

Corrosion Fatigue Crack Growth and Threshold Stress Intensity Factors of Shipbuilding Steel

Vivek Srivastava, K Sridhar

Abstract—Conjoint action of the cyclic load and corrosive chloride ions, present in seawater leads to complex corrosion fatigue phenomena of high strength steels used in ship building applications and has resulted into premature failure of marine structures. Hence, corrosion fatigue crack growth rate (CFCGR) measurements have been carried out for indigenously developed high strength shipbuilding steel using a 50 kN servo-hydraulic at four different frequencies and also with and without cathodic protection. Threshold stress intensity factor ranges (ΔK -threshold) have been found to decrease with frequency. Fractography revealed transgranular type of failure mode at 10 Hz in air and at 1 Hz in 3.5 wt% NaCl whereas at 0.1 Hz and 0.01 Hz in 3.5 wt% NaCl, intergranular failure mode was observed. Also the effect of cathodic protection by applying sacrificial anodes on ΔK -threshold was studied at the frequency of 0.1 Hz in 3.5 wt% NaCl. It was found that ΔK -threshold for cathodically protected sample was slightly higher as compared to that of unprotected sample. Fractography revealed less severe intergranular attack for cathodically protected sample as compared to that of unprotected sample. Also number of fatigue loading cycles for a given amount of crack growth was found to be increased by three times for cathodically protected sample as compared to that of unprotected sample thereby indicating enhanced residual life for the cathodically protected component.

Index Terms Corrosion Fatigue, Crack Growth Rate, Cathodic Protection, HSLA Steel

1 INTRODUCTION

HIGH strength steels used for ship building applications are subjected to corrosive environment and cyclic loading due to sea waves and operating machinery. The conjoint action of this cyclic load and corrosive chloride ions, present in sea water leads to complex corrosion fatigue phenomenon that results into premature failure of marine structures. Hence the need to determine fatigue crack growth rate of ship building steels in simulated environment is considered of utmost importance.

The main parameters which affect the corrosion fatigue crack growth rate are stress intensity factor range, load ratio, electrochemical potential, environment, cycle frequency [1]. Two significant variables which are evaluated from corrosion fatigue measurements are (1) threshold stress intensity factor range (2) fatigue crack growth rate (FCGR). The first variable i.e. threshold stress intensity factor range (ΔK -threshold) corresponds to difference between maximum stress and minimum stress in a fatigue loading cycle. This ΔK -threshold is the minimum stress intensity factor range below which there is no significant crack growth and if the structural component is subjected to ΔK below this threshold value, the component can ideally withstand infinite number of stress cycles. This variable (ΔK -threshold) is constant for a given material of construction and is therefore used for fail-safe design of marine structures and components. The second variable i.e. fatigue crack growth rate (FCGR) is the increase in crack length per stress cycle and is generally linear over a certain stress intensity factor range (ΔK) on a log-log scale and is represented by the so called Paris equation [2] :

$$da/dN = C(\Delta K)^m \quad (1)$$

This equation is indicatively used for theoretical life prediction and residual life estimation of the structural component in marine environment.

Once designed and put into service, the marine structure can be protected from corrosion by various cathodic protection techniques like (1) use of sacrificial anodes and (2) by applying impressed current. First technique is the use of sacrificial anodes carefully selected and designed based on e.m.f series so that it is less noble than the material of the marine structure and hence acts as a anode which sacrificially dissolves into the electrolyte and making the structure to be protected as cathode thereby retarding its corrosion. Second technique of cathodic protection is the impressed current cathodic protection (ICCP) where a direct current is impressed between an inert anode and the structure which forces the electrode potential down to immune region or below a protection potential [3], [4]. However when applied potential is more negative, environmental effect of hydrogen embrittlement occurs due to reduction of water at crack tip [5], [6].

The objective of the present study are to investigate the corrosion fatigue behavior of a marine high strength steel in air and sea water at different loading frequencies, and to investigate the effect of cathodic protection by means of applying sacrificial anodes on the corrosion fatigue behavior of this steel at a particular representative frequency.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials

Structural steel studied is a high strength low alloy (HSLA) steel, denoted as 249B. This steel, quenched and tempered, exhibits a tempered martensitic microstructure as illustrated

in Fig.1. The nominal chemical composition and mechanical properties are indicated in Table 1 and 2 respectively. For the present investigation samples of 16 mm thickness plate were taken from the final production run batch of this steel.

Table 1 : Chemical composition of 249B steel (wt. %)

Fe	C	Si	S	P	Ni	Cr	Mo
Bal	≤ 0.10	≤ 0.30	≤ 0.010	≤ 0.02	1.6-2.0	0.40-0.50	0.25-0.30

Table 2: Mechanical properties of 249B steel

YS	UTS	E	Elongation
MPa	MPa	GPa	%
≥ 650	≥ 720	210	≥ 18

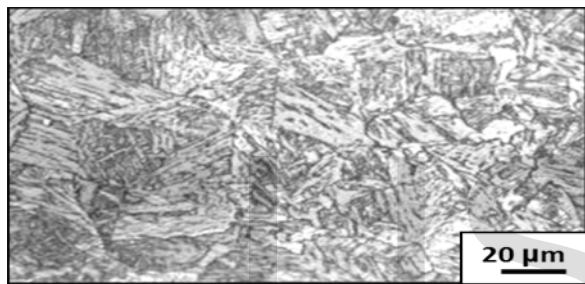


Fig 1: Microstructure of 249B steel consisting of tempered martensitic microstructure

For entire corrosion-fatigue testing of the studied steel in air and seawater media, used fracture mechanics compact-tension (CT) specimens with chevron notch were machined in the T-L direction of the specimen steel plate. The CT specimens were oriented so that the crack growth would occur parallel to the plate rolling direction. Schematic drawing of CT specimen with dimensions is given in Fig 2.

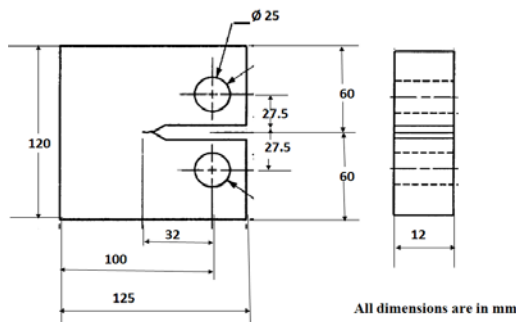


Fig 2 : Schematic drawing of CT specimen with dimensions

2.2 Experimental Procedure

The ASTM E647-08 procedure [15] was followed to determine the fatigue crack growth data, with crack-length measurements made using the compliance technique. Compliance were computed from crack mouth displacements measured using crack opening displacement (COD) gauge of 10 mm gauge length fixed on integral knife edges machined across crack mouth of the CT specimen. The CT specimens were tested in a computer-controlled servo-hydraulic machine with a load capacity of 50 kN and loading frequency capacity of 0.001 to 10 Hz. The machine was orientated horizontally so that the part of CT specimen to be cracked could readily be immersed in an aqueous 3.5 wt. % NaCl contained in a test cell. Aqueous sodium-chloride solution was used instead of actual sea-water to prevent crack closure effects due to calcareous deposits, and the aqueous sodium-chloride was dosed to give the same pH as the sea-water.

Fatigue experiments were performed under load-control mode with a load ratio of 0.1. As ASTM standard entails, the "driving force" - the stress intensity factor range (ΔK) was varied by K-decreasing procedure by limiting the normalized K-gradient, $C = (1/K)^*(dK/da)$ to the value of -0.08 mm^{-1} for near-threshold Fatigue Crack Growth Rate (FCGR) measurements and constant-load (K-increasing) procedure for steady state FCGR measurements. Experiments in air were performed at the frequency of 10 Hz and experiments in aqueous environment (3.5% NaCl - referred henceforth as sea water-SW) were conducted at three different frequencies of 1, 0.1 and 0.01 Hz in freely corroding condition. Fatigue pre-cracking of each CT specimen was carried out in air for air experiment tests and in air and subsequently in SW for SW experiment tests.

The pH and the salinity of the medium were monitored every alternate day and the chloride solution was changed with fresh NaCl solution based on the need and the condition of the same. For cathodic protection study, frequency employed was 0.1 Hz and the sacrificial anodes used were made of commercially available aluminum-indium alloy. Fractography of the fractured fatigue tested samples in air and corrosion fatigue tested samples in seawater was conducted using LEO 1414 scanning electron microscope (SEM) to analyze the fracture morphology and understand the crack propagation and failure mechanism.

3 RESULTS AND DISCUSSION

3.1 Effect of frequency on corrosion fatigue behavior

The resultant plot between rate of crack growth i.e. da/dN vs stress intensity factor range i.e. ΔK on log-log scale for air at 10 Hz and sea water at 1, 0.1 and 0.01 Hz is presented in Fig. 3. The plot clearly shows that there is marginal difference in the threshold stress intensity factor range values and crack growth rates in the case of specimen tested in air at 10 Hz and that in sea water at 1 Hz. The threshold stress intensity factor range values at 0.1 Hz is quite low as compared to that at 1 Hz whereas threshold values at 0.01 Hz is quite close to that at 0.1

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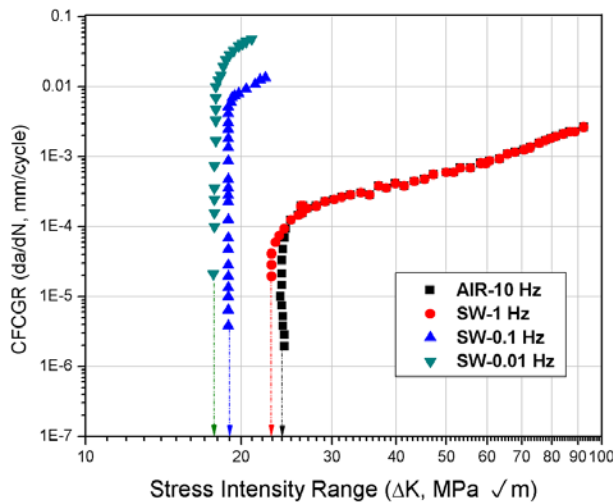


Fig 3: CFCGR plot (da/dN vs ΔK) of 249B Steel at various frequencies

Table 3 gives the comparative values of ΔK-threshold and Paris constants (m & C) for testing carried out in air and sea water. From the table it is clear that the ΔK-threshold has reduced from 24 MPa (m)^{1/2} in air to that of 18 MPa(m)^{1/2} in 3.5wt% NaCl at 0.01 Hz. This clearly indicates the conjoint role of chloride attack on the freshly created crack faces and that of the fluctuating load (fatigue) on lowering the threshold stress intensity factor range [7]. Also it can be observed that lower the frequency, the FCGR value in Paris region plateau is higher which is reported by Vosikovsky [5] as well. This is actually due to environmental effect of hydrogen embrittlement because of water reduction at crack tip resulting into higher values of the Paris constants. Paris constants (m and C) computed from experimental CFCGR plots are material-specific and can be utilized for fatigue life assessment of structures constructed from the steel material by integrating Equation (1) discussed in previous section.

Table 3: Threshold stress intensity factor range and Paris constants as a function of frequency of corrosion fatigue testing

Specimen Code	Medium	Fatigue Loading Frequency (Hz)	Threshold Stress Intensity Range, (MPa√m)	Paris Exponent, m	Paris Coefficient, C (MKS units)
AIR-10Hz	Air	10	24	2.40	4.84 E-11
SW-1 Hz	3.5 % NaCl	1	23	2.44	4.09 E-11
SW-0.1Hz	3.5 % NaCl	0.1	19	3.98	2.63 E-12
SW-0.01 Hz	3.5 % NaCl	0.01	18	4.48	2.85 E-12

In order to establish the underlying mechanism on the said behaviour of the steel when tested in chloride medium, fractography was carried out using SEM. The fractured surface was thoroughly cleaned with cleaning solution as per the ASTM standard G1 for removal of corrosion products from ferrous-based materials before observing under SEM. The fractography obtained from SEM observation is shown in Fig 4. From the figure, it is evident that fractography in air (Fig. 4a) revealed transgranular features with cleavage facets which changed to transgranular fracture morphology with finer pits at discrete locations when tested in 3.5 wt% NaCl at 1 Hz (Fig. 4b). This is attributed to the attack of chloride ions on the newly formed crack surface during the progress of testing.

On further reducing the frequency to 0.1 Hz, fractographic features revealed deep secondary intergranular cracks along with numerous pits on the fractured surface (Fig. 4c). This is because the time duration available corrosion-induced attack on the crack face subjected to fatigue loading increases with decreasing frequency of testing. Finally at 0.01 Hz frequency of testing, the fractography exhibited severe intergranular cracking along with de-cohesion of grains at various locations on the crack face (Fig. 4d). This could be attributed to the susceptibility of grain boundary regions for corrosive attack especially at very low frequencies (0.01 Hz) due to higher exposure time duration availability at the crack front to aggressive chemical species (chloride ions)[8]. The effect becomes more significant under cyclic loading conditions and this has led to much lower threshold values of stress intensity factor range as compared to that in air.

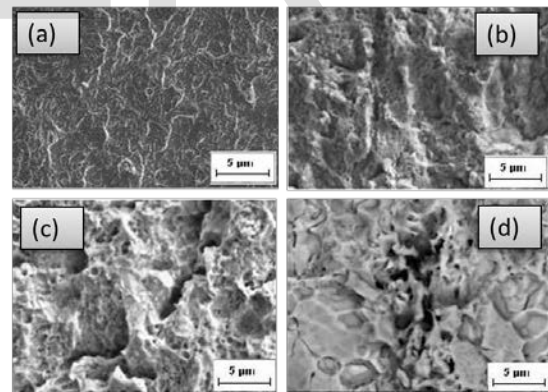


Fig 4(a-d): Fractography of fatigue tested samples in air and 3.5 wt % NaCl (SW) at various frequencies

3.2 Effect of Cathodic Protection on Corrosion Fatigue Behavior

Fig 5 presents the da/dN vs delta K plot without and with cathodic protection (by applying sacrificial anodes) at 0.1 Hz in sea water. It reveals clearly the positive effect of cathodic protection as the threshold stress intensity factor range is little higher (18 MPa (m)^{1/2}) for protected specimen than that for unprotected sample (16 MPa (m)^{1/2}). These values are the average of the values obtained experimentally for two number of

samples to establish repeatability of the data. From Fig 5, at a given crack growth rate viz. 1.00×10^{-3} , cathodically protected sample can sustain a stress intensity factor range ΔK of approx. $\approx 30 \text{ MPa(m)}^{1/2}$ whereas unprotected sample can sustain only $\approx 18 \text{ MPa(m)}^{1/2}$. Fig 6 shows that for around 10 mm (a(f) - a(i)) of crack growth range, number of fatigue loading cycles required for freely corroding unprotected sample is approximately 37,700 cycles (N(f-fc) - N(i-fc)) whereas the same for cathodically protected sample is approximately 1,14,000 cycles (N(f-cp) - N(i-cp)) which is three times more. This indicates that larger number of fatigue loading cycles is required for same amount of crack growth in cathodically protected sample as compared to that in freely corroding cathodically unprotected sample which essentially means that the residual life of the cathodically protected component is enhanced. It is well reported that threshold stress intensity factor range value increases under cathodic protection [9] and threshold and near threshold behavior in structural steels have a significant role on calculated lifetimes of components [10]. Thus the main benefits of cathodic protection are gained in the threshold/near threshold region of fatigue crack growth [9].

arises due to quasi-cleavage or intergranular fracture along with the presence of secondary cracks and is representative of hydrogen affected crack growth [11-14]. Thus cathodically protected sample shows less susceptibility towards planar mode of failure as compared to that of cathodically unprotected sample.

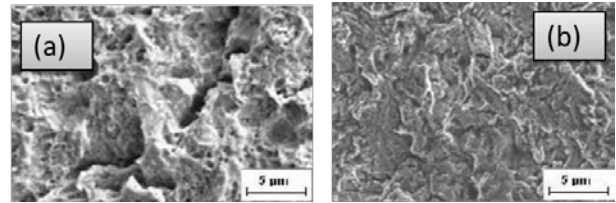


Fig 7: Fractography of specimens tested at 0.1 Hz in 3.5% NaCl without and with CP (cathodic protection)

4 CONCLUSIONS

Corrosion fatigue behavior of a high strength steel for marine applications in air and 3.5% NaCl at different frequencies and effect of cathodic protection (by sacrificial anodes) were studied. It was found that the threshold stress intensity factor range (ΔK -threshold) decreased with decreasing frequencies and severity of corrosive attack increases due to higher exposure time of aggressive chloride ions on the crack front at lower frequencies. SEM fractography also indicated increasing degree of damage in terms of intergranular cracking and decohesion of grains at decreasing frequencies. Threshold stress intensity factor range (ΔK -threshold) increased for cathodically protected specimen as compared to that of unprotected sample. Larger number of cycles is needed in case of cathodically protected specimens for the same amount of crack growth which means that the residual life of the component is enhanced due to cathodic protection. Also fractography suggests less severe planar mode damage for the cathodically protected component as opposed to freely corroding component.

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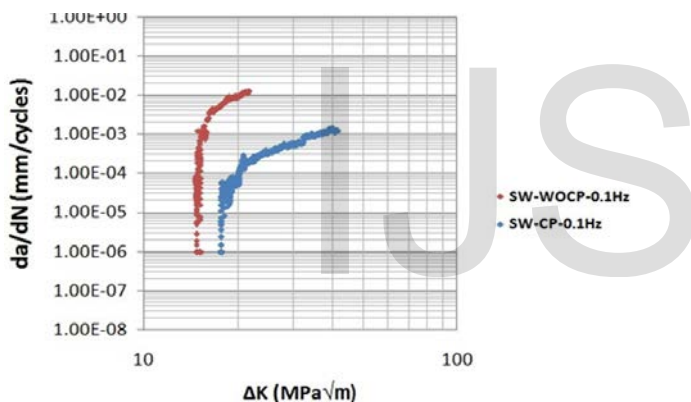


Fig 5: Comparative da/dN vs delta K for cathodically protected and unprotected specimens tested at 0.1 Hz in 3.5% NaCl(SW)

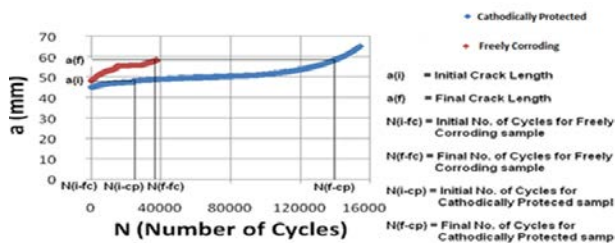


Fig 6 : Crack length (a) vs number of cycles (N) plot for cathodically protected and freely corroding specimens

Fig 7 shows the fractography of the cathodically protected and unprotected sample. Fractography of tested samples in seawater indicate planar mode of failure in both cases but less severe in cathodically protected sample (Fig. 7b) as compared to that of unprotected sample (Fig. 7a). Planar mode of failure

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