ESTIMATION OF STRESS INTENSITY FACTOR FOR CORROSIVE ENVIRONMENT

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology

In

Metallurgical and Materials Engineering

By

Sagar Ranjan Pradhan(10604035)

&

Arijit Bhattacharjee(10604006)

Department of Metallurgical and Materials Engineering.

National Institute of Technology

Rourkela

2010

ESTIMATION OF STRESS INTENSITY FACTOR FOR CORROSIVE ENVIRONMENT

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology

In

Metallurgical and Materials Engineering

By

Sagar Ranjan Pradhan(10604035) & Arijit Bhattacharjee(10604006)

Under the guidance of

Prof.B.B.Verma

Dept. Metallurgical and Materials Engg.

Prof.P.K.Ray

Dept. Mechanical Engg.

Department of Metallurgical and Materials Engineering.

National Institute of Technology

Rourkela

2010

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled, "ESTIMATION OF STRESS INTENSITY FACTOR FOR CORROSIVE ENVIRONMENT" submitted by Sagar Ranjan Pradhan (10604035) and Arijit Bhattacharjee (10604006) in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Metallurgical & Materials Engineering at the National Institute Of Technology, Rourkela is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Date:

Dr.B.B.Verma	Dr.P.K.Ray
Dept. of Metallurgical & Materials Engineering,	Dept. of Mechanical Engineering
National Institute of Technology	National Institute of Technology
Rourkela	Rourkela

ACKNOWLEDGEMENT

We express our heartfelt gratitude and regards to our project guide Dr.B.B.Verma, Head of the Department, Department of Metallurgical & Materials Engineering, National Institute of Technology, Rourkela for his guidance. He always bestowed parental care upon us and evinced keen interest in solving our problems. An erudite teacher, a magnificent person and a strict disciplinarian, we consider ourselves fortunate to have worked under his supervision. We are also grateful to him for providing us necessary facilities during the course of our work.

We are highly grateful to Prof.P.K.Ray, Department of Mechanical Engineering, NIT Rourkela, for his constant guidance, support and stimulating ideas.

We are thankful to Dr.A.K.Panda & Dr.M.KUMAR, Project Coordinators, Department of Metallurgical & Materials Engineering,NIT Rourkela for giving us such a mind stimulating and innovative project.

We wish to place our deep sense of thanks to Mr.Heymbram for his cooperation

Date: Sagar Ranjan Pradhan(10604035)

Place: Arijit Bhattacharjee (10604006)

INDEX

ABSTRACT

Corrosion fatigue refers to the damage and failure of material under the combined action of cyclic stresses and corrosive environment, which affect the life of fatigue critical structures, such as, aero structures, submarine hulls, offshore structures etc. Several surveys have shown that 20-40 % of all engineering failures are due to corrosion fatigue [1]. The corrosive environment may be considered as a condition of enhanced crack growth rate (under constant stress intensity factor) or decrease in net ΔK to maintain the same crack growth rate. In the present investigation an attempt has been made to develop a model to correlate net ΔK with crack length and frequency. The developed model was validated using experimental data generated for 7475-T7351 alloy in aqueous solution of 3.5% NaCl. It is also noticed that the frequency significantly does affect the crack growth rate (constant ΔK) and the maximum crack growth rate is usually achieved at an intermediate frequency.

INTRODUCTION

From the century long research we know that the presence of aggressive environment enhances the fatigue crack growth rate and decreases component life drastically. The simultaneous action of cyclic stress and chemical attack is known as corrosion fatigue [13]. It is one of the major factors that affect the life of aerospace structure, especially which are exposed to marine environment. Traditionally prediction of fatigue life methodologies was based on smooth specimen yielding and fatigue data in most air environment where the time-dependent chemical action of aggressive environments has been often ignored [2-4]. There are several approaches to incorporate the environmental effects into fatigue life prediction such as (i) fracture mechanics approach by incorporating elastic plastic fracture mechanics parameters to characterise the influence of microstructure [16] (ii) life prediction by measuring the crack growth rate for those materials, environment, loading and frequency conditions which are exactly selected to reproduce a specific application. Ford, Wei, Nicholas and co-workers advocate the development of crack growth models which enable prediction of the effects of important variables, particularly ΔK, environment chemistry and frequency [5-11]. These models are based on empirical curve fitting, linear superposition of mechanical fatigue and monotonic load environmental cracking data.

LITERATURE SURVEY

CORROSION FATIGUE

Corrosion-fatigue is simultaneous action of cyclic stress and corrosive environment. It is observed that all engineering structures experience some form of alternating stress and are exposed to corrosive environments during their service life. The environment plays a very significant role in the fatigue of high strength structural materials like steels, aluminum alloys and titanium alloys. In a corrosive environment the stress level at which it could be assumed a material has infinite life is lowered or removed completely. As compared to a pure mechanical fatigue, there is no fatigue limit load in corrosion-assisted fatigue. Much shorter failure times and much lower failure stresses can occur in a corrosive environment compared to the condition where the alternating stress is in a non-corrosive environment. In normal fatigue testing of smooth specimens, about 90% of the life is spent crack nucleation and only the remaining 10% in crack propagation. However in corrosion fatigue, crack nucleation is facilitated by corrosion and typically about 10 % of life is sufficient for this stage. The rest, 90% of life is spent in crack propagation.

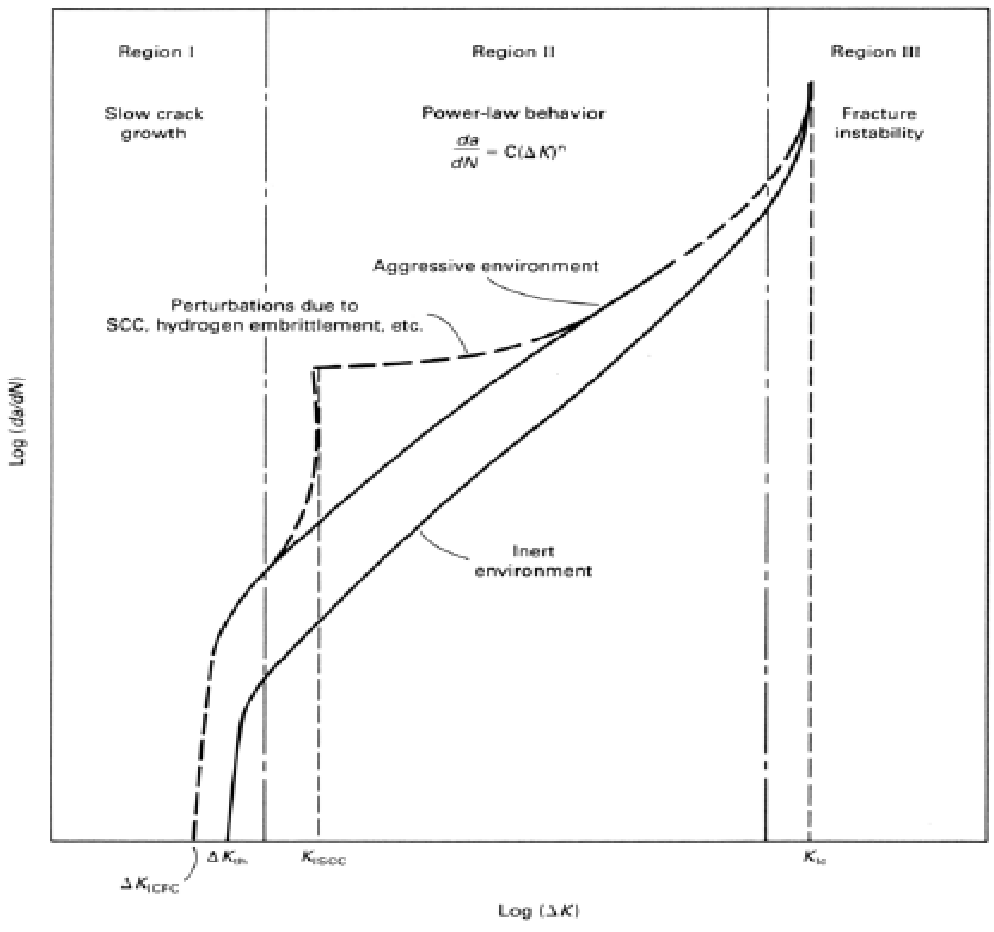

Fig.1. Schematic representation of role of corrosive environment on fatigue crack propagation. [12]

Fig.1 illustrates, corrosion process have strong influences on the fatigue life of a structure. The existence of a regime in which slow crack growth occurs according to Paris law is eliminated, and small cracks grow quickly into large cracks.[13]

Due to the deleterious effect of corrosion fatigue it is highly essential to study it in detail. Many corrosion fatigue models have been proposed such as:

CORROSION FATIGUE SUPERPOSITION MODEL [14]

A model developed by Wei, Landes and Bucci which accounted for effects of environment, test frequency, wave form, and load ratio on corrosion fatigue crack propagation behavior. Crack extension rate under corrosion fatigue conditions was approximated by a superposition of intrinsic fatigue crack growth rate (inert atmosphere) and the crack extension rate due to a sustained load is as follows:

$(da/dN)_T = (da/dN)_{fat} + \int (da/dt)K(t)dt$

Where $(da/dN)_T$= total corrosion fatigue crack growth rate

$(da/dN)_{fat}$=fatigue crack growth rate defined in an inert atmosphere

da/dt=crack growth rate under sustained loading

K(t)=time dependent change in stress intensity factor

One of the peculiar characteristic of this model is its linear character, which implies no interaction between the purely mechanical and environmental components.

QUANTITATIVE CORROSION FATIGUE CRACK GROWTH MODEL[15]

Linear superposition concept was first proposed by Wei, Landes, Gallagher and Bucci where prediction of environment enhanced crack growth rate, da/dN_e , by combining inert environment fatigue crack growth rate, da/dN_m , with time-dependent, monotonic load environment crack growth rate, da/dN_{scc}.

$da/dN_c = da/dN_m + da/dN_{scc}$ (1)

da/dN_{scc} is computed by integrating the sustained-load crack growth data and the applied time-dependent stress intensity factor in a single fatigue load cycle K(t). Mathematically, da/dN_{scc} is given by:

$$da/dN_{scc} = \int_0^{1/f} [da/dt(K)][K(t)]dt \quad (2)$$

K(t) is stated as a function of time , employing the loading parameters ΔK and R(or K_{min} and K_{max})

An example of a sinusoidal load cycle, with frequency f, is:

$K(t) = K_{min} + \Delta K/(2-\cos(2\pi ft))$ (3)

The linear superposition model reasonably predicts environmental fatigue crack propagation rates as a function of ΔK ,R ,f and waveform.

This model is able to predict the effects of variables such as stress ratio, frequency, environmental activity, yield strength, loading waveform and microstructure on the fatigue crack growth in corrosive environment.

MODIFIED HOBSON MODEL [16]

Here corrosion fatigue failure is described to be a multiple stage process namely; pit development, short crack growth, and long crack growth. Corrosion fatigue crack growth rates are predicted by employing models. Elastic plastic fracture mechanics parameters were incorporated to characterise the influence of microstructure. Two empirical corrosion fatigue crack growth models, including a superposition model discussing the inert air and environmental terms involved in the corrosion fatigue process were presented.

EMPERICAL CURVE FITTING[15]

The empirical curve fitting approach required systematic regression analysis of relatively extensive experimental Fatigue Crack Propagation data to determine the functional relationships between da/dN and ΔK, as well as other associated variables such as frequency, R and hold time. A notable example of this is provided by the analysis of corrosion fatigue cracking in welded steel tubular joints for oil and gas platforms used in marine environments [17]. As input to a similitude-based fatigue life prediction, Hudak and co-workers empirically described the upper bounds on these data sets with a four-variable model describing three commonly observed crack growth regions [17]:

$$1/(da/dN)=A1/ LAMETAK^{n1} + A2/ LAMTAK^{n2} - A/ [(1 - R)Kc]^{n2} \quad (4)$$

where A, A1, n1, A2, n2 are empirical constants and Kc represents the onset of final fracture. An agreement was demonstrated between predicted fatigue lives and measured fatigue life for large scale welded tubular components. Life prediction was particularly quite accurate for the air environment case where extensive Fatigue Crack Propagation data were available and where the effect of loading frequency is of no importance.

MSE MODEL [15]

The modified sigmoidal equation (MSE) model was first proposed to represent Fatigue Crack Propagation data for the superalloy, AFll5 [18]. This growth rate relationship is of the form:

$$(da/dN)=\exp(B)[(\Delta K/\Delta K^*)^{P} \{\ln(\Delta K/\Delta K^*)\}^{Q} \{\ln(K_0/K)\}D] \quad (5)$$

This equation represents a sigmoid shape with the lower asymptote Δ K*, representing the threshold value of ΔK and the upper asymptote, ΔK_C, representing the critical or maximum value of Δ K for overload fracture. The remaining four coefficients (B, P, Q and D) depend on the four test parameters, T, f, R and τ_c. These coefficients, however, interact complexly in controlling the shape and location of the sigmoid curve, making it difficult to determine B, P, Q and D as functions of T, f, R and τ_H. To tackle this difficulty, alternate coefficients were introduced as [19, 20]:

$$da/dN=\exp(B')[(\text{del } K/\text{del } K_i)^P \{\ln(\text{del } K/\text{del } K^*)\}^Q\{\ln(\text{del } K_c/\text{del } K)\}^D] \quad (6)$$

$$\text{where } P=(da/dn_i)'-Q/\ln(\text{del } Ki/\text{del } K^*) + D/\ln(\text{del } K_c/\text{del } K_i) \quad (7)$$

$$B'=\ln(da/dNi)-Q\ln[\ln(\text{del}K_i/\text{del } K^*)] - D\ln[\ln(\text{del } K_c/\text{del } K_i)] \quad (8)$$

The new parameters, del K_i, da/dNi and $(da/dN_i)'$, represent the horizontal and vertical locations of the inflection point, as well as the slope at that point, respectively. The parameters Q and D are shaping parameters such that the da/dN versus del K relationship is symmetric when Q=-D.

SINH model [15]

A second curve fitting approach which utilises a hyperbolic sine fimction, was developed principally for interpolating elevated temperature fatigue crack growth data for nickel-based superalloys [11, 21].

.

EXPERIMENTATION

The material used in this study was 12.5 mm thick plate of 7475 aluminium alloy of chemical composition (in wt%) 5.73 Zn, 2.14 Mg, 1.15 Cu, 0.02 Cr, 0.05 Fe, 0.04 Si and Al (balance). The alloy was supplied in T7351 thermomechanically treated condition (yield stress = 495 MPa and elongation = 14%). The T7351 treatment involved solution treatment at 470ºC, water quenching and controlled stretching from 1.5-3.0% followed by artificial ageing in two staging: 121ºC for 25h subsequently at 163ºC for 24-30h. Fatigue crack growth studies were performed on 50 mm wide and 12.5 mm thick CT-specimens machined in TL orientation. The dimensional details of CT-specimen are provided in Fig. 2.

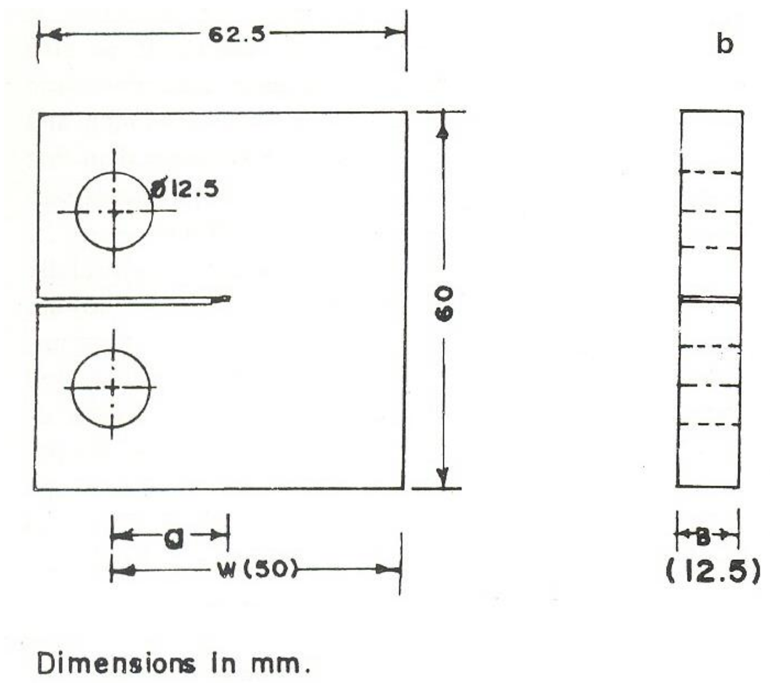

Fig 2. Dimensional details of (a) CT-specimen

The polished and degreases specimens were then pre-cracked to a total crack length of nearly 17 mm (*a*/*w* ~ 0.34) before performing the crack growth studies. The fatigue crack growth rate (FCGR) studies were conducted on pre cracked CT- specimens in tension-tension, sinusoidal loading condition at stress ratio, R= 0.2. The tests were conducted under constant load range condition, corresponding to a rising stress intensity range, ΔK, with the crack extension. The tests were carried out using a 100 kN servo hydraulic testing machine. All air tests were conducted at a frequency of 1 Hz. The environmental tests were performed in a plastic bath in aqueous solution of 3.5% NaCl at room temperature contained in a plastic bath whose pH was monitored and maintained at 8.2.aqueous solution at frequencies 0.0166, 0.022, 0.17, 0.45, 0.6, 0.90, 1.7 Hz. The crack extension was monitored using the direct current potential drop technique. [22]

MODELLING METHODOLOGY

Since for the calculation of ΔK_{net} there is no definite formula available in the text books our work is mainly to formulate method to calculate it. For the prediction of ΔK_{net} we first plot the da/dN verses crack length (*a*) as shown in figure 3. For different frequency in NaCl environment (as mentioned in experimental work).

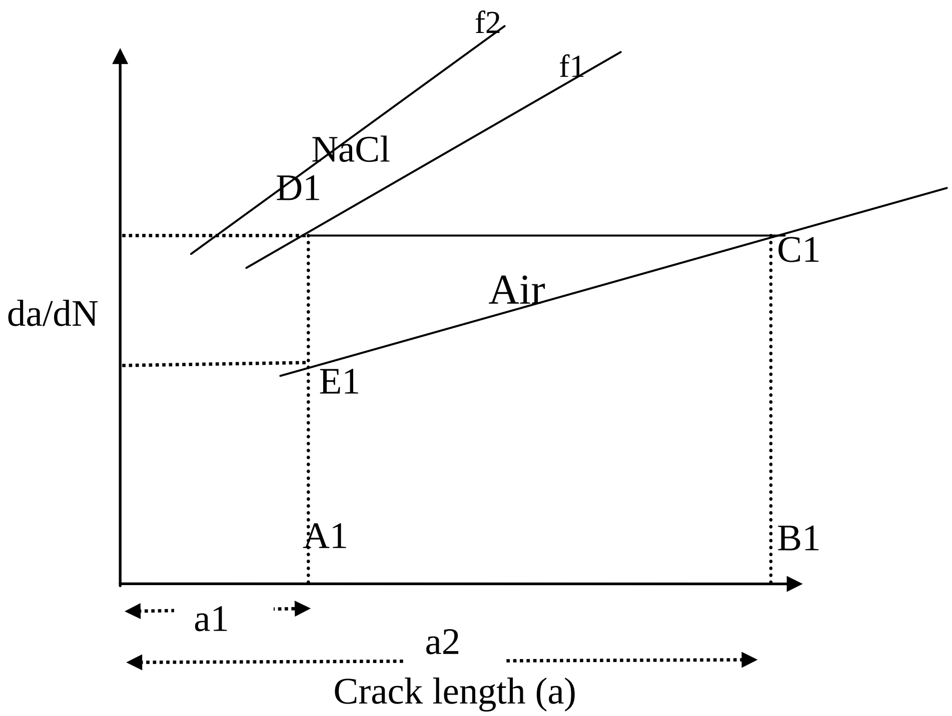

Fig 3 . da/dN vs crack length for different frequency

Since frequency has negligible effect on fatigue properties in air so the effect can be neglected. For calculation of ΔK_{net} for crack length a1 we extrapolated the point D1 to point C1 for the same da/dN for NaCl and that of air and ΔK_{net} (air equivalent) was calculated for crack length a2.

RESULT AND DISCUSSION

The crack length (*a*) verses number of cycle (*N*) for air and NaCl environment as mentioned in experimental work was plotted and curve was fitted. One of the graph showing relation between a vs N for air (3Hz) and NaCl (0.022Hz) is shown in fig 4(a) and (b).

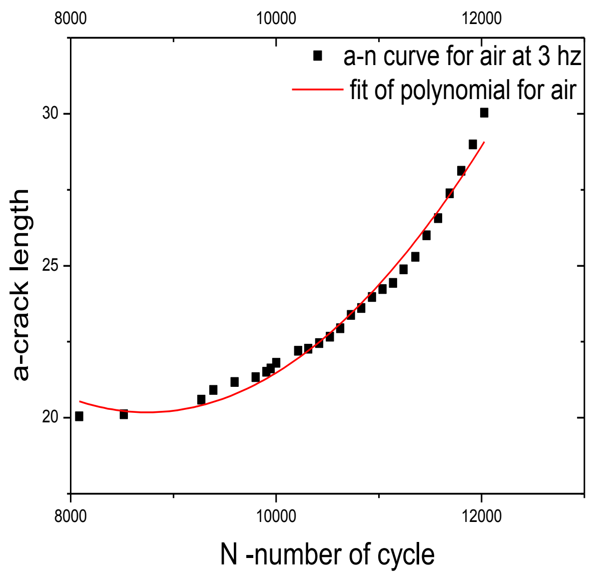

Fig:4 (a) a vs N plot for air

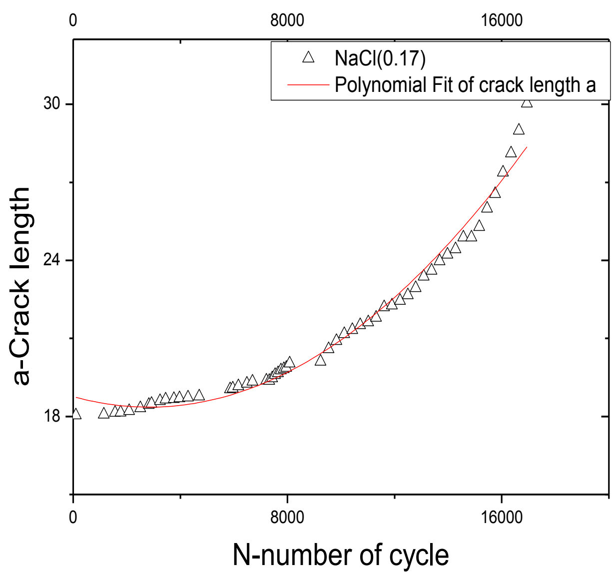

Fig:4(b) a vs N plot for NaCl

From the *a-N* plot da/dN was calculated. ΔK_m(mechanical) was calculated using the formula

$\Delta K_m = (\Delta P)(f(a/w))/BW^{1/2}$

where $f(a/w)= ((2 + (a/w))/(1-(a/w))^{3/2})[0.886+4.64(a/w)-13.32(a/w)^2+14.72(a/w)^3-5.6(a/w)^4]$ for C(T) specimen . [14]

da/dN vs ΔK_m was plotted as shown in fig 5.

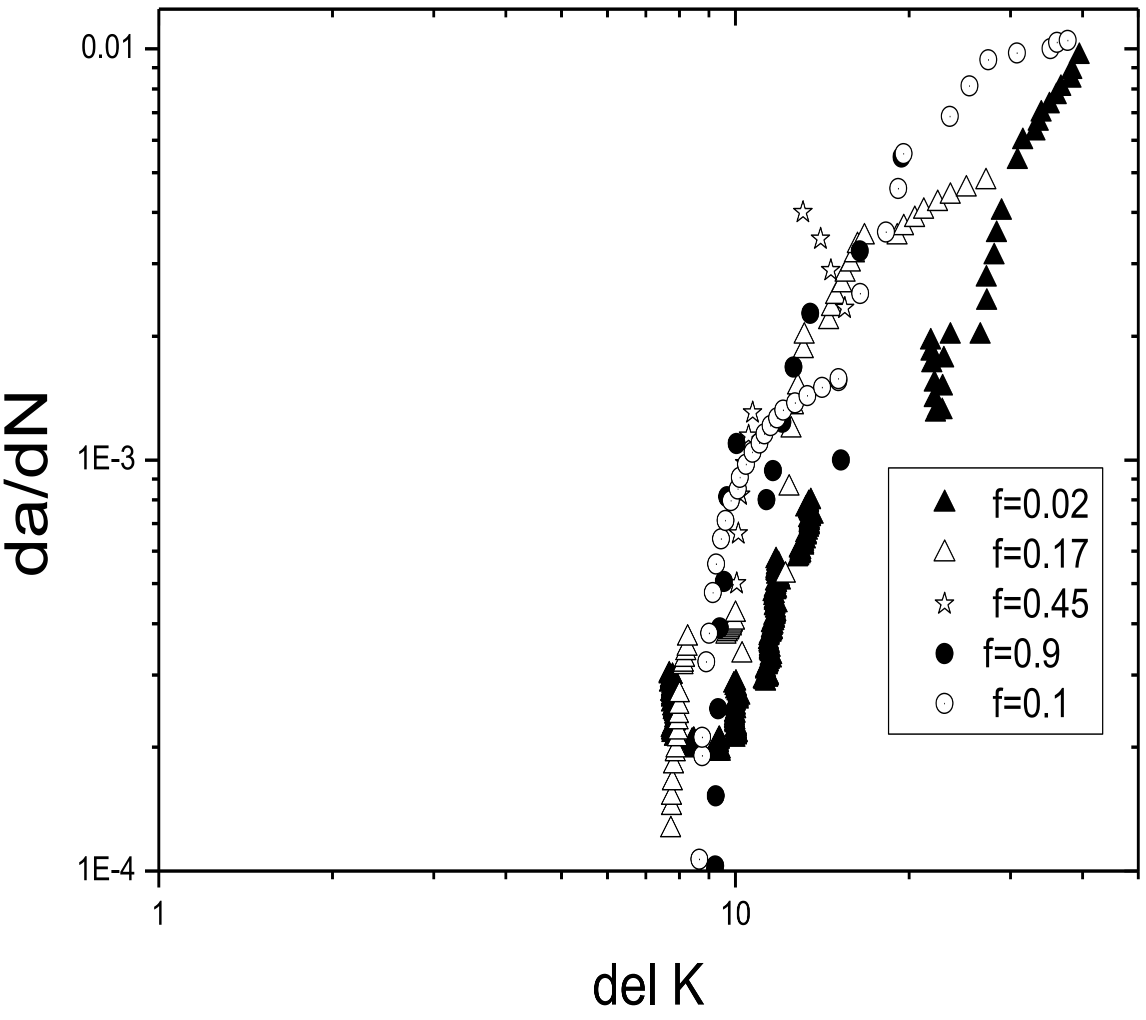

Fig5: Plot showing da/dN vs ΔK_m [22]

da/dN verses crack length (a) was plotted as shown in figure 6

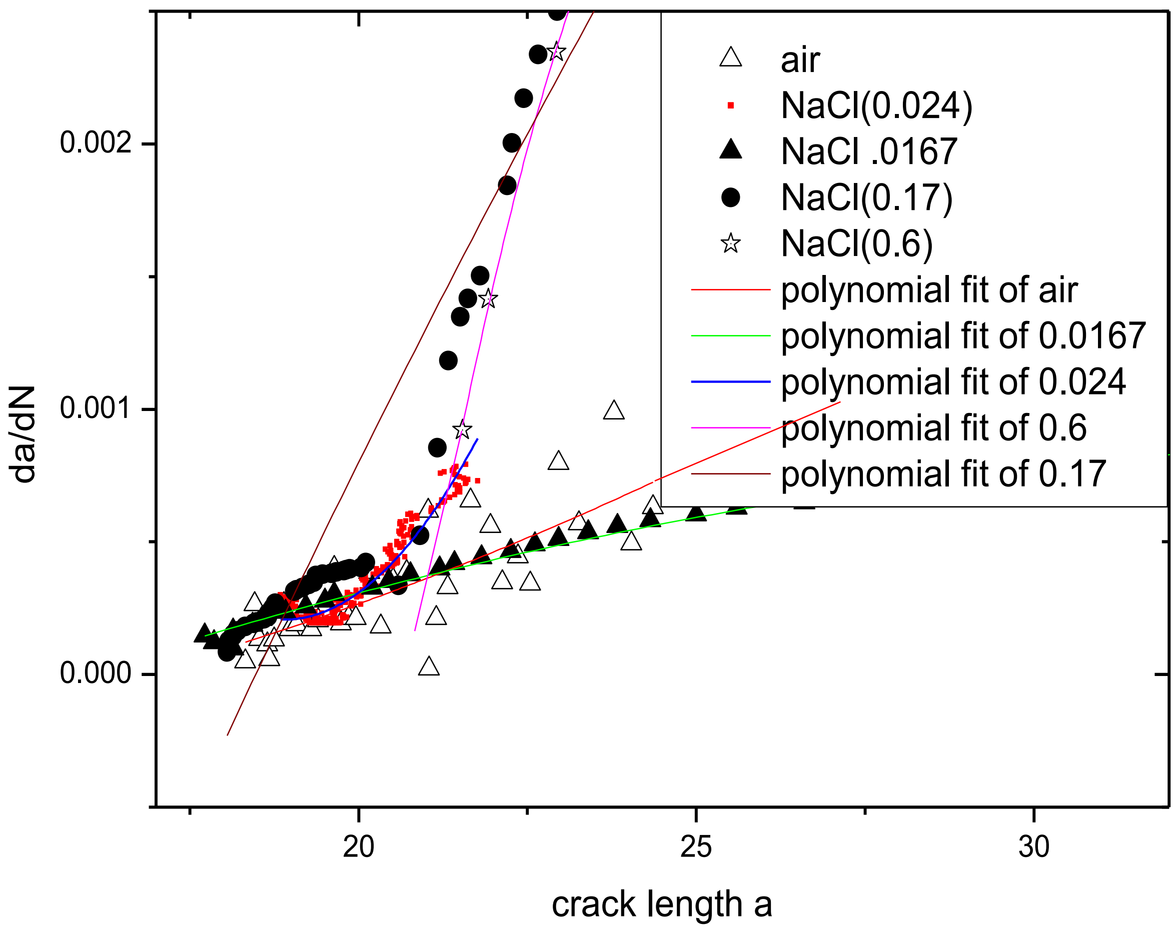

Fig6 : Graph between da/dN vs Crack length(a)

From the graph it is clear that with increase in frequency from 0.0167 Hz to 0.6 Hz the slope of da/dN verses crack length increases for NaCl environment, the effect of frequency on da/dN in air is negligible[22] hence neglected. An attempt to calculate ΔK_{net} is done by calculating the ΔK_{net} (air equivanlent of corrosion) by the following method

(i) Let the crack for which ΔK_{net} is to be calculated be a1for 0.6Hz
(ii) From the graph da/dN corresponding to C1 is extrapolated to meet the curve for air and ΔK_{net}(air equivalent) was calculated where crack length corresponds to a2 as shown in figure7.

ΔK_{net} verses crack length was plotted and the following behaviour was observed as shown in figure 8.

From the graph it is clear that the slope of ΔK_{net} versus crack length increases with increase in frequency . ΔK_{net} is expressed as

ΔK_{net} =X(a/w)^2 + Y(a/w)+Z

Where X, Y & Z varies with frequency as follows (Fig 9(a), (b) & (c))

$X= -80934.76f^2 + 31147.7f – 465.44$

$Y= 64479.7f^2 - 22002f + 359.74$

$Z= -13400\ f^2 + 4109.3f-62.55$

Where f is the frequency in Hz

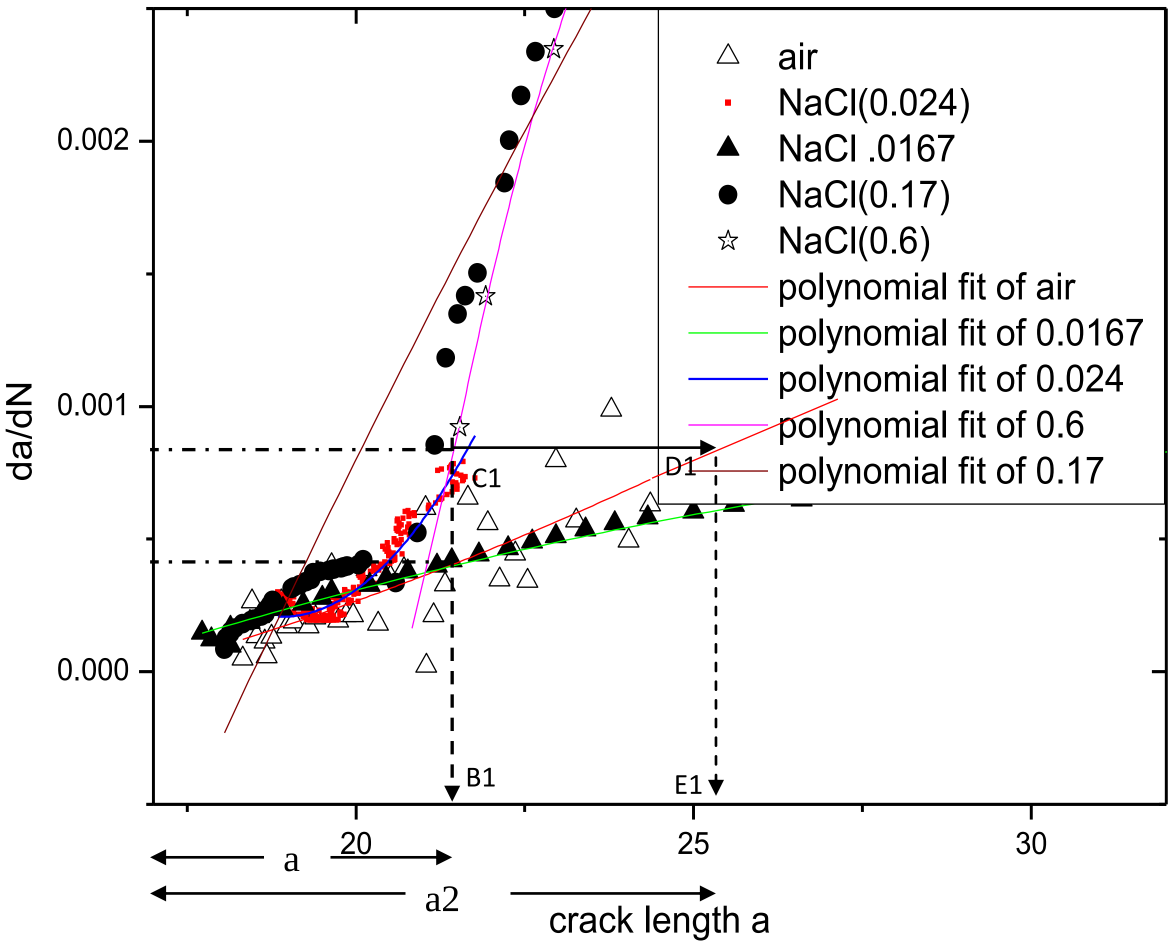

Fig 7: Calculation of ΔK_{net} by extrapolation.

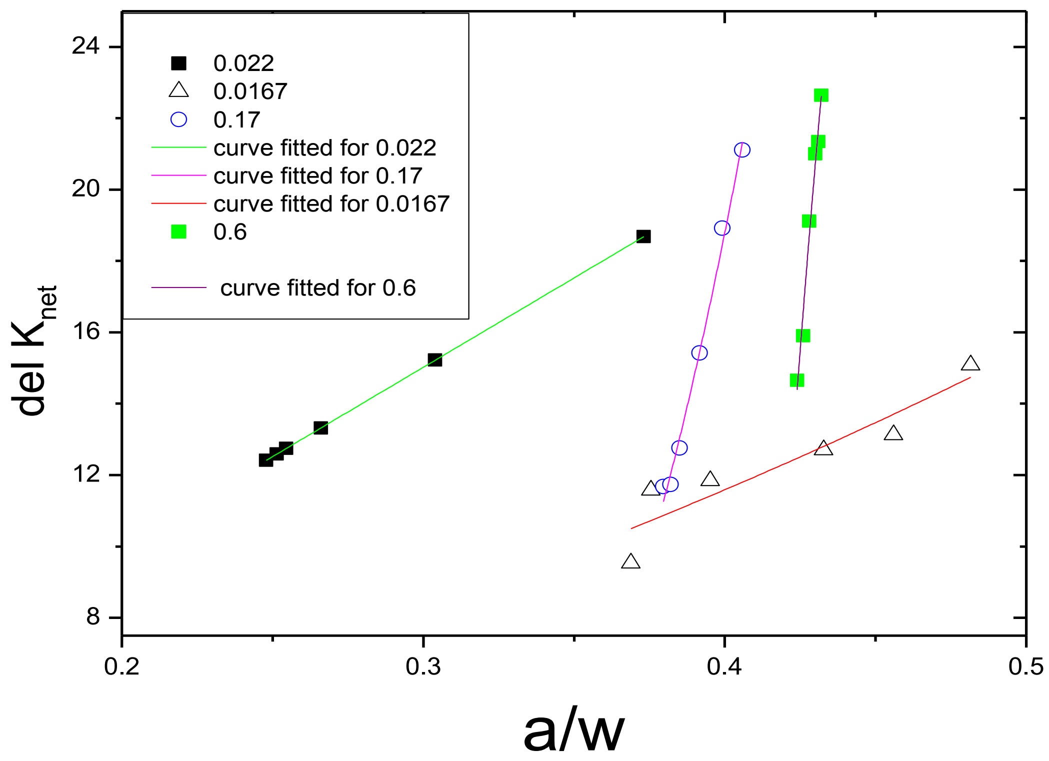

Fig 8: Relation between ΔK_{net} vs a/w

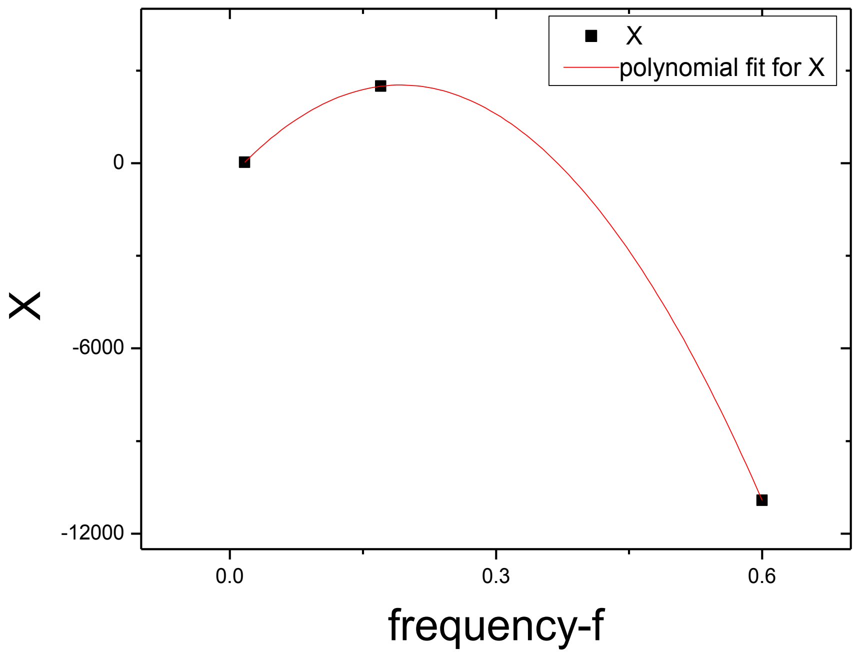

Fig 9(a) : Graph between X vs frequency-f

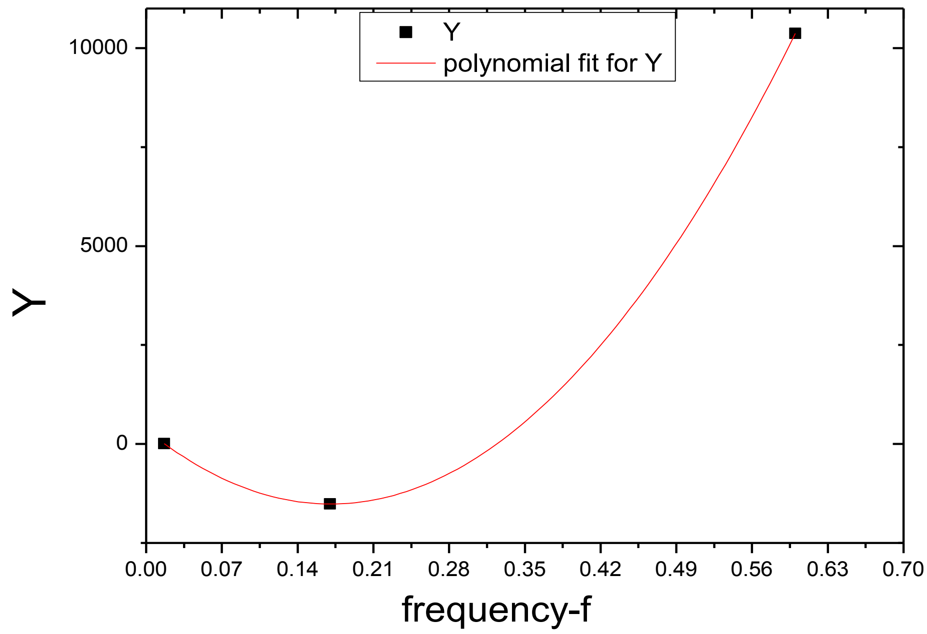

Fig 9(b) : Graph between Y vs frequency-f

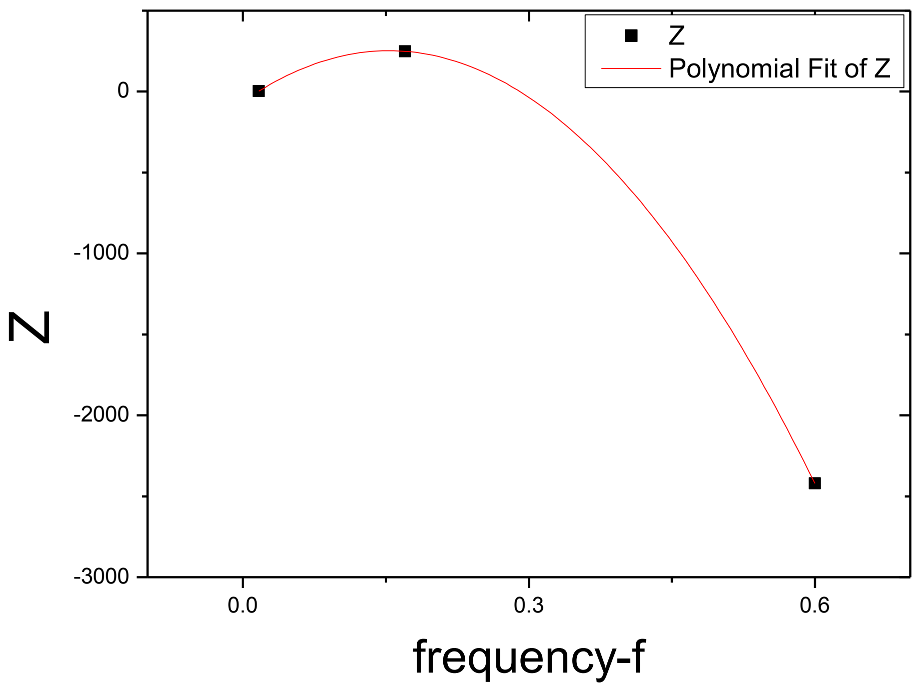

Fig 9(c) : Graph between Z vs frequency-f

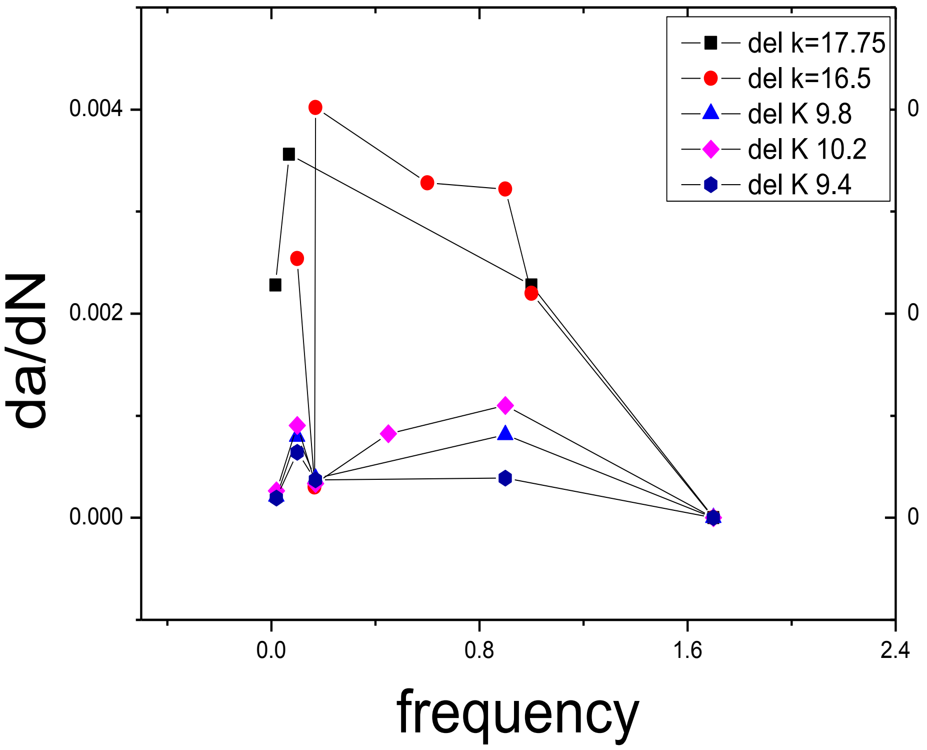

Fig 10: Relation between da/dN verses frequency

From figure 10 it is clear that da/dN vs frequency follows a definite trend i.e. da/dN increases to a higher value and then again decreases with increase in frequency.

VALIDATION OF THE MODEL

The equation obtained for ΔK_{net} is as follows

$\Delta K_{net} = X(a/w)^2 + Y(a/w) + Z$

Where X, Y & Z varies with frequency as follows (Fig 10(a), (b) & (c))

$X = -80934.76f^2 + 31147.7f - 465.44$

$Y = 64479.7f^2 - 22002f + 359.74$

$Z = -13400\, f^2 + 4109.3f - 62.55$

For validation we considered frequency= 0.022 Hz and crack length (a) as 20.081mm we obtained the theoretical value as 13.15 Mpa$(m)^{1/2}$. On comparing with the experimental value (12.41 Mpa$(m)^{1/2}$) we found the error as 5.96%.

CONCLUSION

The conclusions drawn are as follows

1. Fatigue test frequency affects significantly the crack growth rate. At low frequency the required level of ΔK to maintain a given crack growth rate is higher than higher frequency test.

2. Increase in test frequency increases slope of the ΔK_{net} vs (a/w) curve.

3. Following equation was developed to correlate net stress intensity factor in corrosive environment, crack length and frequency

   $\Delta K_{net} = X(a/w)^2 + Y(a/w) + Z$

   Where X, Y and Z varies with frequency as follows

   $X = -80934.76f^2 + 31147.7f - 465.44$

   $Y = 64479.7f^2 - 22002f + 359.74$

   $Z = -13400\,f^2 + 4109.3f - 62.55$
   Where f is the frequency in Hz
   The above equation can effectively be used to estimate stress intensity factor in aggressive environment.

4. The crack growth rate is a function of frequency in corrosion fatigue. The maximum crack growth rate usually achieved at an intermediate frequency (0.3 to 0.8Hz).

REFERENCES

[1] M R Bayoumi, Fatigue behaviou of a commercial aluminium alloy in sea water at different temperature, Engng. Fracture Mechanics, **45**, pp 297-307, 1993.

[2] Gough HJ. Corrosion fatigue of metals. J Inst Metals 1932;49:17-92.

[3] McAdam Jr DJ, Geil GW. Pitting and its effect on fatigue limit of steels corroded under various conditions. Proc ASTM 1941;41:696-701.

[4] Wescott BB. Fatigue and corrosion fatigue of steels. Mech Engng 1938;60:813-29.

[5] Fracture Mechanics*: Perspectives and Directions, ASTM STP 1020* (eds., R. P. Wei and R. P. Gangloff), p. 233,ASTM, Philadelphia, PA (1989).

[6] R. P. Wei and J. D. Landes, Mat. Res. Stds. 9, 25 (1969).

[7] R. P. Gangloff and D. J. Duquette, in Chemistry and Physics of Fracture (eds., R.M. Latanision and R.H. Jones), p. 612, Martinus Nijhoff Publishers BV, Netherlands (1987).

[8].P. L. Andresen and F. P. Ford, Mater. Sci. and Eng. *A* 103, 167 (1988).

[9] R. P. Wei, in Fatigue 87 (eds., R. O. Ritchie and E. A Starke, Jr.), p. 1541, EMAS, West Midlands, UK (1987).

[10] F. P. Ford, D. F. Taylor, P. L. Andresen and R. G. Ballinger, "Environmentally Controlled Cracking of Stainless and Low-Alloy Steels in Light Water Reactor Environments", *EPRI* Report, No. NP-5064M, EPRI, Palo Alto, CA (1987).

[11] R. H. Van Stone, Mater. Sci. and Eng. A103, 49 (1988).

[12] ASM Metal Handbook, vol 13A, corrosion fundamentals, testing and protection.

[13] G.E.Dieter – SI Metric Edition , page no 426

[14]R.W.Hertzberg – fourth edition, page no 647

[15] Quantitative models on corrosion fatigue crack growth rate in metals: part1 S.S.Kim S.J.Choe and K.S.Shin Metals and materials vol 4 No.1 1998,pp 1-13

[16] Emperical corrosion fatigue life prediction of high strength steel by G. Murtaza, R. Akid Engg Fracture Mechanics 67(2000) 461-474

[17] S. J. Hudak, O. H. Burnside and K. S. Chan, J. Energy Resources Tech., *ASME Trans.* 107, 212 (1985)

[18] D. A. Utah, in Air Force Wright Aeronautical LaboratoriesReport, *AFWAL-TE-* 80-4098, Accession No. ADA093992 (1980).

[19] T. Nicholas, G. T. Haritos and R. R. Christoff, A/AA J. Propulsion and Power 1, 131 (1985).

[20] M. L. Heil, "Crack Growth in Alloy 718 Under Thermal Mechanical Cycling", *Ph.D.* Dissertation, Air Force Institute of Technology, Wright-Patterson AFB, OH, Dec (1986).

[21] R. H. Van Stone, O. C. Gooden and D. D. Krueger, "Advanced Cumulative Damage Modeling", Final Report, AFWAL-TR-88-4146, Wright-Patterson Air Force Base, OH (1988)

[22] Fatigue crack initiation and extension in a 7xxx aluminium alloy in saline environment by B B Verma, J D Atkinson and P K Ray (paper communicated).