ANALYTICAL FORMULATION TO PREDICT TIME TO FAILURE OF THE STRESS CORROSION CRACKING

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ASTRACT:

This work presents an Analytical model to predict the time to failure of the stress corrosion cracking (SCC) using laboratory experimental data that related stress intensity factor (K) to crack growth rate (V). Current analysis has been implicated on austenitic stainless steel in 42% chloride magnesium ($MgCl_2$) at 154 ^oC and the results were in agreement with the experimental recorded data. The present analysis generates very beneficial information about the mechanical and environmental effects on the failure of specific environment and this information is difficult to be obtained from laboratory experiments.

KEYWORDS: Stress Corrosion Cracking, Failure Time Prediction, 304SS, 42% Boiling $MgCl_2$

صياغة تحليلية لتنبؤ عمر الفشل لتشققات التاكل الإجهادي

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الخلاصه:

تقدم الدراسة الحالية نموذجا تحليلي لتنبؤ زمن الفشل لتشققات التاكل الإجهادي وذلك من خلال استخدام بيانات لاختبارات عملية عن قيم العلاقة ما بين معامل تركيز الإجهاد و معدل إنتشار الشق. تم تطبيق الدراسة الحالية على الصلب الاوستنايتي عديم الصدا و المغمور في كلورايد المغنيسيوم بتركيز (42 %) ودرجة حرارة مقدراها (154 ^oC) وكانت النتائج متقاربة مع نتائج الاختبارات العملية. إضافة لذلك تقدم الدراسة الحالية معلومات هامة ومفيدة عن التاثيرات الميكانيكية و البيئية على عمر الفشل في بيئة معينة و هذه المعلومات يصعب الحصول عليها من خلال الاختبارات العملية.

NOMENCLATURE:

a: Crack length
A: Constant
CTOD: Crack Tip Opening Displacement
e: The base of natural logarithm
E: Young's modulus
FEM: Finite Element Method

J: The J-integral
K: The stress intensity factor
K_I: Simultaneous stress intensity factor
K_{IC}: Fracture toughness
K_{ISCC}: Threshold stress intensity factor for stress corrosion cracking
LEFM: Linear Elastic Fracture Mechanics
n: Constant
r: Radius of plastic zone
SCC: Stress Corrosion Cracking
SGBEM: Symmetric Galerkin Boundary Element Method
t_f: Failure time
V: The total crack growth
Y: The yield strength
θ: Crack opening angel
υ: Posson's ratio
σ: The applied stress

INTRODUCTION:

The stress corrosion cracking (SCC) is a time dependent crack growth caused by mechanical, electrochemical and metallurgical conditions. Ability of predicting crack growth under SCC conditions is important for safety analysis of structural components in different industries.

Abou- Sayed et al. [**Abou- Sayed, 1981**] have proposed a procedure for prediction SCC growth rates based on the determination of the Crack Tip Opening Displacement (CTOD) by finite element methods. This procedure depends on the application of the stationary crack relation between CTOD and the J-Integral of the DBCS model to the work hardening material. They showed that crack growth rates are higher than the rates obtained from LEFM analysis.

Smith [**Smith, 1985**] has developed a methodology for prediction the growth rate of SCC by obtaining an appropriate correlation between theory and experimentally determined relation that related K to V when LEFM conditions are valid and when LEFM conditions are not operative. The result of Smith's analysis showed that the predicted relations between K and V for these two cases are different the result clearly exposes the limitations of LEFM procedure for prediction SCC growth rates.

Kosaki [**Kosaki, 1992**] analyzed a reaction model to evaluate SCC lives of stainless steel (304 type) in high temperature pure water by constant load. He obtained a certain correlation between SCC life parameters. He also found that the dependency of the applied load on SCC life by an expression in the form of a hyperbolic tangent functions.

Pauchard et al. [**Pauchaard, 2002**] introduced a model for prediction of failure time of the glass fibers. According this model the time to failure (t_f), of a glass fiber under a given stress loading is a function of: the strength of the fiber in an inert environment, fracture toughness, yield strength and the two constants A and n particular parameters describing SCC crack growth rate depends on material and environmental.

NIKISHKOV [**NIKISHKOV, 2008**] developed a computational procedure for modeling of crack growth under stress corrosion cracking (SCC) conditions. He modeled the crack by the symmetric Galerkin boundary element method (SGBEM) and used a finite element method (FEM) for stress analysis of the uncracked structural component. His analysis success to provide a crack growth criterion in the three-dimensional cases based on the J-integral vector.

The main aim of this paper is to provide analytical expression to calculate the time to failure of the stress corrosion cracking on different stress levels by using laboratory experimental data.

DERIVATION OF THE SCC FAILURE TIME MODEL:

The theoretical model is based on introducing environmental parameters to the non-environmentally assisted cracking mode. The non-environmentally assisted cracking model was proposed by Rice and Soenson and developed by Smith to involve SCC growth rates [**Smith, 1982**]. The governor equation of this model is related the crack growth rate in J-integral term to the stress intensity by the form of:

$$\frac{dJ}{da} = \theta.Y - \frac{4(1-\nu^2)Y^2}{\pi E}\ln(\frac{e\pi K^2}{2rY^2}) \quad (1)$$

Where a: crack length, e: the base of natural logarithm, E: Young's modulus, J is the J-integral, K: is the stress intensity factor, r: radius of plastic zone, Y: yield strength, θ: Crack opening angel, and υ: Posson's ratio. Knowing that J and θ can write as:

$$J = \frac{8(1-\nu^2)Y^2}{\pi E}\ln(\sec(\frac{\pi\sigma}{2Y})) \quad (2)$$

$$\theta = \frac{4(1-\nu^2)Y^2}{\pi E}\ln(\frac{2ea}{r}\tan^2(\frac{\pi\sigma}{2Y})) \quad (3)$$

Where σ is the applied stress. For LEFM concept J can be calculated from the following equation:

$$J = \frac{K^2(1-\nu^2)}{E} \quad (4)$$

So dJ/da in equation (1) can be replaced by $\left(\frac{2K(1-\nu^2)}{E}\frac{dK}{da}\right)$ and this leads to:

$$\frac{2K(1-\nu^2)}{E}\frac{dK}{da} = \theta.Y - \frac{4(1-\nu^2)Y^2}{\pi E}\ln(\frac{e\pi K^2}{2rY^2})$$

$$\ln(\frac{e\pi K^2}{2rY^2}) = \frac{\pi E\theta}{4(1-\nu^2)Y^2} - \frac{2K(1-\nu^2)}{E}\frac{dK}{da}\frac{\pi E}{4(1-\nu^2)Y^2}$$

$$(\frac{e\pi K^2}{2rY^2}) = \exp(\frac{\pi E\theta}{4(1-\nu^2)Y^2})\exp(-\frac{\pi K}{2Y^2}\frac{dK}{da})$$

$$K^2 = \frac{2rY^2}{e\pi}\exp(\frac{\pi E\theta}{4(1-\nu^2)Y^2})\exp(-\frac{\pi K}{2Y^2}\frac{dK}{da}) \quad (5)$$

Substituting Eq. (2) and (3) to Eq. (5):

$$\frac{8Y^2}{\pi}\ln(\sec(\frac{\pi\sigma}{2Y})) = \frac{4Y^2}{\pi}(\tan^2(\frac{\pi\sigma}{2Y}))\exp(-\frac{\pi K}{2Y^2}\frac{dK}{da}) \qquad (6)$$

After rearrangement:

$$\frac{\ln(\sec^2(\frac{\pi\sigma}{2Y}))}{(\tan^2(\frac{\pi\sigma}{2Y}))} = \exp(-\frac{\pi K}{2Y^2}\frac{dK}{da}) \qquad (7)$$

Or

$$\frac{da}{dK} = (\frac{\pi K}{2Y^2}) / \ln\left(\frac{(\tan^2(\frac{\pi\sigma}{2Y}))}{(\ln(\sec^2(\frac{\pi\sigma}{2Y}))}\right) \qquad (8)$$

The last equation represents the mechanical contribution of the total crack growth rate of the SCC. The well accepted procedure for prediction the failure time of the SCC is to use laboratory experimental data that related stress intensity factor (K) to the crack growth rate (da/dt) by the form of V(da/dt)=AK^n based on Linear Elastic Fracture Mechanics (LEFM) concept [**smith, 1985**]. he total crack growth can be calculated from the following equation:

$$AK^n = \frac{\pi K}{2Y^2\ln\left(\frac{(\tan^2(\frac{\pi\sigma}{2Y}))}{(\ln(\sec^2(\frac{\pi\sigma}{2Y}))}\right)}\frac{dK}{dt} \qquad (9)$$

Where A and n are constants and V is the total crack growth of the SCC. Substituting Eq. (8) into Eq. (9) leads to:

$$AK^n = \frac{\pi K}{2Y^2\ln\left(\frac{(\tan^2(\frac{\pi\sigma}{2Y}))}{(\ln(\sec^2(\frac{\pi\sigma}{2Y}))}\right)}\frac{dK}{dt} \qquad (10)$$

In LEFM concept there are two values of (K): K value below which SCC will not occur that called threshold stress intensity factor for SCC (K_{ISCC}), and K value above which rapid plastic fracture will occur that called fracture toughness (K_{IC}). Then the time to failure (t_f) at any value of stress intensity factor (K_I) can be calculated from:

$$\int_{0}^{tf} dt = \int_{K_I}^{K_{IC}} \frac{\pi K^{1-n}}{2AY^2 \ln\left(\dfrac{(\tan^2(\dfrac{\pi\sigma}{2Y}))}{(\ln(\sec^2(\dfrac{\pi\sigma}{2Y}))}\right)} dK \tag{11}$$

After integration failure time (t_f) will become:

$$t_f = \frac{\pi/(2AY^2(2-n))}{\ln\left(\dfrac{(\tan^2(\dfrac{\pi\sigma}{2Y}))}{(\ln(\sec^2(\dfrac{\pi\sigma}{2Y}))}\right)}\left[K_{IC}^{(2-n)} - K_I^{(2-n)}\right] \tag{12}$$

Where K_I is the stress intensity factor at any moment between K_{IC} and K_{SCC} i.e $K_{ISCC} \le K_I \le K_{IC}$ Note that if the integrand has n=2 the expression for t_f will contain natural (ln) terms.

RESULTS AND DISCUSSIONS:

In this item the application of the proposed model to the austenitic stainless steels in boiling saturated magnesium chloride solution was discussed. The present analysis was applied to predict the failure time of sensitizing AISI 304 stainless steel in 42% chloride magnesium ($MgCl_2$) at 154 ^oC, the practical case which is widely occurred in nuclear power and chemical plant components. The values of parameters that are needed for calculations are those considered in literature [**Sarvesh, 2010**]. The calculated parameters for the current system from the literature are listed in **table (1)** and the environment's constants A and n are calculated from Eq. (9) by setting

$$n = \frac{\ln(V_{Initial}/A)}{\ln(K_{ISCC})} \tag{13}$$

With $V_{Initial}=8.63\text{x}10^{-11}$ [**Rieck, 1986**] for realistic solution to Eq. (12) the value of the constant n is varying from 4 to 9 and for current system n=4.555 and $A=1\text{x}10^{-42}$. After introducing these values to Eq. (12) and taking the value of stress ratio (σ/y) varying from 0.56 to 0.76 as shown in **Figure (1)** (to measure the effect of stress ratio on the failure time). **Figure (1)** shows that the time to failure is highly depended on the stress ratio magnitude and when replacing the value of K_I with the K_{ISCC} value to calculate the total failure time after introducing the value of stress ratio varying from 0 to unity the failure time can be drawn as a function of the stress ratio and the result can be shown in the **figure (2)**. **Figure (2)** shows that the failure time is a function of the stress value even though in fixed value of stress intensity factor the fact that emphasis that LEFM concept cannot directly applied on the SCC especially at high stress value and by using current analysis it can study the full time behavior against other SCC parameter by obtaining the effect of crack growth rate on the failure time.

The calculated failure time (t_f) as shown in **figure (3)** is highly depended on crack growth rate. **Figure (3)** shows the relation between failure time (t_f) and crack growth rate at K_{ISCC} value at the stress ratio (σ/Y) is equal to 0.64 [**Sarvesh, 2010**]. From **figure (3)** the failure time (t_f) can be divided in to three stages as compared with the crack growth rate (V): stage (I) in which the failure time decreases rapidly from high to a moderate (t_f) values, stage (II) in which the failure time is decreased slightly at a moderate (t_f) values, and stage (III) at which the failure time is decreased rapidly from moderate to low (t_f) values similar to the stage (I) vertical line. Here it important to refer that many studied were held to emphasis the direct relation between the stress intensity factor (K_I) and the stress crack growth (V) in the stress corrosion cases that also stated that the relation between (K_I) and (V) is also divided in to three stages: stage (I) (initiation period), stage (II) (propagation period) and stage (III) (failure period) [**Smith, 1980 and 1984**]. To understand this behavior the cracking rate (V) has been evaluated by two parameters (dK_I/dt) and (da/dK_I). These two parameters can be calculated from Eqs. (11) and (8) respectively and **Figs.(4) and (5)** show the effect of failure time on these two parameters.

Returning to the Eq. (9) the two parameters (dK_I/dt) and (da/dK_I) are multiple by each other and that is mean values of these two parameters will specify the value of the total crack growth rate (V). From **Figures (4) and (5)** it can concluded that stress corrosion crack is initiated by the effect of the parameter (dK_I/dt) that recorded by many studies as the environmental effect and since it's magnitude started from zero value at a life time lower than the starting life time of the (da/dK_I) parameter so this parameter will drive the other parameter (da/dK_I) that recorded by recent studies as mechanical effect on the total crack growth. After initiation region these two parameters will have approximately equal effect on the total crack growth (V) since they have approximately similar decay line at similar life times. At still low failure time near K_{IC} value it can see from **figure (5)** that fast failure initiated by the effect of the parameter (da/dK_I) because it's value decreases rapidly at a life time greater that the life time of (dK_I/dt) parameter. So (da/dK_I) parameter will drive the total crack growth to the failure region. These three conclusions are coincide with many other studies conclusion that stated that stress corrosion cracking initiated by the electrochemical effect of the environment and propagated by the conjoint effects of electrochemical and mechanical parameters and at last fast rapid mechanical plastic fracture caused the last failure. In other words, mechanical effect of the stress corrosion cracking will not started until the environment effect causes a defect in the material with a sufficient magnitude and this emphases why the (da/dK_I) parameter not initiated from zero value and this magnitude is specified by K_{ISCC} value. Then stress corrosion cracking will continue at a regular rate until it reaches to a value that the material can't sustain the applied load and this value of applied load is limited by K_{IC} value.

CONCLUSIONS:

A combined model has been developed to predict failure time of the stress corrosion cracking. Present analysis based on introducing the environmental contribution of the total crack growth rate in to the non-environmental sub-critical crack growth relation. This work is a successful attempt to formulate the failure time of the stress corrosion cracking in a general formula that is not depending on the loading and shape factors. So this formula can be used to analyze any experimental data or to transfer K-V experimental data to K-t_f data and vice versa. Also present analysis show that the failure time is a function of the stress value even though in fixed value of stress intensity factor the fact that emphasis that LEFM concept can not directly applied on the stress corrosion cracking phenomenon especially at high stress value.

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Table (1) SCC Parameters for AISI 304 SS in 42% $MgCl_2$ at 154 ^oC

K_{ISCC} (MPa $m^{1/2}$)	K_{IC} (MPa $m^{1/2}$)	**Y** (MPa)	**E** (GPa)
8.632	76.303	308	198

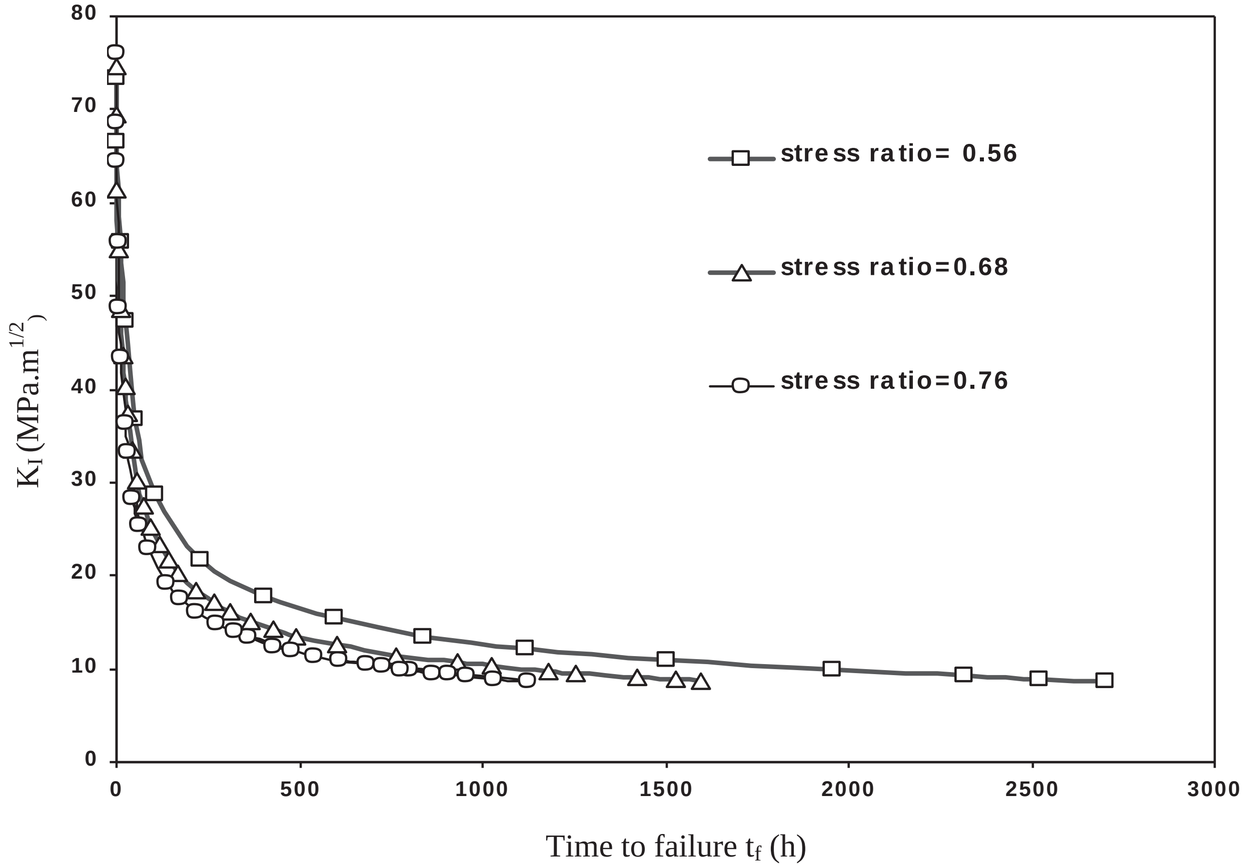

Fig.1: K_I Vs. time to failure (t_f) plots for current analysis system with different stress ratios

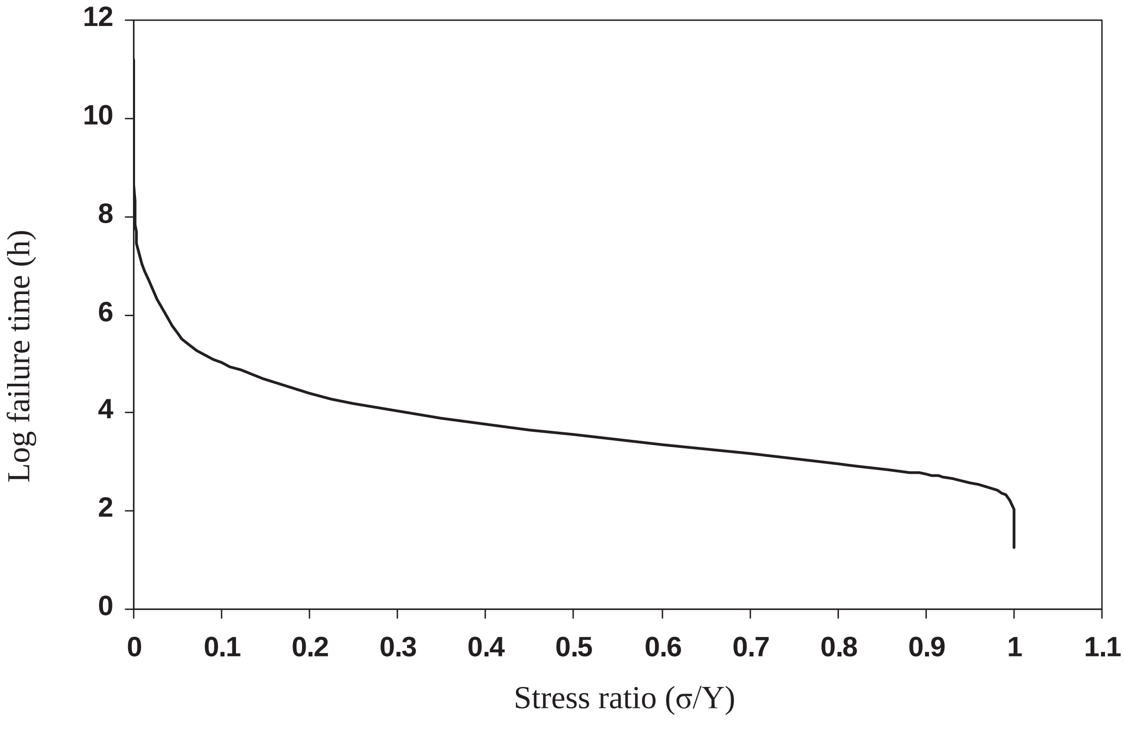

Fig.2: The time to failure (t_f) Vs. stress ratio (σ/Y)

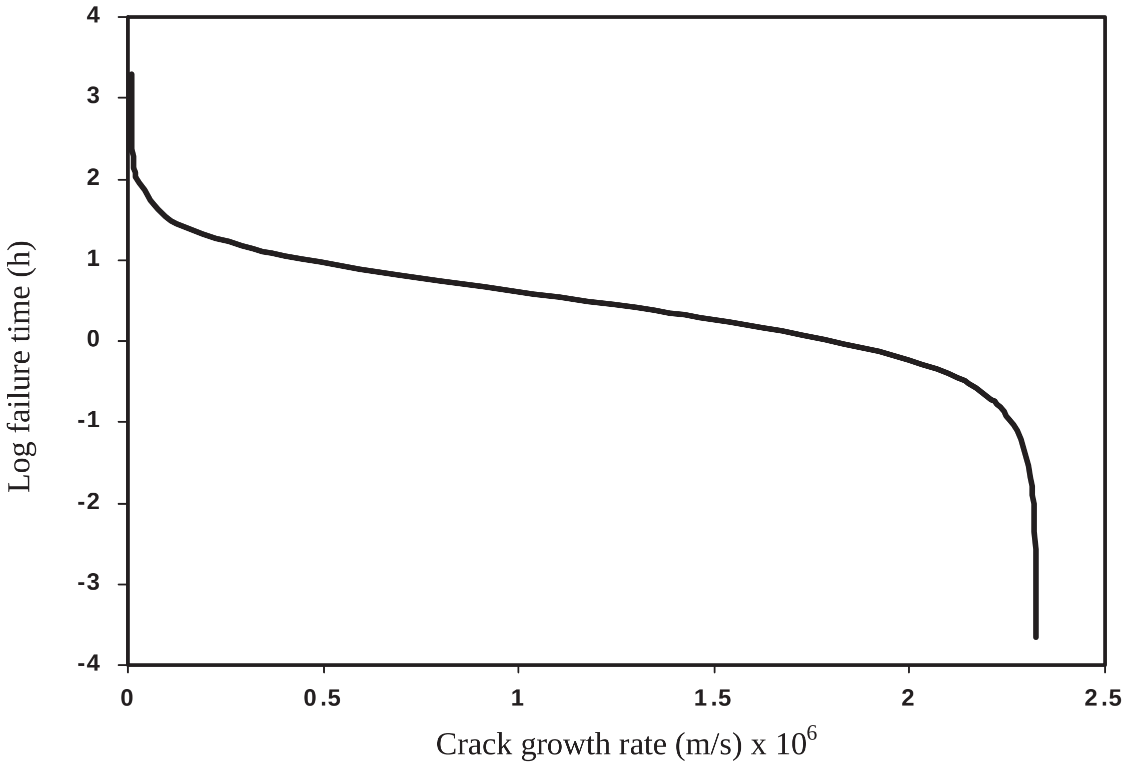

Fig.3: The time to failure (t_f) Vs. crack growth rate (V) at stress ratio of 0.64

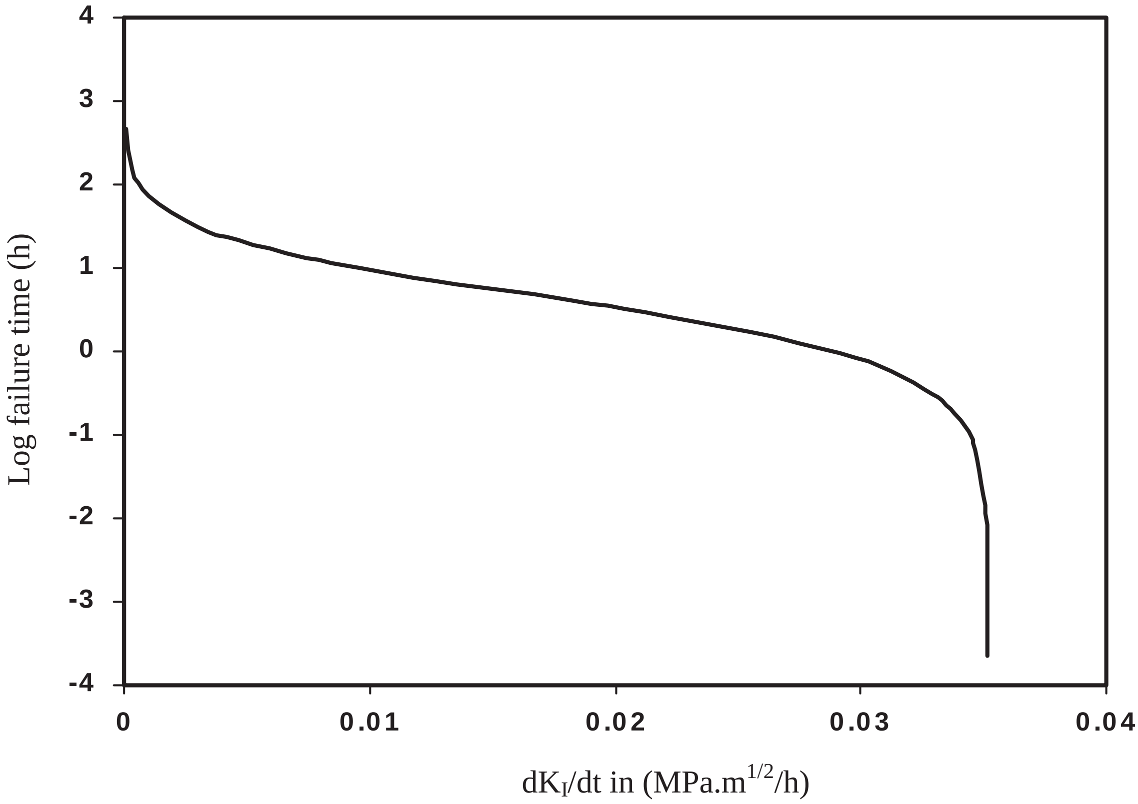

Fig.4: The time to failure (t_f) Vs. Stress intensity factor changing rate at stress ratio (σ/Y) of 0.64

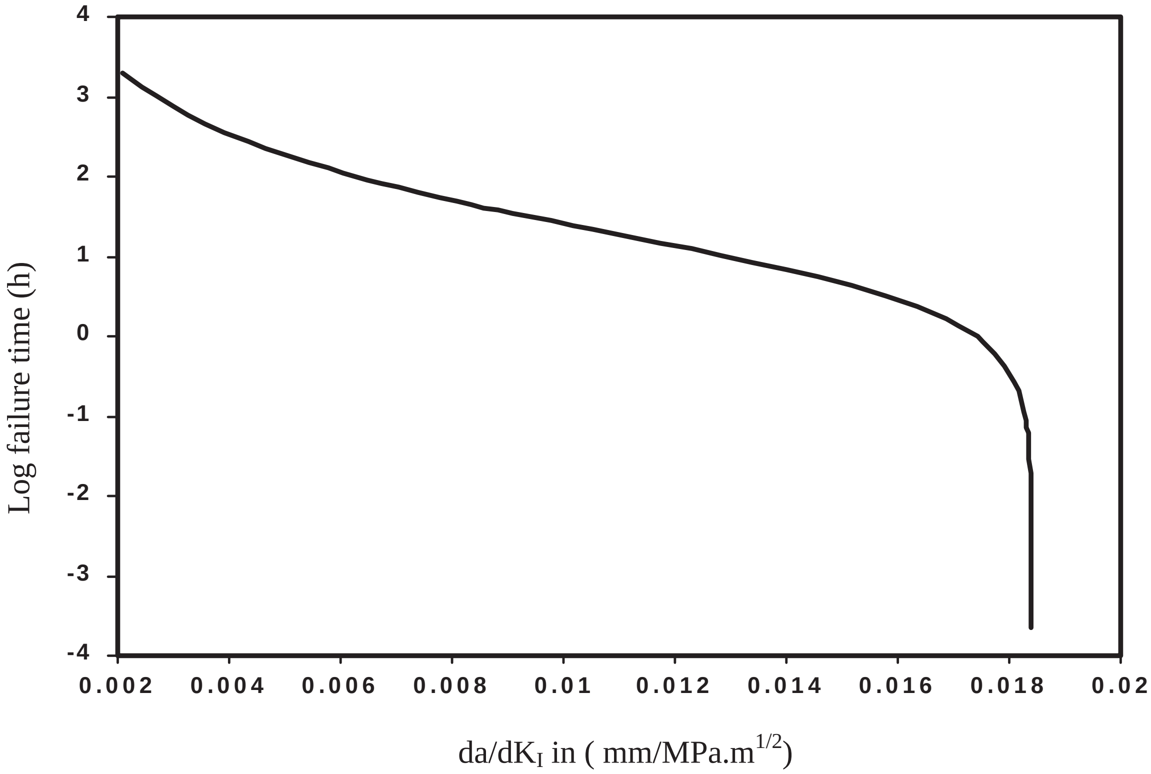

Fig.5: The time to failure (t_f) Vs. crack growth changing with stress intensity factor at stress ratio (σ/Y) of 0.64