc}

RESUME

Les vitesses des fissures en fatigue ont fait l'objet d'étude dans un environnement corrosif, composé d'une solution d'eau à 3.15% de NaCl. L'objectif de ce travail est de monter l'influence de la corrosion sur les paramètres C et n de la loi de Paris-Erdogan. Il en résulte que la relation est linéaire dans deux conditions d'essais, air et corrosion. Cependant les valeurs de C obtenues dans la corrosion sont augmentées de 10 pour la même valeur de n prise dans l'air. En analysant les résultats donnés par la littérature pour des aciers de même type, 35 NCD 16 et SAE 51100, on retrouve les mêmes comportements.

Mots clés: Acier à haute résistance, fatigue, corrosion, propagation de fissures, , K_{Iscc}

INTRODUCTION

In the presence of an aggressive species, for instance, sodium chloride solution, the fatigue resistance of many materials is lowered. The behavior of the fatigue crack growth within aqueous solution is found to be sensitive to loading waveform and frequency [1-6]. On the basis of gathered data, corrosion fatigue crack growth rate as a function of crack tip stress intensity factor (ΔK_I) may be grouped into three types [2-5] in terms of their relation to the threshold stress corrosion intensity factor, K_{Iscc}. Type A represents those steel–environment systems which are relatively immune to stress corrosion cracking. It is most found in the aluminum–water systems. In this case, environment effects resulted from the interaction of fatigue and simultaneous environmental attack. Type B behavior is representative of material–environment systems that exhibit a significant sensitivity to stress corrosion cracking, i.e., hydrogen–steel systems. Environmental crack growth is directly related to sustained load crack growth with no interaction effects. Finally, type C represents the behavior of most alloy–environment systems. Above K_{Iscc}, the behavior approaches that of type B, whereas below K_{Iscc}, the behavior tends towards type A, with the associated interaction effects.

In a recent work [7], FCG results in air on a typical high tensile mining chain steel have been reported with regards to the effects of frequency and tempering temperature. The investigation has revealed that lowering the tempering temperature from 500 °C to 200 °C or dropping the test frequency from 78 Hz to 0.6 Hz resulted in an increase of FCG rates. In addition a linear relationship between the parameters of the Paris law [8] (C and n) has been demonstrated. In the present study, the effect of a corrosive environment on the previous relationship is investigated. Results on the environment-applied stress interaction are presented and then compared to those reported in the literature with regards to K_{Iscc}.

EXPERIMENTAL APPROACH

A high tensile low alloy steel (DIN 17115) Werkstoff 1.6753 or W 1.6753 of the specification given in Table 1 was used. Single edge notched uniaxial specimens [7,9] were prepared from a 31mm diameter heat treated bar. The heat treatment simulated the conditions adopted in the manufacturing process of the mining chain. After one hour quench from 890°C in agitated water, the bar was tempered for three hours at temperatures of 200°C and 500°C, which were regarded as lower and upper bounds of the tempering temperatures. All FCG tests at a lower frequency of 0.6 Hz were carried out on a Nene (M3000-S) re-circulating ball screwdriver machine. They were performed under a stress ratio of 0.1 in a 3.5% weight of sodium chloride solution of distilled water with a pH of 6.90 to 7.10. The surface dimension of the crack was monitored using a traveling microscope with a 20x magnitude by means of which the crack can be observed through a Perspex box wherein the NaCl solution was circulating. The fatigue crack growth lengths were measured using the direct current potential drop method.

Table 1: Specification of W1.6753 steel for DIN 17115

Element	C	Si	S	P	Mn	Ni	Cr	Mo	Al
Specification (Weight %)	0.20	0.25	0.014	0.015	1.48	1.04	0.31	0.46	0.026

RESULTS AND DISCUSSION

FCG analysis in 3.5% NaCl solution

Corrosion crack growth rates were obtained using the secant method suggested by ASTM E647-78T. First, the crack length was measured as a function of elapsed cycles. In practice, it was easy to see from the potential drop when sufficient crack growth had occurred to obtain an accurate measurement. Then the data were subjected to numerical analysis to establish the rate of crack growth. The crack growth rate (da/dN) was obtained from the fitted data of the crack length (a) versus number of cycles (N) plot. Values of (da/dN) were plotted on log scales as a function of the stress intensity factor range (ΔK_I). Stress intensity calculations were performed using standard compliance functions following the value of (a/W), as stated by equations (1) and (2):

For a/W < 0.6

$$\Delta K_I = \Delta P/(B.W)\,(\pi a)^{1/2}\,[1.12 - 0.23(a/W) + 10.6(a/W)^2 - 21.7(a/W)^3 + 30.4(a/W)^4] \quad (1)$$

For a/W > 0.6

$$\Delta K_I = \Delta P/(B.W)\,(\pi a)^{1/2}\,[\,[1.07(1+3.03(a/W))] \div [2\,[\Delta a / W(1-a/W)^{3/2}\,]^{1/2}]\,] \quad (2)$$

where ΔP and B are the mean applied load and the specimen thickness respectively.In order to complete the analysis, the Paris-Erdogan law [8]:

$$da/dN = C(\Delta K_I)^n \quad (3)$$

is used to establish the profile of the stable corrosion fatigue crack growth region as a function of frequency and tempering temperature.

Corrosion fatigue - K_{Iscc}

For any crack growth situation, the most dominant cracking mechanism is likely to control the growth rate. In the presence of corrosive environment, it is difficult to say by which process the crack has grown. Corrosion fatigue curves in Figures 1 and 2 show that FCG rates follow the behavior of most alloy environment systems [2-5]. The usual linear region of FCG curves in air found at intermediate ΔK_I is shifted up in the presence of the aggressive environment, resulting in highly elevated crack velocity plateau. It is clear that this behavior observed within the two tempering, suggests that ΔK_I is above K_{Iscc} ranging from 15 to 17 $MNm^{-3/2}$ according to temper limits. To understand the corrosion fatigue behavior in W1.6753, a comparative analysis is made with results reported by IRSID on a 35 NCD 16 steel [10]. Tab II summarizes the yield strength and fracture properties: both steels are quenched and tempered at the same lower and upper tempering temperatures. Critical stress intensity factor values (K_{IC}) were almost similar while values of K_{Iscc} for W1.6753 steel are slightly higher. It is worth noting that the 35 NCD 16 steel contained high percentages of Carbon (0.34%) and Nickel (4.1%) with less Manganese (0.39%) resulting in high strength. Results depicted in Figures 1 and 2 imply that for both steels, the fatigue crack propagates within the same range of da/dN and ΔK_I values. It is found that W 1.6753 steel in both air and corrosive environments presents lower fatigue crack growth rates than the 35 NCD 16 steel. Observing the behavior in the aggressive environment, all corrosion fatigue data were higher than those in air nevertheless W1.6753 steel shows a better corrosion fatigue resistance. As reported above, the CFCG rates should be considered with regards to K_{Iscc}. The main feature is for values of ΔK_I above K_{Iscc}, where FCG rates are increased to reach a plateau values for both tempering temperatures. It is reported in the literature [11] that a static load, stress corrosion cracking is responsible for high crack growth rates within this region. The current data may be compared to predictions from theoretical models for corrosion fatigue. Environmentally assisted fatigue crack growth behavior has been described with superposition [3] and process-competition [4,5]. In the case of W1.6753 steel, the process-competition model is likely to be the most dominant cracking mechanism, assuming that the crack grows at a given ΔK_I by the faster of the mechanical and environmentally assisted mechanism. It is therefore concluded that stress-corrosion fatigue is the primary mechanism of fatigue of W1.6753 steel in NaCl solution. The superposition model is rather announced for the 35 NCD 16 steel where SCC contributes to the sudden increase of the mechanical FCG.

Table 2: Mechanical properties of W1.6753 and 35 NCD 16 steels.

Material	Quench (°C)	Temper (°C)	σ_y *MPa*	K_{IC} (MNm$^{-3/2}$)	K_{Iscc} (MNm$^{-3/2}$)
W1.6753	890	200	1477	98	15
		500	1080	107	17
35 NCD16 [10]	875	200	1992	71	13
		500	1512	104	15

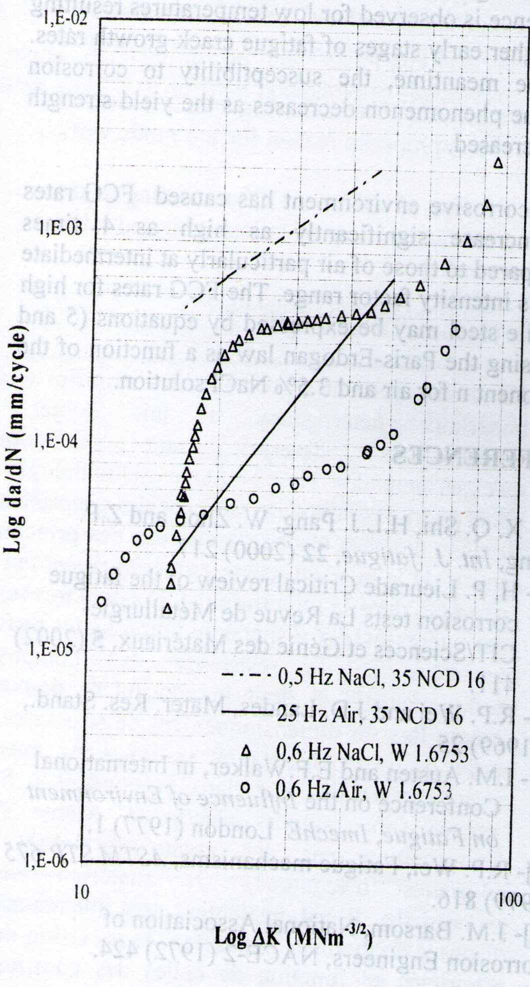

Figure 1 : Comparison of corrosion fatigue crack growth behavior in W1.6753 and 35 NCD 16 [20] steels at 200 °C tempering.

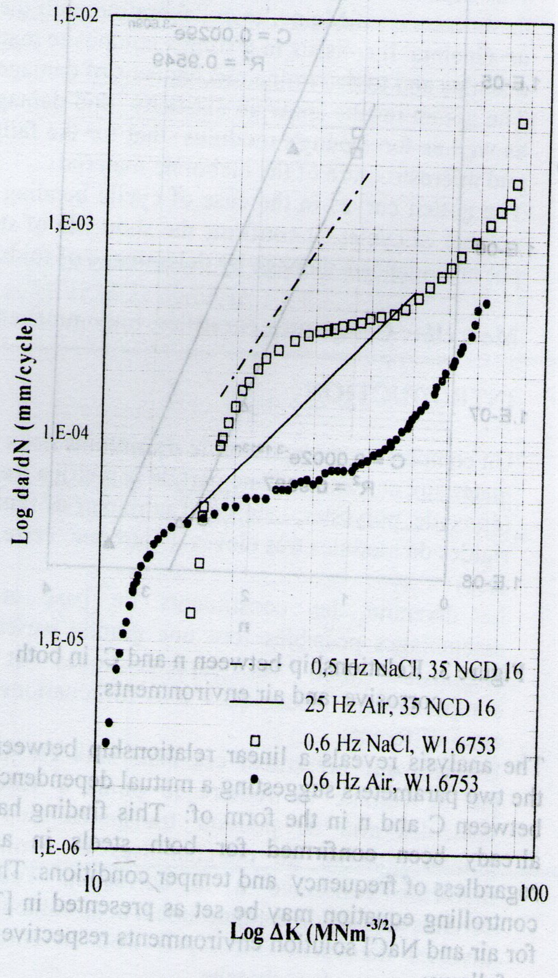

Figure 2 : Comparison of corrosion fatigue crack growth behavior in W1.6753 and 35 NCD 16 [20] steels at 500 °C tempering.

C and n parameters under corrosion fatigue:

In order to complete the CFCG study in these steels, the parameters of the Paris-Erdogan law [8] are obtained using a computer linear correlation for the prescribed data. In air, higher frequencies show higher n and lower values of C for all tempering temperatures. In NaCl solution, tempering is the most likely controlling parameter of C values since for low tempering, values of C are high and vice-versa. However, the parameter "n" is around 1 for W1.6753 steel while it ranges from 1.7 to 3.4 for 35 NCD 16 steel.

It is interesting to study the correlation between C and n as a function of testing frequency, tempering temperature and environment [7, 12-15]. To achieve this goal, a plot of Log C versus n is constructed as depicted in Figure 3.

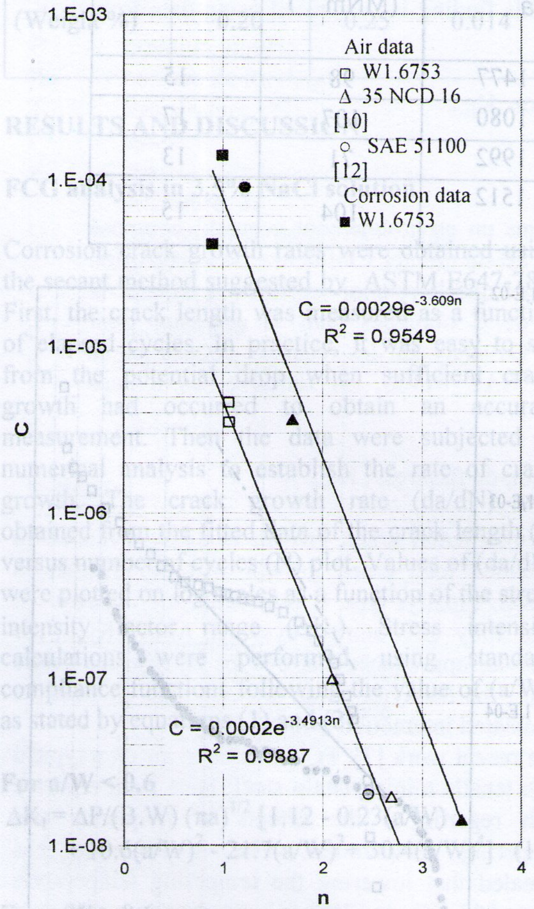

Figure 3: Relationship between n and C in both corrosive and air environments.

The analysis reveals a linear relationship between the two parameters suggesting a mutual dependence between C and n in the form of: This finding has already been confirmed for both steels in air regardless of frequency and temper conditions. The controlling equation may be set as presented in [7] for air and NaCl solution environments respectively as follows:

$$da/dN_{air} = 2.0\ 10^{-4}\ e^{-3.491\,n}\ (\ K_I)^n \quad (5)$$

$$da/dN_{cor} = 2.9\ 10^{-3}\ e^{-3.609\,n}\ (\ K_I)^n \quad (6)$$

with da/dN in mm/cycle and K_I in $MNm^{-3/2}$. Both equations are obtained with very high determination coefficients (R^2).

From Figure 3, it is concluded that corrosive environment shifts up by a factor of 10 the linear behavior of the relationship between C and n.

These equations relate in a simpler way the crack growth rate to K_I through the exponent n including in each equation aspects of tempering, frequency and environment.

$$n = a\ \mathrm{Log}C + b \quad (4)$$

CONCLUSION

Essentially, it is confirmed that W 1.6753 steel used for mining chains is very sensitive to corrosion fatigue crack propagation at low frequency. Stress-corrosion fatigue is the primary fatigue mechanism in NaCl solution.

With regards to tempering temperature, the influence is observed for low temperatures resulting in higher early stages of fatigue crack growth rates. In the meantime, the susceptibility to corrosion fatigue phenomenon decreases as the yield strength is decreased.

The corrosive environment has caused FCG rates to increase significantly as high as 4 times compared to those of air particularly at intermediate stress intensity factor range. The FCG rates for high tensile steel may be expressed by equations (5 and 6) using the Paris-Erdogan law as a function of the exponent n for air and 3.5% NaCl solution.

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