CRACK PROPAGATION STRENGTH OF A ENVIRONMENT CORROSION RESISTANT STRUCTURAL STEEL

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Abstract *Fatigue fracture is the most common structural failure mode and it has been subject of research for a long time. This kind of fracture is caused by crack initiation and propagation through the component, with each one of these processes taking different amount of time from the fatigue life. A component or structure containing a crack can have its remaining life compromised with respect to the one originally designed. In order to evaluate the remaining life, one should know the fatigue crack propagation properties of the material and a corresponding propagation law. The objectives of this work are then: (i) obtain mathematical expressions for the fatigue crack propagation rate as a function of the stress intensity factor; and (ii) evaluate three fatigue crack propagation models (Paris, Forman and Priddle). The Paris model is valid for the Region II of the fatigue crack propagation rate versus the stress intensity factor log-log diagram. The Forman model is valid for the Regions II and III and the Priddle model is valid for all the three regions of this diagram. The three models are applied to data obtained from two specimen tests and results are compared.*

Keywords: Fatigue, fracture, crack, fatigue crack propagation

1. Introduction

Fatigue fracture has being a constant matter of study by the researchers. The most old model and the most used is the Paris model, valid for region II of crack propagation stage represented in a log-log crack propagation rate versus stress intensity factor graph. This region has a linear behavior and is valid from a considerable crack size. When the crack size has very small dimensions, the propagation rate is also very small, near to 10^{-6} mm/cycle, or less, located thus, at the region I. The most portion of the useful life of one cracked structure or component corresponds to the region I of crack propagation. Thus, knowing the initial crack length and the loading conditions, it can be verify before if the rate propagation of the crack is situated at the region I and thus, this crack will can be submitted to a higher number of cycles until to situate at the beginning of the region II. On this case the straight application of Paris equation return very conservative and the remaining life is higher than the remaining life determined by the Paris equation. Some fatigue crack propagation models consider two of the three regions and some models that consider the three regions. The models that consider the three regions has not being considered by the researches, the majority of the works has being considered only the Paris-Erdogan model, which is applied only on the linear region in a fatigue crack propagation log-log graph. This model is very conservative. The major part of a component or structure life occurs at region I (Barson and Rolfe, 1999). The comparison of mathematical models, mainly the models that consider the three regions of the crack propagation rate versus stress intensity factor, for SAC 50 steels will be of great utility in design of components and structures.

2. Fatigue

Fatigue fracture is in general considered the most serious type of fracture in machine pieces or structures. This is due to the fact of fatigue fracture can occur in service, without excessive overloads, and under normal operation conditions.

Crack growth can occur with the stress intensity factor lower than K_{IC}. At this case, it is said that there is sub-critical crack growth. Fatigue crack growth is a typical example of sub-critical crack growth.

The American Society for Testing and Materials (ASTM E 1823) defines Fatigue as the process of localized degradation, progressive and permanent, that occurs on the material submitted to a variations in stress and strains, and that produces the formation of a crack or complete fracture after the occurrence of a sufficient number of cycles. Examples of components that bear the fatigue phenomena are: automobile on the roads, planes on the air, resting and take-off, bridges submitted to vehicles movements and nuclear reactors. A crack fatigue can nucleate and propagate to fracture. The number of cycles required to initiate a crack is the fatigue crack initiation life, N_i. The number of cycles required to propagate a fatigue crack to a critical size is called the fatigue crack propagation life, N_p. The total fatigue life, N_t, is the sum of the initiation and propagation lives (Barson and Rolfe, 1999):

$$N_t = N_i + N_p \qquad (2.1)$$

There is no simple or clear delineation of the boundary between fatigue crack initiation and propagation. The crack initiation phenomena results of the plastic deformation process. The experience shows that, in general, the crack initiates in plastic deformation concentration regions (Suresh, 1991).

The fatigue fracture process in a specimen or in a piece can be divided in three phases:

Phase I: crack initiation (tangential stresses). On phase I the crack initiate at the surface and propagate in one defined crystallographic direction. The crack length at this stage is limited to a few grain diameters. This stage is mainly controlled by shear stress. The critical solicitations move the dislocations that form persistent slip bands thus generating intrusions and extrusions. These extrusions and intrusions give origin to micro cracks, formed by punctual plastic deformations (Suresh, 1991).

Phase II: propagation (normal stresses). Phase II characterized by a crack propagation, first at one direction perpendicular to major principal stress, where the phase I to phase II transition is marked by a reduction on the shear stress and a increase on the normal stress (Suresh, 1991).

Phase III: final fracture. With the increase on the normal stress, it reach the critical value of the fracture toughness and the crack propagates fast to fracture (Suresh, 1991).

2.1 Fatigue under Stress Control

Three approaches are considered for the study of fail in materials, in special the steel: high cycle fatigue, low cycle fatigue and fracture mechanics. When stress or strain act on the elastic regime of the material, that occurs with low loads and high number of cycles, the phenomena is called high cycle fatigue or fatigue controlled by stress. When the loading such that the plastic deformations reach significant values within each cycle, in general with high loads and low cycles, the phenomena is known as low cycle fatigue, or fatigue controlled by deformations (Collins, 1993). The two first approaches refer to flaw initiation process, while the approach by fracture mechanics refer to flaw propagation. On the case of high cycle fatigue, the elastic deformations control the fail. The study of fatigue by fracture mechanics is made when the initial flaw size is known and the life time (number of cycles) up to reach a critical size is determined.

2.2 Fatigue Crack Propagation

Fatigue crack propagation use the fracture mechanics concepts, in other words, the stress intensity factor range, described bellow.

Consider a crack through thickness submitted to a remote stress that varies cyclically between maximum and minimum values, constant, that is, cyclic load (Fig. 2.1). From this Figure some definitions employed in fatigue are presented (Anderson, 1995).

It are defined:

Stress range:

$$\Delta\sigma = \sigma_{máx} - \sigma_{min} \qquad (2.2)$$

stress intensity factor range:

$$\Delta K = K_{máx.} - K_{mín.} = \Delta\sigma\sqrt{\pi a}\, f\left(\frac{a}{W}\right) \qquad (2.3)$$

stress amplitude:

$$\sigma_a = \frac{\sigma_{máx} - \sigma_{mín}}{2} \qquad (2.4)$$

mean stress:

$$\sigma_m = \frac{\sigma_{máx} + \sigma_{mín}}{2} \qquad (2.5)$$

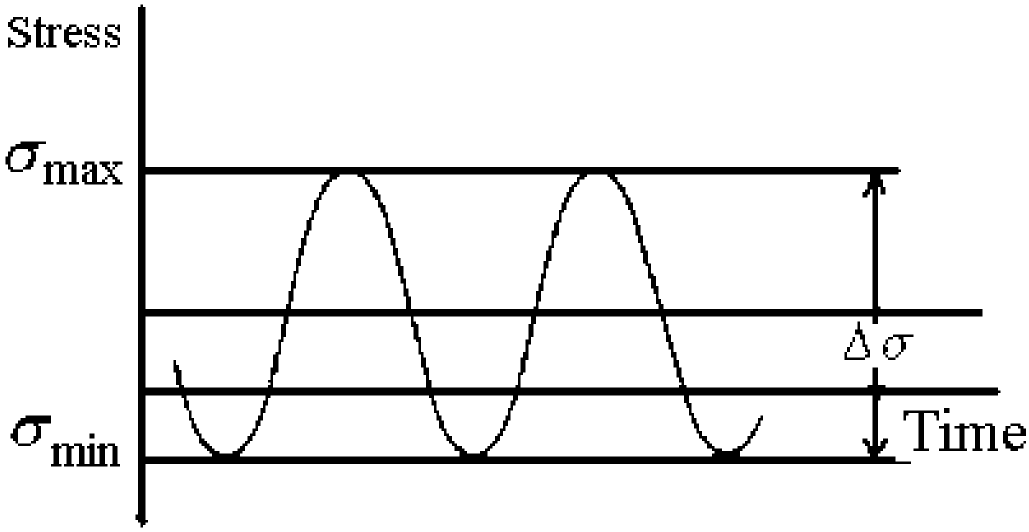


Figure 2.2: Fatigue cyclic stress parameters de with constant amplitude

Stress ratio:

$$R = \frac{\sigma_{mín}}{\sigma_{máx}} \tag{2.6}$$

If R = -1, it is said that the stress are completely reversed and it has; $\sigma_{mín} = -\sigma_{máx}$.

The fatigue crack propagation rate is defined as the ratio of crack extension, Δa, by the number of cycles, ΔN, that is, $\Delta a/\Delta N$, and, at the limit, da/dN.

$$\lim_{\Delta N \to 0} \frac{\Delta a}{\Delta N} = \frac{da}{dN} \tag{2.7}$$

When the stress ratio $R = \sigma_{min}/\sigma_{máx}$ is the same, then ΔK correlate crack propagation rates in specimens with different stress range and crack size of different geometry, that is:

$$\frac{da}{dN} = f(\Delta K, R) \tag{2.8}$$

Several factors have influence on the fatigue crack propagation rate: strength level, grain size, microstructure, anisotropy and others On Fig. 2.2 are presented these factors for steels in different regimes of fatigue, and the region where each one of then has influence. On this Figure it can be observed that the fatigue crack growth depends strongly of the microstructure region I of the propagation threshold ΔK_{th} and on the region III, when $K_{máx}$ comes near of K_{IC}.

On region I it has observed a plane fracture, with facets of cleavage, witch are the results of propagation highly crystallographic. On region II, the fatigue failure occurs by a mechanism of ductile transgranular with formation of striations at the surface fracture. On region III occurs the static fracture as cleavage, coalescence of micro-cavities or inter-granular, with the striations mechanisms The ΔK_{th} is defined as the value bellow which existing fatigue cracks do not propagate under cyclic loading (Godefroid, Lopes e Rebello, 1997).

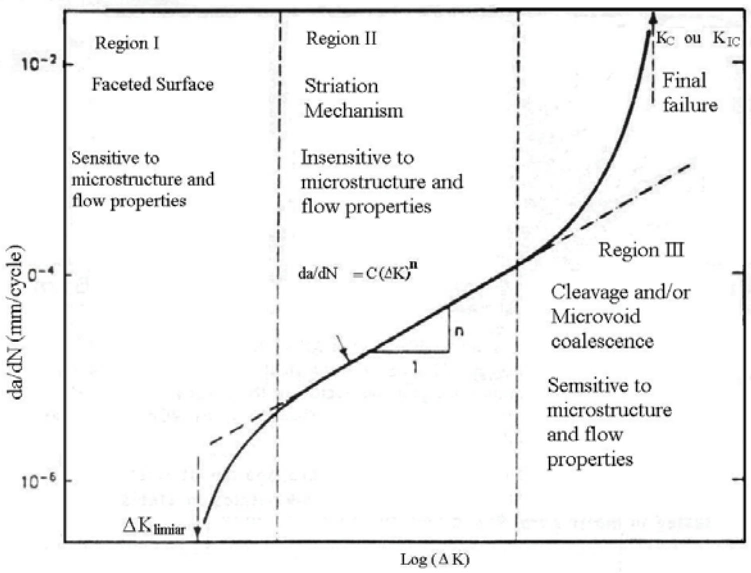


Figure 2.2: Scheme of variation of fatigue crack growth, da/dN, with alternative stress intensity (Adapted from Godefroid, 1997)

2.2 Crack Propagation Models

There are more than 100 models of fatigue crack propagation, some of then involving one or two regions and others involving the three regions of propagation. Some models are presented bellow:

Paris model: Paris and Erdogan (1963) were the first to discover a relationship type power law to describe the fatigue crack growth on region II. The proposed relationship by then is an empirical model and is presented bellow, where *C* and n are constants of the material, experimentally determined:

$$\frac{\mathrm{d}a}{\mathrm{dN}} = C(\Delta K)^{\mathrm{n}} \tag{2.9}$$

Forman, Kearney and Engle model: Forman, Kearney and Engle (1967) proposed one equation valid for the II and III regions, based on physical considerations; *C* and n, are constants of the material and K_c is the critical value of K, that is, the fracture toughness of the material.

$$\frac{\mathrm{d}a}{\mathrm{dN}} = \frac{C(\Delta K)^{\mathrm{n}}}{(1-\mathrm{R})K_{\mathrm{C}} - \Delta K} \tag{2.10}$$

Priddle model: Priddle (1976) developed a relationship valid for regions I, II e III, where the ΔK threshold is not a constant of material, but depends of R. It is a relationship considering the behavior of the power laws at high and low ΔK values; *C* and n are constants of the material:

$$\frac{\mathrm{d}a}{\mathrm{dN}} = C\left(\frac{\Delta K - \Delta K_{\lim iar}}{K_{\mathrm{c}} - K_{\mathrm{máx}}}\right)^{\mathrm{n}} \tag{2.11}$$

3. Methodology

3.1.Material

The material used on this work is the structural steel employed in building construction, bridges and other applications, USI-SAC 50, 12 mm in thickness, supplied by USIMINAS in plates with dimensions 1000 mm x 300 mm, beveled in V and 1/2 V respectively. On Tab. 3.1it is presented the chemical compositions of the material, supplied by the manufacturer.

Table 3.1: Chemical composition of SAC-50 steel, thickness 1 mm, supplied by the manufacturer

Thickness (mm)	Elements (% in weight)										
	C	Mn	Si	P	S	Al	Cu	Nb	Ti	Cr	Ni
12	0.12	1.13	0.34	0.024	0.013	0.037	0.26	0.022	0.009	0.44	0.20

The welding were made using the Covered Electrode Welding Process, groove in V and 1/2 V cut-out in dimensions of 500 mm X 150 mm. The welding procedure, according to EPS n° MC 7622 supplied by Usiminas Mecânica, were: Bevel type: V, angle of 45°, 22.5 in each one of the pieces of the joint and 1/2 V, angle of 45° in one of the pieces of the pieces: wall: 2 mm; gap: 3 mm; Number of passes: 06.

Welding parameters: tension: 20 V for all passes; current: 110 A for the first pass; 220 A, for the other passes; electrode: AWS E 7018G, 3,25 mm of diameter for the first pass and 5 mm of diameter for the other passes; welding mean speed: 300 mm/min.

It was realized tension tests to obtain the yield stress and the tensile strength to be employed on the fatigue pre cracking calculations.

The fatigue crack propagation specimens were type compact tension, according the ASTM E 647 standard (2000), removed of the BM at T-L orientation and of the welded joints with notch located on HAZ and on MZ, according the scheme showed on Fig. 3.1. After machining the specimens were pre-cracked up to a size equal to 3 mm, as established on the standard, in three stages with the aim to not introduce plastic deformation at the crack tip. The crack propagation tests were realized on INSTRON model 8802 equipment with 250 kN in capacity, and the data collected from a software of the INSTRON, to posterior processing using the Paris, Forman and Priddle equations for crack propagation models.

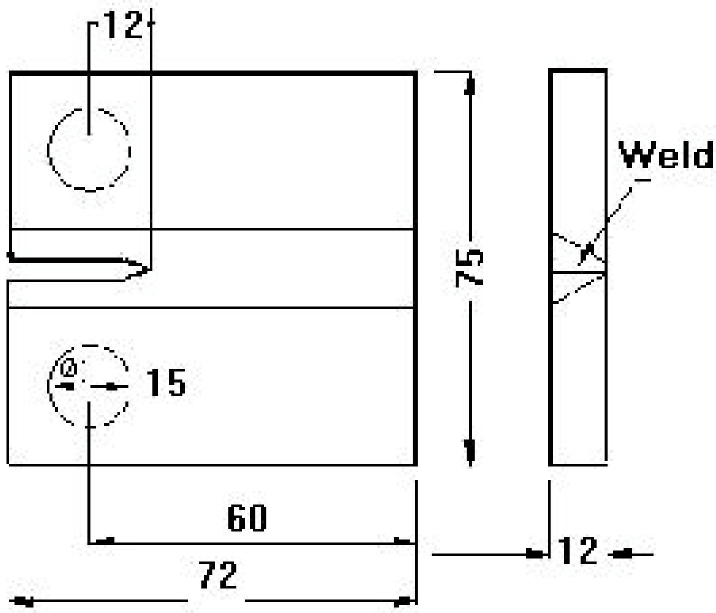


Figure 3.1: drawing of fatigue propagation test specimens

4. Results and Discussion

On Fig. 4.1 are presented the da/dN x ΔK curves obtained from fatigue crack propagation tests in three specimens BM01, Z5 and F01, with notch localized on BM, HAZ and MZ respectively and realized according the standard ASTM E 647 (2000), using the equipment INSTRON, model 8802 capacity 250 kN. From the obtained graphs the adjustments corresponding to Paris, Forman and Priddle were realized, obtaining the respective equations in each case:

For the BM:

Paris equation (region II):

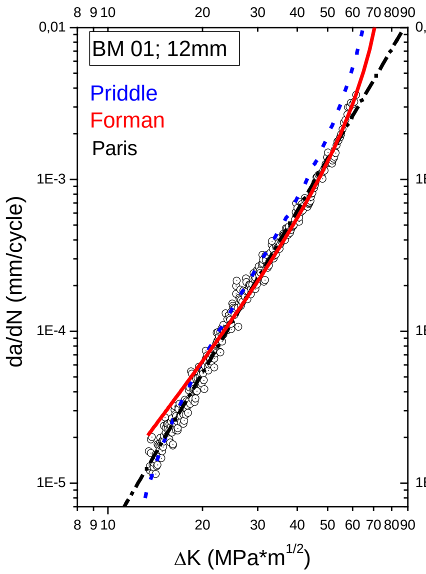
$$\frac{da}{dN} = 1.571 \text{x} 10^{-9} \text{ x} (\Delta K)^{3.486} \tag{4.1}$$

Forman equation (regions II e III):

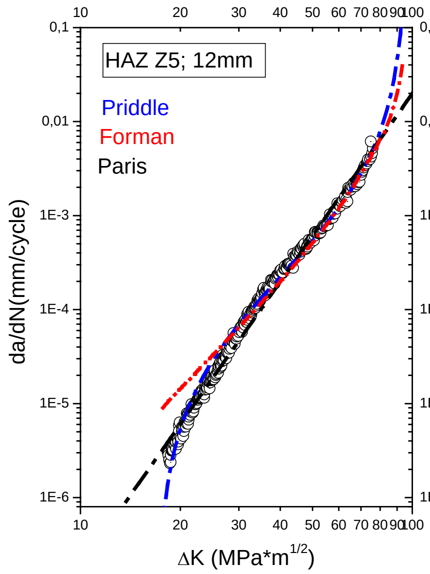
$$\frac{da}{dN} = 1.847 \mathrm{x} 10^{-6} \mathrm{x} \left(\frac{\Delta K^{2.548}}{80 - \Delta K} \right) \tag{4.2}$$

Priddle equation (Regions I, II e III)

$$\frac{da}{dN} = 1.41 \mathrm{x} 10^{-3} \mathrm{x} \left(\frac{\Delta K - 10}{88 - K_{max}} \right)^{1.636} \tag{4.3}$$



(a)



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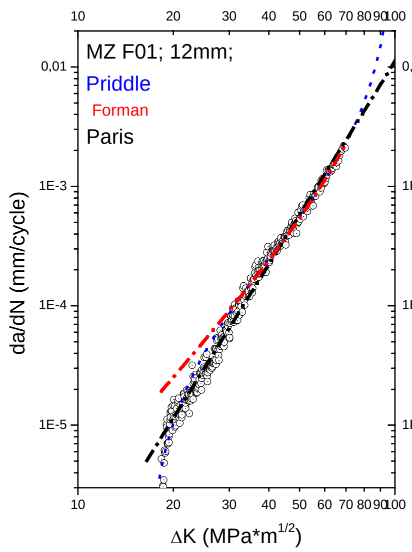

(c)

Figure 4.1: Graph of d*a*/dN x Δ*K* of the specimens BM01, Z5 and F01

For the HAZ:

Paris Eq. (região II):

$$\frac{da}{dN} = 4.043 \mathrm{x} 10^{-12} \mathrm{x} (\Delta K)^{4.813} \tag{4.4}$$

Forman Eq. (regiões II e III):

$$\frac{da}{dN} = 4.696x10^{-8}\, x\left(\frac{\Delta K^{3.361}}{102 - \Delta K}\right) \qquad (4.5)$$

Priddle Eq. (regiões I, II e III):

$$\frac{da}{dN} = 1.08x10^{-3}\, x\left(\frac{\Delta K - 17}{106 - K_{max}}\right)^{1.592} \qquad (4.6)$$

For the MZ:
Paris Eq. (região II):

$$\frac{da}{dN} = 1.190x10^{-10}\, x(\Delta K)^{4.28} \qquad (4.4)$$

Forman Eq. (regiões II e III):

$$\frac{da}{dN} = 4.092x10^{-7}\, x\left(\frac{\Delta K^{2.847}}{96 - \Delta K}\right) \qquad (4.5)$$

Priddle Eq. (regiões I, II e III):

$$\frac{da}{dN} = 1.280x10^{-3}\, x\left(\frac{\Delta K - 16}{114 - K_{max}}\right)^{1.536} \qquad (4.6)$$

The number of cycles to fracture using each one of these equations were determined and the number of cycles obtained for each specimen were compared The results are presented on Table 4.1:

Number of cycles				
	Test	Paris Eq.	Forman Eq.	Priddle Eq.
Region of the notch	528,000	201,992	371,309	532,193
	1,410,000	232,995	575,040	1,492,033
	827,000	184,036	429,476	804,412

As can be observed the Paris Eq. is very conservative, the Forman Eq. give better results relative to Paris Eq. and Priddle Eq. give results near to real results. The differences are due to the fact that ΔK_{th} was not determined for all three specimens but they were estimated from the obtained graphs. As the bellow values of ΔK for the BM started in a high propagation rate, the estimated values of ΔK_{th} rest in poor precision, inducing to major errors. Because of this, the results were more divergence. It can be to conclude from these results that the use of crack propagation models that consider the three regions are more near to the actual results.

5. Conclusions

From the tests realized on this work it can be concluded:

1 The specimens with notch localized on HAZ presented a major resistance to crack propagation;
2 The specimens with notch localized on the BM and HAZ presented identical behavior relative to crack propagation;
1. From the studied models (Paris, Forman e Priddle), the Paris model is more conservative and the Priddle model is more near to the experimental results being the Forman model presents intermediate results.

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