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ESCOLA DE ENGENHARIA DE SÃO CARLOS

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Propagação de trinca por fadiga na liga AA7050-T7451 considerando o efeito do meio ambiente, razão de tensões, direção de laminação e forma de onda.

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Fatigue crack propagation in AA 7050-T7451 alloy considering environment, stress ratio, rolling direction and waveform effects

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RESUMO

BARBOSA, J. F. C. **Propagação de trinca por fadiga na liga AA7050-T7451 considerando o efeito do meio ambiente, razão de tensões, direção de laminação e forma de onda..** Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2017.

Os principais fatores modificadores extrínsecos e intrínsecos da taxa de propagação de trincas na liga AA7050-T7451 foram avaliados para fornecer subsídios para projetistas de estruturas aeronáuticas, com base na filosofia de tolerância ao dano. A metodologia experimental consistiu em ensaiar corpos de prova do tipo *compact tension* (CT) da liga nas direções de laminação TL e LT, para verificar seu comportamento sob diferentes razões de tensões, forma de onda e condição ambiente. Os valores de razão de tensão estudados foram 0,1 e 0,5, as formas de onda foram senoidal e trapezoidal ou de Dwell, em condições normais de laboratório, ao ar, e névoa salina 3,5% NaCl, em massa, para simular um ambiente marinho. No caso dos ensaios Dwell, os resultados foram conferidos pelo método de queda de potencial eléctrico (QPE), além do método de flexibilidade elástica.

Usando os coeficientes de Walker calculados a partir dos resultados obtidos, pôde-se projetar com precisão o comportamento da propagação de trinca na região de Paris e prever a vida em fadiga usando os diagramas da/dN e S-N para diferentes valores da razão de tensões. O ambiente corrosivo aumenta tanto a taxa de propagação de trinca, quanto o valor de ΔK_{th} por causa da formação de óxidos na trajetória da trinca, que geram um efeito de fechamento sobre a mesma. Quanto à forma de onda, verificou-se que o carregamento Dwell diminui a taxa de propagação de trinca, diminuindo a inclinação das curvas $\log (da/dN)$ versus $\log (\Delta K)$ na região de Paris, ao invés de deslocá-la paralelamente como ocorre com ligas de titânio. A mudança da direção de laminação de LT para TL aumenta a taxa de propagação de trinca por fadiga (PTF) tanto na região de *threshold*, quanto na região de Paris, onde a mudança de taxa é pequena.

Palavras-chave: – Propagação de trinca por fadiga (PTF), determinação da taxa de propagação de trinca, técnicas de medição de trinca, método de queda de potencial eléctrico (QPE), corrosão por fadiga, carregamento Dwell.

Abstract

BARBOSA, J. F. C. **Fatigue crack propagation in AA 7050-T7451 alloy considering environment, stress ratio, rolling direction and waveform effects**. Dissertação (Mestrado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, São Carlos, 2017.

Main extrinsic and intrinsic modifiers factors of crack growth rate in AA7050-T7451 were assessed in order to provide tools for aeronautical structures designers. These tools cover most necessary information to project aircraft's structures using the studied alloy, under damage tolerance philosophy. The experimental methodology consisted of use CT specimens, on TL and LT rolling direction to test its behavior under different conditions of stress ratio, force waveform, and the environment. The stress ratio values were 0.1 and 0.5, the force waveform used were sine and trapezoidal or Dwell under normal air laboratory conditions and salt fog 3.5%NaCl weight in order to simulate the marine environment. In Dwell tests, results were checked with the electrical potential drop technique (DCPD) in addition to the crack opening displacement (COD) method.

Using the Walker coefficients, calculated on the present research, could be projected accurately the crack propagation behavior on Paris region and do fatigue life predictions using da/dN and S-N diagrams for different stress ratio values. The corrosion environment increases both crack growth rate and ΔK_{th} due to oxides formation on the crack path that generates a crack closure effect. Dwell carrying makes decrease the crack growth rate by decreasing the slope of the Paris line on $\log (da/dN)$ versus $\log (\Delta K)$ curve, instead of shifting down the line as occurs on titanium alloys. Rolling direction change from LT to TL increase the FCG rate in both threshold and Paris region, where the rate change use to be small.

KEY WORDS- Fatigue crack growth (FCG), crack growth rate determination, crack length measurement techniques, potential drop method (DCPD), crack opening displacement method (COD), corrosion fatigue, stress corrosion cracking (SCC), Dwell carrying.

ABBREVIATIONS

ASTM	American Society for Testing and Materials
CNPq	<i>Conselho Nacional de Desenvolvimento Científico e Tecnológico</i>
COD	Crack Opening Displacement
CT	Compact Tension
DCPD	Direct Current Potential Drop
EESC	<i>Escola de Engenharia de São Carlos</i>
EMBRAER	<i>Empresa Brasileira de Aeronáutica S.A.</i>
FCC	Face Cubic Centered
FCG	Fatigue Crack Growth
FEA	Finite Elements Analysis
ISO	International Organization for Standardization
LEFM	Linear Elastic Fracture Mechanics
LT	Longitudinal Transverse
MIL-HDBK	Department of Defense Handbook
MPT	Multi-Purpose Test
SAE	Society of Automotive Engineers
SCC	Stress Corrosion Cracking
TL	Transverse Longitudinal
USP	<i>Universidade de São Paulo</i>

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1 INTRODUCTION

1.1 BACKGROUND

The metallic structures for aircraft were invented in Colombia by Carlos Alban. He presented his work in 1887 but the patent of the system of metal casing balloon was granted to him on October 9 of 1888. His friend Ferdinand von Zeppelin, on his balloons, applied Alban's develop.

In 1920 it was produced the junkers-F13 in Germany, the first aluminum structure aircraft, and in the same year began to operate in the second airline in the world called SCADTA (Avianca). The history of Al-Zn-Mg aluminum alloys or 7xxx series begun when the 7075 alloy was developed in secret by Sumitomo metal industries in Japan in 1936, looking for faster and stronger aircraft for the imperial Japanese Navy. The 7075 was used for the first time in the frame of the famous Mitsubishi A6M Zero, in the World War II, its use increased the flight time and for that reason, the use was extended to others countries since 1943 marketed as Alcoa. This alloy is still considered excellent for aircraft and aerospace application although hasn't the best corrosion resistance, that has been improving using an Alclad layer, modifying the temper and developing new 7xxx alloys as 7050.

Today the aeronautical structures are also made of composites materials because the high mechanical strength and corrosion resistance but present some disadvantages that make the aluminum still a good or sometimes the best alternative. Some of the disadvantages are that the strength varies from batch to batch, poor lightning strike protection, ultraviolet light degradation, do not warn prior to failure and poor available knowledge about fatigue behavior.

1.2 STATEMENT OF THE PROBLEM

In general, crack growth in aircraft structures occurs due to maneuvers, gusts and service loading. Some of them under fatigue and or corrosive environment. A good team of fatigue structures designers must use the available knowledge to avoid the crack nucleation and/or control the crack propagation.

EMBRAER or *Empresa Brasileira de aeronáutica S.A.*, use the AA7050-T7451 as one of the selected structural material and therefore has a need of knowledge of the material behavior in as many conditions as possible of carrying and environments. This kind of knowledge is only

developed by research and for that reason request a series of tests and provides the necessary material for the laboratory of mechanical tests of EESC-USP. This was how were developed works as the Moreto (2012) or Pascoal (2014) and the present research continued going deeper in the same direction in order to supply new tools for designers. The aspects of fatigue structure design touched in the present work are highlighted, in Figure 1.

Figure 1 Aspects of fatigue structures design touched on the present research

Source: Schijve (2001)

The AA7050-T7451 is used on aeronautical structural members as ribs, spars and other internal structures made of thick plate as mention Prasad (2014). The requirements of those members are shown in Figure 2.

Figure 2 Property requirements for jetliner and military transport application

Source: Prasad (2014)

1.3 SCOPE

The main objective is to evaluate the effect of extrinsic parameters (stress ratio, environment, and waveform) and an intrinsic parameter (rolling direction) on fatigue crack growth rate of a high strength aluminum alloy AA7050-T7451 used commonly for aeronautical structural purposes. The second objective is using some of the previous results to analyze the accuracy of Walker, Forman and Pearson empirical relationships to characterize the effect of stress ratio on fatigue crack growth rate. The stress ratios used are 0.1 and 0.5; the environments under the material is tested are air and salt spray 3.5% NaCl; the waveforms of applied forces are sine and Dwell and the rolling directions studied are TL and LT.

1.4 DISSERTATION LAYOUT

The present research cover a wide area of fatigue behavior of the AA7050-T7451 under several conditions of crack propagation in order to provide tools for structural designers from a phenomenological point of view. It means the focus of the present work is to show results of fatigue tests, compares them according to each study variable and discuss under the literature

review the involved mechanisms to explain the results, without to intend the proposition of any new or modification of the available mechanism in the current knowledge.

1.5 DOCUMENT ORGANIZATION

The central chapters of the document and its parts are described as follows.

The literature review is divided into general fatigue concepts, crack growth modifiers, environment-assisted fatigue, and Current source circuit.

The methodology explains conditions, software and procedures to carry out the tests identified on Figure 31 - Tests conditions and its designation.

In the results section are presented the Paris region crack growth graphs and fitting and also the threshold region graphs and ΔK_{th} results of each.

In the discussion section are presented comparisons between results in order to understand the influence of each study variable and compare with the literature review. In addition is presented an in-depth analysis of rolling direction influence on crack growth under Walker, Forman and Pearson theories and an application example of a result generated in the present research.

The conclusion chapter, bringing back the original questions about the influence in crack growth of different modifiers factor and using the experimental evidence, resumes what this research conclude in a more general manner.

The appendices contain an additional information that the reader could found interesting, but is not indispensable to understand how the research was made.

2 LITERATURE REVIEW

In the present chapter is contained the concepts needed to carry out the present research, starting with a brief historical approach.

The fatigue and fracture history is the failures history. Ancient Romans prevented cracks openings, basing on arc them stone architecture, Leonardo da Vinci was the first to study the strength of wires and found that the resistance is a function of length because longer wires possess more cracks (KUMAR, 2009), then with the industrial revolution appears a lot of machines and structures that failed due to fracture. According to NORTON (2011), the first notice of fatigue failure was on 1843 when Rankine published a paper in which he said, “The material had crystallized and become brittle due to fluctuating stress” and in that way, engineers started to consider the difference between statics and dynamics stresses. Twelve years later, August Wohler made an investigation known as fatigue failure, where he tested axles to failure under fully reverse loading as train axles. In 1870 he published his findings as the endurance limit of steels and developed the Wohler S-N diagram to characterize the behavior of a material under completely reverse loading.

Subsequent catastrophes, especially related to the first and second world war and civil aircraft operation, motivate researches that generate the science known as fracture mechanics in 1948 when George Irwin create the concepts of stress intensity factor and energy release rate, and latter Wells in 1961 create the crack tip opening displacement and Rice the J-integral in 1968.

2.1 FATIGUE LIFE STAGES

SCHIJVE (2001) summarizes knowledge of 20th century of fatigue like this: “repeated loads applications can start a fatigue mechanism leading a nucleation of a microcrack, crack growth, and ultimately to complete failure of a structure”. The previous idea is expressed in Figure 3.

The crack initiation is a surface phenomenon due to variable stress with an amplitude under yield stress. The micro-plasticity is concentrated in a couple of grains that can generate a plastic deformation at the surface of the material on slip bands, caused by shear stress in shear planes that change from grain to grain. Some surface grains according to its orientation and size favor the creation of cyclic slips as shown in Figure 4, where a) surface slip planes on slip bands and b) slip directions and slip plane on aluminum, face center cubic (FCC) metal.

Figure 3 - Stages of the fatigue life and relevant factors

Source: adapted of Schijve (2001) and Milella (2013) by the author

Once microcrack passes through a grain, the material makes anisotropic, the stress concentrates at the crack tip and new slip systems could be activated causing the deviation of the crack growth but tending to be perpendicular to the applied force. After some grains, the crack growth rate increases with crack length. The crack growth resistance change from a surface to a bulk material property.

The process to change from micro to macrocrack growth is different for each material, but in general resumed in Figure 5.

Figure 4 - Slip planes

a) Slip bands b) slip plane on FCC structure

Source: adapted from Milella (2013) by the author

Figure 5 - Scenarios of fatigue crack growth

Source: Schijve (2001)

2.2 FATIGUE LOADING

At the beginning of fatigue studies, the rotating machinery was the base but the concepts developed can be applied in general for any variable carrying. The symbol σ is the same used in mechanics of materials for stress in MPa.

Figure 6 - Basic concepts on variable carrying

Source: adapted from Norton (2011) by the author

Stress range

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad (1)$$

Alternating component

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2)$$

Mean component

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (3)$$

Stress ratio

$$R = \frac{\sigma_{min}}{\sigma_{max}} = \frac{K_{min}}{K_{max}} = \frac{P_{min}}{P_{max}} \quad (4)$$

In the present research were used only positive values of R on tests as shown in Figure 6 (c) but also analytically R zero value, as shown in Figure 6 (b). The K named on equation (4), is the stress intensity factor explained on stage II section.

2.3 WOHLER S-N DIAGRAM APPROACH

For stage I, II and III of fatigue life, the Wohler S-N diagram was the first approach. This methodology is based on a diagram that shows alternating stress vs life in cycles to predict the life of a component under fatigue. Steels and titanium alloys present an endurance limit tending to infinite life but others like aluminum used in the present research show no endurance limit and for that reason, components for long life must be designed for 5×10^8 cycles as shown in Figure 7. Today using adequate instrumentation is possible to generate S-N diagrams whose line represents nucleation instead of final failure by measuring microcracks.

Figure 7 - Wohler S-N diagram

Source: adapted from Norton (2011) by the author

2.3.1 R effect on S-N diagram

Usually, S-N diagram is plotted as S_a vs N to study the mean stress influence but in order to study the R effect, is plotted as S_{max} vs N , as shown in Figure 8.

Figure 8 - R effect on Smax-N diagram

Source: Adapted from Lalanne (2009) by the author

2.3.2 Rolling direction effect on S-N diagram

In the case of S-N diagram, as shown in Figure 9, the influence of rolling direction is that the longitudinal direction specimens present longer life than transverse.

Figure 9 - Rolling direction effect on S-N diagram

Source: adapted from Milella (2013) by the author

2.3.3 Aluminum S-N diagram equation

According to Norton (2011), the S-N line for a material like aluminum without endurance limit can be described by Log-Log scale using equation (5).

$$S_{ar} = aN^b \quad (5)$$

Where S_{ar} is the stress amplitude for zero mean failure stress in MPa that correspond to N cycles using the constants a and b calculated with equations (6) and (7).

$$\text{Log}(a) = \text{Log}(S_m) - b\text{Log}(N_1) \quad (6)$$

$$b = \frac{1}{Z} \text{Log}\left(\frac{S_m}{S_f}\right) \quad (7)$$

Where

$$Z = \text{Log}(N_1) - \text{Log}(N_2) \quad (8)$$

And the variables N_1 , N_2 , S_m and S_f corresponds to the coordinates of two points $P_1(N_1, S_m)$ and $P_2(N_2, S_f)$ that together generates the S-N non-endurance limit line. N_1 and N_2 correspond to 1000 and 5×10^8 cycles respectively. The S_m stress for the first point is calculated with equation (9).

$$S_m = 0.75 S_{ut} \quad (9)$$

The S_f stress for the second point is calculated with equation (10).

$$S_f = C_{load} C_{size} C_{surf} C_{temp} C_{reliab} S_f^* \quad (10)$$

Where S_f^* is a S_{ut} function and the C coefficients depends on work conditions of the designed mechanical element. The use and explanation of equation (10) for a plate of AA7050-T7451 is available on discussion chapter, section Walker coefficient result application.

2.3.4 Projection of S-N diagram for non-zero mean component and different R-values

A carrying on a ductile metal, with a mean component different to zero, can be converted into an equivalent zero mean component (σ_{ar}) using equation (11) in order to be used in an S-N diagram.

$$\sigma_{ar} = \frac{\sigma_a}{1 - \frac{\sigma_m}{\sigma_u}} \quad (11)$$

Where σ_u is the ultimate tensile strength of the material.

A standard S_{max} -N diagram based on minus one R-value can be projected to another R-values using equation (12) or the Walker equation for S_{max} -N diagrams.

$$\sigma_{ar} = \sigma_{max} \left(\frac{1-R}{2} \right)^\gamma \quad (12)$$

Where γ is the Walker constant for each material, according to Dowling (2011).

2.4 FRACTURE MECHANICS APPROACH

2.4.1 stage I: nucleation

According to Figure 3, this stage is related with K_t or stress concentration factor concept that is common for both S-N and fracture mechanics approaches. The K_t is defined for the ellipse as the ratio of maximum or local stress (σ) to the remote stress (S) as expressed by equation (13) and shown in Figure 10 (b).

$$K_t = \frac{\sigma_y}{S} \quad (13)$$

Figure 10 - stress concentration factor K_t

Source: Dowling (2007)

The hole works as stress raiser as a function of the hole curvature radius (ρ) but when ρ tends to zero, the hole turns a slitlike crack and σ_y becomes infinite, as shown equation (14) and Figure 10 (a).

$$\sigma_y = S \left(1 + 2 \frac{c}{d} \right) = S \left(1 + 2 \sqrt{\frac{c}{\rho}} \right) \quad (14)$$

The specimens used for the present research had notches with stress concentration factors K_t but they were pre-cracked, so passed directly to stage II of fatigue life, the crack growth.

2.4.2 stage II: crack growth

According to Figure 3, for stage II or crack growth, the characteristic parameter is the stress intensity factor K , which is a fracture mechanics concept to measure the severity of a crack situation and depends on crack size, stress, and geometry. If the material behaves in a linear elastic manner, the approach used is called linear elastic fracture mechanics (LEFM). As shown in Figure 11, the crack length (a) is measured from the centerline, and the stress intensity factor K is calculated as:

$$K = S\sqrt{\pi a} \quad (a \ll b) \quad (15)$$

The geometry of test specimen change K , and to account it, it is necessary to use a geometric factor F to calculate the stress intensity factor as shown in equation (16).

$$K = FS\sqrt{\pi a} \quad (16)$$

When the remote stress S and therefore the local stress σ varying from maximum to minimum value is because of the change of applied force according to equation (17).

$$\Delta P = P_{max} - P_{min} \quad (17)$$

Figure 11 - Wide plate with crack length a

Source: adapted from Dowling (2007) by the author

The change of force generates a change of stress and consequently change of stress intensity.

$$\Delta K = K_{max} - K_{min} \quad (18)$$

According to the direction of applied force, a segment of the crack front can be classified into three modes as shown in Figure 12. A mechanical component can suffer one of the modes or a mixture. In the present research was studied mode I that is the most critical of three.

Figure 12 - Crack front modes

Source: Kumar (2009)

Figure 13 - da/dN - Delta K regions

65

Source: Milella (2013)

When a crack begins to propagate, do it per cycle da/dN (mm/cycle), but may be as small as 10^{-10} m/cycle close to lattice parameter, hard to detect by normal non-destructive test (NDT), that's is why is considered nucleation but still not propagation.

Each cycle the crack grows faster (da/dN) and ΔK increase showing three regions in a sigmoidal curve during propagation as shown in Figure 13.

Region I called threshold zone, is that where below a threshold value ($\Delta K_{th} < 6 \text{ MPa}\cdot\text{m}^{0.5}$) there is no apparent growth, according to MILELLA (2013).

Region III is where the crack growth is high and increasing while ΔK approaches to its fracture limit ΔK_I .

Region II there the curve behave as a straight line on Log-Log scale, this relation is known as Paris-Erdogan as shown in equation (19).

$$\frac{da}{dN} = C \Delta K^m \quad (19)$$

The present research is about aluminum and some aluminum crack growth behavior are shown in Figure 14.

Figure 14 - da/dN for different aluminum alloys

Source: Milella (2013)

2.4.3 stage III: final failure

As shown in Figure 3 and Figure 13 the characteristic parameters on final failure are K_I and K_{Ic} . Both are failure stress intensity factors but it depends inversely proportional to specimen thickness. Specifically, the minimum critical K_I failure value corresponds to fracture toughness K_{Ic} as shown in

Figure 15.

Figure 15 - KI vs K_{Ic} Fracture toughness

Source: Dowling (2007)

2.5 CRACK GROWTH MODIFIERS

Some factors modified the crack growth behavior on da/dN vs ΔK sigmoidal curve. The following factors are shown according to empirical results.

2.5.1 Environment

According to Ghali (2010), the cracks propagate more rapidly in a corrosive environment, as shown in Figure 16. The corrosion mechanisms are explained on environment-assisted fatigue section in the present chapter.

Figure 16 - CGR modified by environment

Source: Ghali (2010)

2.5.2 Stress ratio

In the case of stress intensity approach, according to Dowling (2007), “for a given ΔK increasing R increases the growth rate” as shown in Figure 17.

Figure 17 - R influence on FCG of aluminum 7050-T76

Source: Brown (1978)

In order to study the R effect on crack growth, some empirical equations have been developed tending to replace the Paris equation that must be formulated for each R-value. Maddox (1973) and Lalanne (2009) did important reviews of these equations. Some examples are the followings:

Walker equation for crack propagation

$$R=0 \quad \frac{da}{dN} = C_0 \Delta K^m \quad (20)$$

$$R \neq 0 \quad \frac{da}{dN} = C_o \left[\frac{\Delta K}{(1-R)^{1-\gamma}} \right] \quad (21)$$

Where C_o and γ are Walker constants.

Forman equation

$$\frac{da}{dN} = \frac{C_2(\Delta K)^{m_2}}{(1-R)Kc - \Delta K} = \frac{C_2(\Delta K)^{m_2}}{(1-R)(Kc - K_{max})} \quad (22)$$

$$Q = \frac{da}{dN} [(1-R)Kc - \Delta K] \quad (23)$$

Pearson equation

$$\frac{da}{dN} = \frac{C_2(\Delta K)^{m_2}}{[(1-R)KIc - \Delta K]^{0.5}} \quad (24)$$

$$Q = C_2(\Delta K)^{m_2} \quad (25)$$

2.5.3 Rolling direction

The microstructure of the aluminum can affect K_{Ic} because the crystal grain orientation from rolling, as shown in Figure 18.

Figure 18 - influence of rolling direction in K_{Ic} for some aluminum

Source: Dowling (2007).

The influence of rolling direction on crack growth in aluminum have been studied by different researchers as Hudson (1969) and others including some who has studied the same material of the present research AA7050-T7451 as Pascoal (2014) and the results match.

In the case of stress intensity approach, grain orientation acts as a barrier or path for crack propagation in LT or TL respectively, as shown in Figure 19.

Figure 19 - Crack growth vs rolling direction

Source: elaborated by the author

The aspect of AA7050-T7451 alloy microstructure due to the rolling direction is shown in Figure 20.

Figure 20 Optical micrographs of 7050-T7451 plates.

a) longitudinal-long transverse b) longitudinal-short transverse

Source: Liu et al (2009)

2.5.4 Wave form

Sommer (1978) reports that while sine loading generates permanent crack growing as shown in Figure 21 a), Dwell can stop while the holding time as shown in Figure 21 b) or decrease the rate as shown in Figure 21 c).

Figure 21 - Waveform crack growth influence

Source: Sommer (1978)

Figure 22 - Dwell time influence on crack growth rate of titanium

Source: Wang (2015)

Wang (2015) reports that Dwell time can increase the crack growth rate on titanium alloys as shown in Figure 22 and Bania (1978) reports for some microstructures of titanium alloys that “Dwell cycling resulted in a significantly lower fatigue crack growth rate” and suggests the phenomena by a crack tip blunting mechanism.

Figure 23 - Crack path tortuosity due to Dwell loading

Source: Bania (1978)

2.6 MATERIAL PROPERTIES

Different characterization works have been made for AA7050-T7451 as Zamorano (2003). For present research is especially important Pascoal (2014) because characterize the composition and mechanical properties using the same plate used to manufacture the specimens for the present work. Obtained results are shown in Table 1 and Table 2.

Table 1 Chemical composition AA7050-T7451

Element	Zn	Cu	Mg	Zr	Fe	Si	Mn	Ti	Cr	Al
Percentage	6.02	2.25	1.896	0.1	0.05	0.04	0.01	0.03	0.01	Balance

Source: Pascoal (2014)

Table 2 Mechanical properties AA7050-T7451

Magnitude	Pascoal	MIL-HDBK-5J	Unit
σ_y	472.3	441.26	MPa
σ_u	533.6	510.2	MPa
E	64	71	GPa
KIc / TL	38	30.76	MPa*m ^{0.5}
KIc / LT	44.7	35.16	MPa*m ^{0.5}

Source: Adapted from Pascoal (2014) and MIL-HDBK-5J (2003)

The strength resistance is due to copper and copper-magnesium relation of content Ghali (2010).

2.7 HEAT TREATMENT

Standard ASTM B918 (2014) and SAE AMS 2770H (2006) are related.

The rolling procedure in the AA7050-T7451 aluminum shape elongates the grains and set up stresses and strain, that are removed by an annealing process where the shape is heating above the recrystallization temperature at 413°C and holding or soaked in order to recrystallize and relieve the stresses for 2 hours and then cooling slowly. After annealing the material is ready to the heat treatment itself. The heat treatment for AA7050-T7451 is resumed on the followings steps:

2.7.1 Solution treatment

According to Totten (2003, V1), the purpose is to create a solid solution with a maximum of alloying elements in solution in order to obtain better material properties as shown in Figure 25. The alloying elements are located on grain boundaries, vacancies, dislocations and any free space inside the material structure.

The procedure shown in steps 1 and 2 in Figure 24, consist on heating the material from ambient temperature (25°C) until heat treatment temperature (477°C) as fast as possible and then maintain the temperature during the soaking time for the specified period.

2.7.2 Quenching

The purpose is to maintain the supersaturated solid solution and the excess vacancies at ambient temperature. Higher cooling rate helps to obtain better strength and toughness, but also stress corrosion and corrosion resistance. The disadvantage is to generate residual stresses that can be reduced controlling the quench rate, selecting medium (air, water or other fluid) and temperature. Quenching is the step 3 on Figure 24.

2.7.3 Aging

The process occurs at elevated temperature (121°C), it means is an artificial aging, showing in steps 4, 5 and 6 of Figure 24. The purpose of aging is to precipitates the supersaturated solid solution using the vacancies to promote diffusion looking for a uniform material as shown in Figure 25. Some precipitation products that help on material's strength on 7XXX (Al-Zn-Mg) aluminum alloys are $MgZn_2$, Mg_2Si , Al_3Fe , Al_7Cu_2Fe , $Mg(AlCu)$ and Al_2CuMg . The meaning of T7 is solution heat-treated and stabilized and overaged and was developed according to Ghali(2010) to improve resistance to exfoliation and stress corrosion cracking. According to MIL-H-6088G the time of aging for AA7050-T7451 is between 3 to 6 hours.

Figure 24 Heat treatment for AA7050-T7451

Source: elaborated by the author

Figure 25 Temperature vs microstructure while heat treatment of AA7050-T7451

Source: adapted from Totten (2003, V1) by the author

2.8 ENVIRONMENT-ASSISTED FATIGUE

Exist when “a combined action of fatigue loading and environmental corrosion, resulting in a faster growth of a crack”. Kumar (2009). It is an interdisciplinary field that includes chemistry of materials, electricity, mechanics and science of materials. Some of the most important parameters in environment-assisted fatigue are alloy chemistry, heat treatment, humidity, salt concentration, temperature, work hardening and frequency as shown in Figure 26.

Some authors mention the environment-assisted fatigue as a combination of fatigue and stress corrosion cracking (SCC), it means the combined effect of tensile stress and aggressive environment.

Figure 26 - Variation in the crack extension per cycle with frequency in steel alloy 12NI-5Cr-3Mo tested in 3% NaCl solution

Source: Kumar (2009)

The corrosion is high in the vicinity of a crack tip, where stresses are also high and intense plastic deformation, specially influenced by the slip bands that expose new material layers to the corrosive environment.

The present research focuses on the environment-assisted fatigue as a corrosion presented in aeronautical structures under work.

Pit corrosion is not referenced in the present research although can initiate a SCC process but neither has time to act during crack propagation not helped the nucleation in the tests of the present research because specimens just exposed to the corrosion environment at the time of testing and already pre-cracked. The transition from corrosion pit to crack formation is out of the present work

The micromechanisms of environment-assisted fatigue are explained in the followings lines, based on Barnoush (2007), Kumar (2009), MIL-HDBK-5J (2003), Prasad et al (2014), Corrosionpedia(2015) and NPTEL(2015).

2.8.1 Active path dissolution

Is a localized corrosion, at the crack tip, along a susceptible path while the bulk of the material remains a more passive state. The crack initiates where exist a concentration of strength and the corrosion resistance alloy elements are segregated as in the grain boundaries, that is why active path dissolution generates intergranular corrosion.

2.8.2 Hydrogen embrittlement

This mechanism generates a decrease of the toughness or ductility because of the presence of hydrogen molecules inside of the material. The process begins when some hydrogen atoms diffusing through the metal as a function of temperature and concentration gradient, the hydrogens atoms re-combine generating voids of metal matrix and forming hydrogen molecules. They generate an increasing pressure, reducing metal ductility and tensile strength up to the point where crack is opened. Usually, the crack propagation is intergranular because the grain boundaries are more susceptible to the hydrogen atoms movement. Hydrogen embrittlement works together with active path dissolution and film induced cleavage.

According to Barnoush (2007), the hydrogen embrittlement is an interaction of aspects. Mechanical represented by loading, the state of stress and residual stress. Material by the crystal structure, hydrogen solubility and diffusion, hydride formation. Environment by external or internal hydrogen, hydrogen fugacity, and the hydrogen source.

Figure 27 Hydrogen embrittlement interaction aspects

Source: adapted from Barnoush (2007) by the author

Once hydrogen has entered into the material, the hydrogen concentration (C_H) acts as a modifier of the crack propagation rate and ΔK threshold, as shown the blue line on Figure 28, the figure was adapted to remove the temperature effect that not change in the present research.

Figure 28 Hydrogen concentration affecting Delta Kth and crack propagation

Source: Adapted from Barnoush (2007) by the author

2.8.3 Film induced cleavage

Kumar (2009) explains, that structural metal like aluminum, are naturally protected from an oxide passive layer on their surfaces. High stress and quite plastic deformation, and the surface rough because of the slip bands micro-cracks characterize the surrounding of the crack tip. These micro-cracks broke the passive layer on the surface exposing the metal to the corrosive atmosphere.

The film-induced cleavage is an anodic mechanism where the exposed surface in the vicinity of crack tip becomes the anode of an electrolytic cell as shown in Figure 29 and the passive layer work as cathode. The excess of electrons on the anode pass inside the material to the passive layer or the cathode, reducing the hydrogen ions on of the surrounding water-NaCl solution, and some of these hydrogen atoms of water can diffuse helping the hydrogen-embrittlement corrosion mechanisms.

Figure 29 the electrolytic cell formed near the crack tip

Source: Kumar (2009)

2.8.4 AA7050-T7451 Corrosion resistance

A resistance stress-corrosion rating is available on MIL-HDBK-5J (2003,p3-17), there is classified the 7050-T74 aluminum alloy in TL and LT direction as (A) it means a very high rating because “is equal or greater than 75% of the specified minimum yield stress. SCC not anticipated in general applications.” The high corrosion resistance of AA7050-T7451 is due to the quenching process and content of Zn, according to Prasad et al (2014, p20).

“Zinc goes into solid solution within the grains and shifts the pitting potential of the matrix to less noble and decreases the electrochemical potential difference between the grain boundary and the matrix, thus improving static and dynamic corrosion properties”

According to Ghali (2010), the 7xxx series alloys are more resistance to general corrosion than 2xxx but susceptible to SCC and exfoliation corrosion if compared.

2.9 CURRENT SOURCE CIRCUIT

The current source is an electronic circuit, could be dependent or independent. An independent current circuit maintains constant the current flow through a path and then by an electrical resistance. An example is shown in Figure 30

Figure 30 current source circuit

Source: adapted from Hayt et al (2012) by the author

The resistance is a restriction of current passing through the physical element called resistor. The resistance of a resistor is proportional to its material and length but inversely proportional to the cross section as explained in equation (26).

$$R = \rho \frac{L}{A} \quad (26)$$

Where:

R resistance value (Ω)

ρ is the material resistivity in ($\Omega \cdot \text{m}$)

L is resistor length (m)

A is the resistor cross section (m^2)

When the current passes through the resistor occurs a voltage drop calculated using the Ohm's law equation (27)

$$\Delta V = I * R \quad (27)$$

Where

ΔV is the voltage drop (V)

I is the electric current (A).

3 RESEARCH METHODOLOGY

As mentioned in the introduction chapter the goal of the present dissertation is to evaluate the effect of stress ratio, environment, waveform and rolling direction on fatigue crack growth rate of a high strength aluminum alloy AA7050-T7451.

3.1 TESTS DESIGN

In order to achieve the purpose of the present research were planned the tests and a designation for each one as shown in Figure 31.

Figure 31 - Tests conditions and its designation

Source: elaborated by the author

The material AA7050-T7451 was supplied by EMBRAER in plate of 25.4mm (1-inch) thickness and the company suggested the environmental conditions of the tests. Each test was named using a consecutive nomenclature from A1 to F2. Notice that each letter means a family of conditions by force wave (sine or Dwell), environment (air 23°C or salt fog 3.5% NaCl) and

region on $da/dN-\Delta K$ diagram (Paris or threshold), finally the numbers after the letters were used to distinguish the rolling direction (TL or LT) and stress ratio (0.1 or 0.5).

The A1 test was done by others researchers (Pascoal, 2014) and (Moreto, 2012) and the tests A2, A3, A4, and C1 were done by the present author in addition of some of the mentioned researchers in order to add results to validate them.

The present work introduces the study of trapezoidal or Dwell carrying for the material AA7050-T7451 as another possible crack growth rate modifying factor.

In general, the kind of fatigue tests in the present research and its characteristics parameters are shown in Table 3.

Table 3 - Tests performed and its parameters

Test	Pre-crack	Paris	Threshold
Characteristic variables	R 0.1	R 0.1 or 0.5	R 0.1 or 0.5
	Kmax	Pmax	Kmax
	f 15Hz	f 1Hz	f 15Hz
	Final length 3mm	-	End rate
Type of control	Constant load amplitud	Constant load amplitud	Delta K control

Source: elaborated by the author

Paris and Threshold tests were made using stress ratios as shown in Figure 31. The idea of end rate on Threshold tests was to reach 5 points below 10^{-6} mm/cycle in order to calculate ΔK Threshold.

3.2 TESTS SPECIMENS MANUFACTURE

The geometry of the C(T) specimen was selected because according to ASTM (E647, 2013, p11) “requires the least amount of test material to evaluate crack growth behavior” and specimens were made according to the mentioned standard and the clip gage manufacturer (MTS,2017) as shown in Figure 32 and Table 4 .

Figure 32 - Machined C(T) specimen geometry

Source: elaborated by the author

Table 4 - Specimen manufacture data

Length	Source	General parameter	Used parameter	Value (mm)
W	E647	$W > 25$	-	50
h	E647	$H \leq W/16$	$W/16$	3
b	MTS	Fixed	-	4
B	E647	$W/20 \leq B \leq W/4$	$W/4$	12.5
a _n	E647	$0.2W$	$0.2W$	10

Source: elaborated by the author

The designation of geometry symbols used on CT specimens are listed on Table 5 .

The machining process of geometry included electro erosion, drilling and milling then for surface finishing were sanding with sandpaper #400, 600, 1200 and 2000. After that, were made polishing and finally were scratching lines on specimen, each 1 mm to maintain visual control of crack growth.

Before starting, a crack growth test was necessary done into each specimen a pre-crack due to indication of ASTM (E647, 2013, p5). On this case corresponded to 3mm, the same h length on the specimen.

Table 5 - Geometry symbols on CT used specimens

Symbol	Designation
W	width
B	thickness
b	knife edge for clip gage
h	notch height
an	machined notch length
Δa	change in crack length
a	crack length
acor	crack front curvature correction length
afat	fatigue crack length measure from the notch root
ap	Pre-crack length

Source: adapted from ISO12108 and MTS (2017) by the author

3.3 CONTROLLING TESTS ENVIRONMENT

The air environment for tests was controlled by an air conditioner at 23°C and 55% relative humidity (RH). In the other hand, the salt fog environment was controlled generating salt fog using a water solution 3.5% weight NaCl and a neutral acidity of pH 7, both measured externally before and during tests, as shown in Figure 33 in order to prevent crack tip induced phenomena that could change the crack growth rate.

Figure 33 - Controlling solution conditions before corrosion test.

a) Percentage of NaCl

b) pH

Source: elaborated by the author

The salt fog environment circuit is shown in Figure 34. It is composed of the followings items: 1) entrance of external air, 2) motor-compressor unit, 3) pressure regulator, 4) water solution 3.5% NaCl, 5) salt fog generated by pressured air (50kPa) into water solution, 6) compact tension specimen into corrosion camera, 7) salt fog camera for corrosion tests, 8) condensed outlet.

Figure 34 - Salt fog circuit for corrosion tests

Source: elaborated by the author

3.4 FATIGUE CRACK GROWTH TESTS

The test machine was a servo-hydraulic MTS Landmark 370.10. All sine and Dell tests acquire data from a clip gage model MTS 632.05 as shown in Figure 35 but in the case of sine tests, a software called fatigue crack growth (FCG) calculated results da/dN and ΔK automatically.

Figure 35 - Clip gage on C(T) specimen

Source: MTS (2017, p32)

Dwell tests requires the use of a software called multipurpose test (MPT) to create the wave but do not generate results, instead of it da/dN and ΔK had to be calculated manually. For this purpose were selected two techniques: crack opening displacement (COD) and direct current potential drop (DCPD). The first one because can used the same clip gage used during sine wave tests and the second one in order to automate and simplify calculations and according to KALLURI (1988, p1)

“The crack length data measure by DCPD reflect the average crack profile through the entire thickness of the specimen whereas the optical crack length measurement technique measures only the intersection of the crack front with the specimen surface”.

In addition to COD and DCPD, a third method called visual assumed as reference was used to calibrate the others, particularly DCPD.

The designed 1Hz Dwell wave is shown in Figure 36, looking for maintaining open as long as possible the crack in order to help acting the corrosive environment although the low frequency.

Figure 36 - Designed Dwell wave

Source: elaborated by the author

In general for any of the three methods used for crack length measure: visual, COD or DCPD, the calculations of ΔK and da/dN were made as explained in the following lines:

The most important test parameters K_{max} and P_{max} expressed on equations (28) and (29), were obtained solving simultaneously, equations (18), (17) y (4).

$$K_{max} = \frac{\Delta K}{(1 - R)} \quad (28)$$

$$P_{max} = \frac{\Delta P}{(1 - R)} \quad (29)$$

In equation (28) the ΔK referenced is the initial test value, the values used were 6,7 and 8 MPa*m^{0.5} for pre-crack, Paris and Threshold respectively. In the other hand, the ΔP on equation (29) was calculated isolating this term in equation (30) that is specifically for CT specimens, according to (Kumar, 2009).

$$\Delta K = \frac{\Delta P}{B * W^{\frac{1}{2}}} * f(\alpha) \quad (30)$$

The dimensionless parameter α was used to simplify the expression, as equation (31) shows.

$$\alpha = \frac{a}{W} \quad (31)$$

The whole expression $f(\alpha)$ in equation (30), is the geometric parameter, defined by equation (32).

$$f(\alpha) = \frac{(2 + \alpha)(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4)}{(1 - \alpha)^{\frac{3}{2}}} \quad (32)$$

Finally, after knowing crack length by visual, COD or DCPD method, to determine the crack growth rate was utilized the secant method, described by ASTM E647 (2013, p29). Using the mentioned method, the crack growth rate was calculated using the equation (33)

$$(da/dN)_a = (a_{i+1} - a_i)/(N_{i+1} - N_i) \quad (33)$$

Where:

a – crack length (mm)

N – cycle (cycle)

Basically, equation (33) is the slope calculation of the straight line connecting two adjacent (a,N) data points.

3.4.1 Automatic results using FCG software

In the following lines is describe how were generated the da/dN and ΔK results, using FCG software. The procedure is equal to COD technique but automated.

Fatigue crack growth FCG software is proprietary by MTS Systems Corporation and the license belongs to Universidade de São Paulo. The main source of information about the software is the program own help.

The first step in FCG was typing the material's basic information (yield and ultimate stress, elastic modulus, Poisson's ratio, rolling direction), second the specimen properties (h, an, B and W) and finally the test parameters (stress ratio, frequency, force or ΔK range and its type of control).

Next step was to calibrate the clip gage by visual control. The method consists on measure real machined notch length (an) of the specimen to compare with (an) measured by the clip gage to calibrate it. After that, was made the 3mm pre-crack mentioned, taking care by a visual control that the pre-crack length is equal in both faces, using a camera Canon EOS 600D. An example of visual crack length monitoring during a fatigue crack growth test is shown in Figure 37.

Figure 37 - Visual crack length monitoring

Source: elaborated by the author

Once the pre-cracking was performed, the tests continued until catastrophic failure or slightly earlier. Anyway, the specimens were broken hitting them after cooling with liquid nitrogen. According to ISO12108 (2002), the broken specimens were used to examine the through thickness crack front curvature in both pre-crack and final crack lengths across five lines named from a1 to a5. Each line a2, a3 and a4 corresponds to 0.25B, 0.5B and 0.75B respectively. On the other hand, a1 and a5 corresponds to crack lengths at the two specimen faces, as shown in Figure 38. The measures were obtained using a software called image pro-plus.

Figure 38- Fracture face after test

Source: elaborated by the author

According to the previous paragraph, the crack length a , corresponds to the relation described by equation (34).

$$a = a_n + a_{fat} + a_{cor} \quad (34)$$

The standard ISO12108 (2002) suggest the use of linear interpolation, to determine the correction for intermediate data, when the crack curvature varies with crack length a , as shown in Figure 39.

Figure 39 - Crack curvature correction

Source: elaborated by the author

FCG corrected automatically the results of $da/dN - \Delta K$, using the a1 to a5 measures.

3.4.2 Measuring crack size by visual method

During E1 test, side photos were taken while the crack was propagating. After finishing, following the process described in the section: Automatic results using FCG software, the broken specimen were used to fitting a linear interpolation as shown in Figure 39, to determine the crack curvature of each intermediate data. The visual method is considered as a reference to evaluate the others: COD and DCPD, for this reason, were made the curves: Figure 49 - Crack length during E1 test and Figure 50 - Accuracy of COD and DCPD methods.

3.4.3 Measuring crack size by COD

Saxena (1978) explains how this technique monitoring crack growth, using two quantities: apply load P and specimen deflection δ for CT specimens.

Figure 40 - – Linear and non-linear compliance C

Source: adapted from (Ranganathan et al., 1989)

In order to calculate the crack length a , first was calculated the compliance C as the slope of the δ - P diagram, as shows Figure 40. In the case of a straight line it's a trivial calculation as happened in the present research but if the relation is another curve, the slope had to be calculated fitting a polynomial relation δ - P and deriving when force corresponds to P average. Then using equation (35), it was determined the nondimensional compliance comp:

$$comp = E * B * C \quad (35)$$

After that was calculated an auxiliary function U with equation (36) to simplify compliance formulas

$$U = \frac{1}{comp^{0.5} + 1} \quad (36)$$

In the next step using U in equation (37), was calculated the a/W parameter

$$\frac{a}{W} = 1.0010 - 4.6695U + 18.460U^2 - 236.82U^3 + 1214.9U^4 - 2143.6U^5 \quad (37)$$

Finally this a/W expression times W , gave the crack length a , for each specimen.

Where:

comp – nondimensional compliance

E – elastic modulus (MPa)

B – specimen thickness (mm)

C – compliance (mm/N)

U – Auxiliary function for simplifying compliance expressions

a – crack length (mm)

W – specimen length in crack propagation path, from load line to the end (mm)

An example of Dwell wave and corresponding δ vs force diagrams during the E2 test is shown in Figure 41 and Figure 42 in order to determine the compliance on it's point.

Figure 41 - Example of Dwell wave on E2 test

Source: elaborated by the author

Figure 42 – Example of δ vs force on E2 test

Source: elaborated by the author

3.4.4 Measuring crack size by DCPD

Before making voltage drop measurement, the ground connection of the fatigue machine was verified and the isolating system for specimens was based on isolate pins as shown in Figure 43.

Figure 43 - Isolating system

Source: elaborated by the author

The DCPD method is a shortcut to simplify the crack length calculus. The conductivity on a test specimen decreases because the decrease of the cross section, and thus makes increasingly difficult to direct current pass through, increasing the voltage drop. The DCPD circuit is shown

in Figure 44 and the voltage drop obtained in the present research was in the 30 to 60 mV using a current source of 5A using the minimum value suggest according to ASTM E647 (2013, p25).

Figure 44 - DCPD power and control circuit diagram

Source: adapted from ASTM E647 (2013) by the author

The ASTM E647 (2013) presents a calibration curve establishing the voltage drop vs crack length relationship for CT specimens, in the case of using the wire placement shown in Figure 45, but the material AA7050-T7451 presented difficulties to be welded. Subsequent literature review confirmed that the alloy level of resistance spot weldability is B, it means that requires special techniques according to MIL-HDBK-5J (2003, p 3-24).

Figure 45 - Electric potential wire placement

Source: ASTM E647 (2013)

In order to solve the weldability difficult was decided the use of screws, preserving the current in and out wires places but relocating the voltage measurement point to a new close place without compromising the structural stability of the CT specimen. To achieve that goal was made a qualitative finite elements analysis (FEA), looking for low-stress areas under carrying in a whole cycle, to locate the screw holes, as shown in Figure 46.

Figure 46 - FEA for screw holes at low-stress areas

Source: elaborated by the author

Figure 47 - Calibration curve a/W vs V/V_0

Source: elaborated by the author

According to Doremus et al.(2014, p2) “The accuracy of DCPD method depends mainly on the calibration curve” and that is why a new calibration curve for the new wiring geometry had to be developed. For that purpose using the crack length data obtained by the visual method on test E1, the a/W parameter was calculated and using the voltage drop measurements was calculated the V/V_0 parameter, where V_0 is the initial voltage drop. The resulting calibration curves obtained are shown in Figure 47 and Figure 48.

Figure 48 - Calibration curve V/V_0 vs a/W

Source: elaborated by the author

The fitting data of calibration curves are shown in Table 6 and the equations type is described by equation (38).

$$y = \text{intercept} + B1 * X^1 + B2 * X^2 \quad (38)$$

Table 6 - Calibration curve fitting data

Calibration curve	a/W vs V/Vo	V/Vo vs a/W
R ²	0.99515	0.99597
Intercept	-0.59403	0.71499
B1	1.03244	0.80253
B2	-0.16785	0.97195

Source: elaborated by the author

Once obtained the calibration curve, the crack length was calculated as follows:

- taking the voltage drop data of each test, divided into its initial value was calculated the (V/Vo) measured parameter;
- calculating the (V/Vo) normalized parameter dividing the (V/Vo) measured parameter by the normalizing parameter (NP);
- using the calibration curve, the a/W parameter was calculated as a function of (V/Vo)normalized;
- Finally, crack length data was calculated multiplying a/W parameter by W of each specimen.

The mentioned normalizing parameter (NP) was proposed by KALLURI (1988) and was calculated using the equation (39).

$$NP = \frac{\left(\frac{V}{V_o}\right)_{final, measured}}{\left(\frac{V}{V_o}\right)_{final, calculated}} \quad (39)$$

Figure 49 shows the magnitude of crack length obtained by the three methods during the E1 test and Figure 50 shows the accuracy of COD and DCPD methods in relation to the reference visual method also during E1test, as RANGANATHAN(1989) did. The average relative error for both techniques (COD and DCPD) was four percent relative to the visual.

Figure 49 - Crack length during E1 test

Source: elaborated by the author

Figure 50 - Accuracy of COD and DCPD methods

Source: elaborated by the author

The crack length vs time relation during E2 and F1 test are available in Figure 141 and Figure 142 (Appendice 2).

4 RESULTS

In the present chapter are shown individual results of planned tests according to Figure 31 - Tests conditions and its designation, on the methodology. The purpose of the present chapter is to show results and remains its conditions. The Paris tests are presented beginning by Sine tests in air (A tests) and then in fog (C tests). After that are presented the Paris Dwell tests similarly, first in air (E tests) and then in fog (F tests). Finally, the results of all Paris fitted lines are presented in Table 7, while Paris regressions confidence and prediction bands are presented on Appendice 1. The threshold tests are shown after Paris tests, in both conditions air (B tests) and fog (D tests), and the ΔK_{th} results are present in Table 8.

4.1 PARIS TESTS

4.1.1 Paris, sine, air tests (A tests)

A1 test

The A1 test was not made by the author but is important to compare results on discussion chapter. The results obtained by Moreto (2012) and Pascoal (2014) are shown together in order to generate a better curve fitting.

Figure 51 Test A1. Sine, air, Paris, TL, R 0.1

Source: Moreto (2012) and Pascoal (2014)

A2 test

Figure 52 Test A2. Sine, air, Paris, TL, R 0.5

Source: Pascoal (2014) and the author

A3 test

Figure 53 Test A3. Sine, air, Paris, LT, R 0.1

Source: Pascoal (2014) and the author

A4 test

Figure 54 Test A4. Sine, air, Paris, LT, R 0.5

Source: Pascoal (2014) and the author

4.1.2 Paris, sine, salt fog 3.5% NaCl tests (C tests)**C1 test**

Figure 55 Test C1. Sine, salt fog 3.5% NaCl, Paris, TL, R 0.1

Source: Moreto (2012)

C2 test

Figure 56 Test C2. Sine, salt fog 3.5% NaCl , Paris, TL, R 0.5

Source: elaborated by the author

C3 test

Figure 57 Test C3. Sine, salt fog 3.5% NaCl, Paris, LT, R 0.1

Source: elaborated by the author

C4 test

Figure 58 Sine, salt fog 3.5% NaCl, Paris, LT, R 0.5

Source: elaborated by the author

4.1.3 Paris, Dwell, air tests (E tests)**E1 test**

Figure 59 Test E1.COD, Dwell, air, Paris, TL, R 0.1

Source: elaborated by the author

Figure 60 Test E1.DCPD, Dwell, air, Paris, TL, R 0.1

Source: elaborated by the author

E2 test

Figure 61 Test E2. COD Dwell, air, Paris, LT, R 0.1

Source: elaborated by the author

Figure 62 Test E2. DCPD Dwell, air, Paris, LT, R 0.1

Source: elaborated by the author

4.1.4 Paris, Dwell, salt fog 3.5% NaCl tests (F tests)

F1 test

Figure 63 Test F1. COD Dwell, salt fog 3.5% NaCl, Paris, TL, R 0.1

Source: elaborated by the author

Figure 64 Test F1. DCPD Dwell, salt fog 3.5% NaCl, Paris, TL, R 0.1

Source: elaborated by the author

F2 test

Figure 65 Test F2. COD Dwell, salt fog 3.5% NaCl, Paris, LT, R 0.1

Source: elaborated by the author

4.1.5 Paris tests fitting results

The followings are the fitting results of Paris lines made on both air and salt fog 3.5%NaCl.

Table 7 Paris tests fitting results

Test	Technique	C [(mm/ciclo)/(MPa.m ^{0.5}) ^m]	m	R ²
A1	COD	4.03962E-08	3.40295	0.75435
A2	COD	7.08288E-08	3.39007	0.9471
A3	COD	1.17796E-07	2.97231	0.93362
A4	COD	8.90082E-08	3.25099	0.81637
C1	COD	4.42191E-07	2.61559	0.99571
C2	COD	2.56537E-06	2.64515	0.97181
C3	COD	1.71664E-06	2.50391	0.99121
C4	COD	6.97349E-06	2.11922	0.97162
E1	COD	1.58154E-06	1.93767	0.99371
E1	DCPD	1.10859E-06	2.13726	0.9768
E2	COD	1.00254E-06	2.04313	0.99226
E2	DCPD	8.87585E-07	2.13318	0.9364
F1	COD	1.50473E-06	2.37757	0.98961
F1	DCPD	1.11165E-06	2.56563	0.97807
F2	COD	3.29193E-06	2.07579	0.99699

Source: elaborated by the author

4.2 TRESHOLD TESTS

4.2.1 Threshold, air, tests (B tests)

B1 test

Figure 66 Threshold, air, TL, R 0.1

Source: Pascoal (2014)

B2 test

Figure 67 Threshold, air, TL, R 0.5

Source: Pascoal (2014) and the author

B3 test

Figure 68 Threshold, air, LT, R 0.1

Source: Pascoal (2014) and the author

B4 test

Figure 69 Threshold, air, LT, R 0.5

Source: Pascoal (2014) and the author

4.2.2 Threshold, salt fog 3.5% NaCl, tests (D tests)

D1 test

Figure 70 Threshold, salt fog 3.5% NaCl, TL, R 0.1

Source: elaborated by the author

D2 test

Figure 71 Threshold, salt fog 3.5% NaCl, TL, R 0.5

Source: elaborated by the author

D3 test

Figure 72 Threshold, salt fog 3.5% NaCl, LT, R 0.1

Source: elaborated by the author

D4 test

Figure 73 Threshold, salt fog 3.5% NaCl, LT, R 0.5

Source: elaborated by the author

4.2.3 Treshold region, ΔK_{th} results

Table 8 ΔK threshold results

Test	Author	ΔK_{Th} (MPa*m ^{0.5})
B1	Pascoal	3.5
B2	Barbosa	1.84
B2	Pascoal	1.91
B3	Barbosa	Apparent 2.8
B3	Pascoal	2.66
B4	Barbosa	2.11
B4	Pascoal	2.01
D1	Barbosa	3.54
D2	Barbosa	2.22
D3	Barbosa	3.65
D4	Barbosa	3.26

Source: elaborated by the author

5 DISCUSSION

In the present chapter, obtained results are present in a manner to let understand the influence of each variable and highlight differences and similarities with the literature review.

In order to compare results, fixed scales are used, in the Paris tests Delta K varies from 9 to 13 MPa*m^{0.5}, and da/dN from 6E-5 to 1E-2 mm/Cycle, and in the Threshold cases Delta K varies from 1.5 to 7 MPa*m^{0.5}, and da/dN from 1E-7 to 2E-4 mm/Cycle.

An important evidence, points C1 test as nonstandard result or invalid, since all others tests presented similar sensitivity under the crack growth rate modifiers, but C1.

Due to the result's quantity whose designation is shown in Figure 31 in the methodology, the results comparisons also have a designation as explained in Table 9 Results comparisons designation.

Table 9 Results comparisons designation

Study variable	Designation	Tests compared
Rolling direction	H1	A1, A3
	H2	A2, A4
	H3	B1, B3
	H4	B2, B4
	H5	C1, C3
	H6	C2, C4
	H7	D1, D3
	H8	D2, D4
	H9	E1, E2
	H10	F1, F2
Stress ratio	J1	A1, A2
	J2	A3, A4
	J3	B1, B2
	J4	B3, B4
	J5	C1, C2
	J6	C3, C4
	J7	D1, D2
	J8	D3, D4
Environment	K1	A1, C1

Wave form	K2	A2, C2
	K3	A3, C3
	K4	A4, C4
	K5	B1, D1
	K6	B2, D2
	K7	B3, D3
	K8	B4, D4
	K9	E1, F1
	K10	E2, F2
	M1	A1, E1
Measure technique	M2	A3, E2
	M3	C1, F1
	M4	C3, F2
	N1	E1, E1
	N2	E2, E2
	N3	F1, F1

Source: elaborated by the author

5.1 CRACK GROWTH STRESS RATIO INFLUENCE

5.1.1 Experimental evidence

As shown from Figure 74 to Figure 81, the stress ratio influence is in all cases completely according with literature review, it means the crack growth rate rise while the R do, in both air and corrosive environment for Paris and threshold regions. In the Paris case, the values of crack growth rate, increase as function of stress ratio between 30 and 40 percent in J1, J2 and J6 comparisons, but the J5 comparison (C1 vs C2) presents a change of 80 percent.

Figure 74 J1 comparison A1, A2 tests

Source: elaborated by the author

Figure 75 J2 comparison A3, A4 tests

Source: elaborated by the author

Figure 76 J3 comparison B1 ,B2 tests

Source: elaborated by the author

Figure 77 J4 comparison B3, B4 tests

Source: elaborated by the author

Figure 78 J5 comparison C1, C2 tests

Source: elaborated by the author

Figure 79 J6 comparison C3, C4 tests

Source: elaborated by the author

Figure 80 J7 comparison D1, D2 tests

Source: elaborated by the author

Figure 81 J8 comparison D3, D4 tests

Source: elaborated by the author

5.1.2 Analytical assessment

Due to the evident strong influence of stress ratio on crack propagation and the excellent agreement of the obtained results with the literature, it is to analyze the R influence on crack growth rate under three of most recognized theories Walker, Pearson and Forman.

5.1.2.1 Walker equation

Table 7 shows the two fitted lines parameters obtained for A1 and A2 tests. Using these C and m results on the Paris (19) and Walker (21) equations, the Co for Paris with zero R and γ or Walker coefficient for AA7050-T7451 on air and TL rolling direction were obtained. The procedure was repeated for A3 and A4 tests in order to obtain the same results for LT rolling direction. Table 10 Paris Zero R and Walker line constants contains the walker constants results.

Table 10 Paris Zero R and Walker line constants of AA7050-T7451 on air

Direction	TL	LT
Co [(mm/ciclo)/(MPa.m ^{0.5}) ^m]	3.6528E-08	7.41855E-08
γ	0.718731278	0.740592031

Source: elaborated by the author

In order to validate the results Figure 82 and Figure 83, shown the original experimental fitted lines and projected lines using the results founds on Table 10 for Walker coefficients.

Figure 82 Projected vs experimental lines of A1 and A2 tests, using Walker coefficients

Source: elaborated by the author

Figure 83 Projected vs experimental lines of A3 and A4 tests, using Walker coefficients

Source: elaborated by the author

5.1.2.2 Pearson equation

Pearson equation is used to project crack propagation behavior but in addition to be function of ΔK and R , also use K_{Ic} available on Table 2.

First using the Pearson equation in both forms equations (24) and (25) were plotted the Q term vs ΔK for both A1 and A2 data tests as shown in Figure 84.

Figure 84 Q vs ΔK for A1 and A2 tests

Source: elaborated by the author

Due to both tests A1 and A2 (of the four specimens evaluated) have same direction, was possible fit a line in order to calculate C_2 and m_2 of equation (25) as shown in Figure 85.

Figure 85 Q vs ΔK fit line for A1 and A2 tests

Source: elaborated by the author

The fit data results are slope (m_2) and intercept but (C_2) of equation (25) value corresponds to ten to the intercept power as shown in Table 11. Finally using the obtained m_2 , C_2 and K_{Ic} values into equation (24) were projected crack growth rates for different R values, as shown in Figure 86.

Table 11 Pearson fit line constants of AA7050-T7451 on air

Direction	TL	LT
m_2	3.01214	2.82367
intercept	-6.29921	-6.06407
C_2 [MN*m]	5.02E-07	8.63E-07

Source: elaborated by the author

Figure 86 da/dN - ΔK for different R values using Pearson equation on TL direction

Source: elaborated by the author

The projected Pearson line for R equal to 0.1, progress together with experimental fit until ΔK of 20 and then turns a curve, but in the others R values the straight lines turns curves before, due to this theory covers region II and III of sigmoidal curve and the transition from one region

to other is accelerated because a high R value. For this reason is clear that on this case Pearson shifts adequately the projected lines for different R values but tends to curve to the region III behavior before expected. The process was repeated for LT direction using A3 and A4 tests and the equivalent graphs are Figure 87, Figure 88 and Figure 89, and the fitted results are on Table 11.

Figure 87 Pearson Q vs ΔK for A3 and A4 tests

Source: elaborated by the author

Figure 88 Pearson Q vs ΔK fit line for A3 and A4 tests

Source: elaborated by the author

Figure 89 da/dN - ΔK for different R values using Pearson equation on LT direction

Source: elaborated by the author

5.1.2.3 Forman equation

Similarly, of Pearson equation, Forman equation is used to project crack propagation behavior but using K_{Ic} instead of K_{Ic} . The $46 \text{ MPa}\cdot\text{m}^{0.5}$ of K_{Ic} was reported by Pascoal (2014).

First using the Forman equation in both forms, equations (22) and (23) were plotted the Q term vs ΔK for both A1 and A2 data tests as shown in Figure 90. Due to both tests A1 and A2 have same direction, was possible fit a line in order to calculate C_2 and m_2 of equation (23) as shown in Figure 91.

Figure 90 Forman Q vs ΔK for A1 and A2 tests

Source: elaborated by the author

Figure 91 Forman Q vs ΔK fit line for A1 and A2 tests

Source: elaborated by the author

The fit data results are slope (m_2) and intercept but (C_2) of equation (23) value corresponds to ten to the intercept power as shown in Table 12. Finally using the obtained m_2 , C_2 and K_{Ic}

values into equation (22) were projected crack growth rates for different R values, as shown in Figure 92.

Table 12 Forman fit line constants of AA7050-T7451 on air

Direction	TL
m2	3.65341
intercept	-6.3
C2 [MN*m]	5.01E-07

Source: elaborated by the author

Figure 92 da/dN - ΔK for different R values using Forman equation on TL direction

Source: elaborated by the author

On this case Forman equation, neither shifts adequately crack growth line not preserve the straight-line direction on Paris region.

5.1.3 Walker coefficient result application

Although Walker coefficient has already been confirmed to predict R influence, as shown in Figure 82, also can be confirmed using S-N diagram for AA7050-T7451 and projecting for different R values. The S-N diagram was obtained of two sources: MIL-HDBK-5J (2003) Figure 93 and predicting the diagram using tensile test properties.

Figure 93 Longitudinal S-N Curve of AA7050-T7451

Source: MIL-HDBK-5J adapted by the author

In order to obtain the predicted Longitudinal S-N curve as described by literature review, two points were joined $P1(N1, S_m)$ and $P2(N2, S_f)$ where $N1$ and $N2$ corresponds to 1000 and 5×10^8 cycles. S_m corresponds to 400.2 MPa, and was calculated using ultimate tensile stress available on Table 2 on equation (9).

S_f is equal to 54.555 MPa and was calculated using equation (10), each term selected according to Norton (2011) as shown in Table 13.

Table 13 Coefficients parameters for Sf calculus

Coefficient	Value	Reason
C_{load}	1	Axial load
C_{size}	1	Axial load
$C_{surface}$	0.854	Equation (40)
$C_{temperature}$	1	Environmental Temp
$C_{reliability}$	0.702	Material 99.99% reliability
S_f	130MPa	$S_{ut} > 330 \text{ MPa}$

Source: elaborated by the author

$$C_{surface} = A * S_{ut}^b \quad (40)$$

In the present research the material is cold rolled and thus A is 4.51 and b -0.265 in the equation (40).

The a and b constants of S-N line curve of equation (5) was calculated using N1, N2, Sm and Sf into equation (8), (7) and (6). Because on this case stress ratio is minus one, Smas and Sar are equals and the relationship between Smax and N is the shown in equation (41) and represented on Figure 94.

$$S_{max} = 1142.512N^{-0.15186} \quad (41)$$

Figure 94 Predicted Smax-N for AA7050-T7451

Source: elaborated by the author

The predicted S_{max} - N line was projected to other R values in order to compare with the MIL-HDBK-5J (2003) curve for validate ones more the found TL walker coefficient. The projection was made using the Walker equation (12) into equation (41).

Figure 95 Comparison between experimental S-N curves and analytically predicted lines for longitudinal AA7050-T7451

Source: elaborated by the author

Remembering that experimental S-N curves are bands no single lines, it is notorious that in the case of R minus one and zero predicted lines and experimental curves intersects twice on Figure 95 and when R is 0.5 once, it means that both predicted method of S-N curves and the found Walker coefficient are reliable for AA7050-T7451.

5.2 CRACK GROWTH ENVIRONMENT INFLUENCE

The corrosive environment increased the crack growth rate as expected according to literature review.

Analyzing the Paris region in sine wave case (Figure 96 to Figure 99), and comparing with Figure 16, is possible to confirm that the aggressive environment shifts up the crack growth rate, and decrease the slope of the line, due to the final high propagation rate decrease the influence of environment.

In general in sine wave case (Figure 96 to Figure 99) and Dwell wave (Figure 104 and Figure 105) is possible to conclude that the crack growth rate increase due to corrosive environment mainly as function of stress ratio and secondarily as function of rolling direction.

Rolling direction is an intrinsic parameter that helps the intergranular corrosion in reason of grains orientation making grains boundaries more susceptible to hydrogen movements and the stress concentration on crack tip tend to segregates the corrosion resistance alloy elements to there (the grain boundaries). Corrosion on grain boundaries creates a path for hydrogen work (called intergranular corrosion) using the SCC mechanism called active path dissolution that in turn activates the other two: hydrogen embrittlement and film induced cleavage.

Hydrogen enters into the material taking advantage of concentration gradient between salt fog 3.5NaCl and the specimen by diffusion until creates hydrogen molecules capable of generate enough pressure to open cracks helped by a worst mechanical condition as happened when stress ratio R was increased from 0.1 to 0.5.

The corroded surface layer called passive layer, protects against corrosion the material, but when new cracks open, a new corrosion process between salt fog 3.5NaCl environment (electrolyte) and AA7050-T7451 starts turning the crack tip an anode and the passive or corroded layer a cathode as shown in Figure 29, creating an electrical current inside the material. This process is called film-induced cleavage.

Analyzing the threshold region from Figure 100 to Figure 103 is observed three stages from right to the left. The first stage shows as if environment has not influence but the reality is just that corrosion mechanisms need a “while” to begin act, in general from ΔK 8 to 5 MPa*m^{0.5} under 15Hz (unlike 1Hz of Paris tests). The second stage (like on Paris region) shows a bigger crack growth rate in corrosive environment and the third one shows that corrosive environment affects the value of ΔK_{th} . The increase of ΔK_{th} in the saline environment was attribute to be due

to crack closure effect from oxides formation on the crack path according to Gangloff (2005) and also reported by Maciel (2013) and Chemin (2012).

Once again the comparison that involve C1 test, in this case K1 (A1 vs C1) shows a nonstandard result. While in K1 comparison the crack growth rate increases because of the environment just 25 percent, in K2, K3, K4, K9 and K10 do about 70 percent.

Figure 96 K1 comparison A1, C1 tests

Source: elaborated by the author

Figure 97 K2 comparison A2, C2 tests

Source: elaborated by the author

Figure 98 K3 comparison A3, C3 tests

Source: elaborated by the author

Figure 99 K4 comparison A4, C4 tests

Source: elaborated by the author

Figure 100 K5 comparison B1, D1 tests

Source: elaborated by the author

Figure 101 K6 comparison B2, D2 tests

Source: elaborated by the author

Figure 102 K7 comparison B3, D3 tests

Source: elaborated by the author

Figure 103 K8 comparison B4, D4 tests

Source: elaborated by the author

Figure 104 K9 comparison E1, F1 tests

Source: elaborated by the author

Figure 105 K10 comparison E2, F2 tests

Source: elaborated by the author

5.3 CRACK GROWTH WAVE FORM INFLUENCE

All Dwell tests were made using the same R 0.1 value, so this variable do not affects any result here but rolling direction and environment do.

Bania (1978) reported lower fatigue crack growth rate for some titanium alloys due to Dwell wave on air. Observing Figure 23 the crack growth line shifting down and in Figure 21 c) the rate decrease because of the Dwell carrying as occurs on M1 (Figure 106), M2 (Figure 107) and M4 (Figure 109). It suggest that Dwell wave affects the crack growth rate of AA7050-T7451 mainly decreasing the line slope for both rolling directions TL and LT.

Probably the lower fatigue crack growth rate occurs by a crack tip blunting mechanism as Bania (1978) suggest.

Figure 106 M1 comparison A1, E1 tests

Source: elaborated by the author

Figure 107 M2 comparison A3, E2 tests

Source: elaborated by the author

Once again a comparisons that involve C1 test shows a nonstandard result, in this case M3 (C1 vs F1) comparison, Figure 108. The C1 comparison shows higher rate on Dwell case an opposite result than expected since literature point of view and since the others obtained comparisons: M1, M2 and M4 where the average rate change between 30 and 47 percent but in M3 comparison the Dwell influence presented a change of minus 40 percent.

Figure 108 M3 comparison C1, F1 tests

Source: elaborated by the author

Figure 109 M4 comparison C3, F2 tests

Source: elaborated by the author

5.4 CRACK GROWTH ROLLING DIRECTION INFLUENCE

In general, for air (Figure 110 to Figure 114) and corrosive (Figure 116 to Figure 118) tests according to literature review shown less crack growth rate for LT rolling direction in both Paris and threshold regions. It happens due to the LT grains orientation acts as a barrier for crack growth propagation.

The increasing of crack growth rate due to TL rolling direction also cause less ΔK_{th} values in both air and salt fog (Figure 113, Figure 114, Figure 117 and Figure 118).

As evidenced on environmental influence section, the rolling direction is not as influential as stress ratio and that is why in some cases its influence is slight, for example on H1 comparison Figure 110 and H10 comparison Figure 119.

Once again, a comparison that involve C1 test shows a nonstandard result. H5 (C1 vs C3) comparison in Figure 115, is a particular case that shows an opposite behavior where on TL case exhibits higher crack growth rate.

The rolling direction generates an average rate change on air of about 15 percent but is not as homogeneous on fog.

Figure 110 H1 comparison A1, A3 tests

Source: elaborated by the author

Figure 111 H2 comparison A2, A4 tests

Source: elaborated by the author

Figure 112 H9 comparison E1, E2 tests

Source: elaborated by the author

Figure 113 H3 comparison B1, B3 tests

Source: elaborated by the author

Figure 114 H4 comparison B2, B4 tests

Source: elaborated by the author

Figure 115 H5 comparison C1, C3 tests

Source: elaborated by the author

Figure 116 H6 comparison C2, C4 tests

Source: elaborated by the author

Figure 117 H7 comparison D1, D3 tests

Source: elaborated by the author

Figure 118 H8 comparison D2, D4 tests

Source: elaborated by the author

Figure 119 H10 comparison F1, F2 tests

Source: elaborated by the author

5.5 COMPARING CRACK LENGTH MEASURE TECHNIQUES

As related on the methodology chapter, Dwell tests must to be performed using a software called MPT in which da/dN - ΔK results must be calculated manually. The purpose of have been used DCPD as alternative technique in addition of COD was to automate the calculation procedure to generate the da/dN - ΔK results due to the COD calculations are so extend and complicated. In other words DCPD it's a quick verification technique and because of its accuracy and once is well implemented can be used exclusively.

The results of E1 test are shown in Figure 120 manual calculation and Figure 121 fitted lines. Similarly, for E2 and F1 test from Figure 122 to Figure 125.

The crack length measure average error for both measure techniques is four percent, calculated when calibration curve was developed relative to the reference visual technique on E1 test.

E2 and F1 test was performed using the obtained calibration curve without visual reference.

The da/dN curves have errors beyond the 4 percent of the obtained calibration curves on methodology section, due to the derivative method acts as error amplifier when the numerical differentiation is done, as shown from Figure 120 to Figure 125.

Figure 120 E1 test - comparison COD and DCPD techniques

Source: elaborated by the author

Figure 121 E1 test fitted lines - comparison COD and DCPD techniques

Source: elaborated by the author

Figure 122 E2 test - comparison COD and DCPD techniques

Figure 124 F1 test - comparison COD and DCPD techniques

Source: elaborated by the author

Figure 125 F1 test fitted lines - comparison COD and DCPD techniques

Source: elaborated by the author

6 CONCLUSIONS

The scope of the present work was to answer how environment, stress ratio, rolling direction and waveform affects the fatigue crack growth propagation on AA7050-T7451.

6.1 CONCLUSIONS ABOUT STRESS RATIO

The stress ratio changes the crack growth rate in AA7050-T7451, and its influence is expected between 30 and 44 percent of the average value, in both air and corrosive environment, its influence has no exception under any studied crack growth rate modifier condition on the studied material.

Higher stress ratios reflect on higher crack growth rates on propagation and less ΔK_{th} .

In case of mathematical modeling the stress ratio influence on Paris region for AA7050-T7451, the Walker equation is quite advisable due to represents accurately the experimental results unlike the Pearson and Forman equations.

Using the Walker coefficients published on present research is possible to project the crack growth rate on Paris region and make life prediction on da/dN and S_{max} - N diagrams for different stress ratio values on air for both TL and LT rolling direction. No similar publication on TL direction are available.

6.2 CONCLUSIONS ABOUT ENVIRONMENT

The environment is the most influence variable studied in the present research that affects the crack growth rate in AA7050-T7451, generating an average change of rate between 70 and 80 percent.

Although environment-assisted fatigue due to salt fog 3.5%NaCl results in faster crack growth rate, also affects increasing the value of ΔK_{th} due to oxides formation on the crack path generating a crack closure effect.

One Hertz is enough to the hydrogen in the corrosive environment corrode the material's surface and near crack tip where high stress and plastic deformation, generate slip bands that exposed new un-corroded material to hydrogen corrosion mechanisms generating bigger rates on FCG.

Crack growth rate in AA7050-T7451 increase due to corrosive environment mainly as function of stress ratio and secondarily as function of rolling direction.

6.3 CONCLUSIONS ABOUT WAVE FORM

Dwell wave on AA7050-T7451 makes decrease the crack growth rate by decreasing the slope of the line on Paris region instead of shifting down the line as occurs on titanium alloys.

Similarly to stress ratio, the wave form can generates a crack growth rate average change between 30 and 47 percent in AA7050-T7451.

6.4 CONCLUSIONS ABOUT ROLLING DIRECTION

TL rolling direction increases the FCG rate respect to LT, in both threshold and Paris region in AA7050-T7451.

On Paris region, the rolling direction has a slight influence of about 15 percent in average crack growth rate on air for the studied alloy.

6.5 CONCLUSION ABOUT INSTRUMENTATION

The DCPD can be used not only as a fast verification of COD method for crack measure on fatigue tests, but as efficient crack length measure method for AA7050-T7451.

6.6 SUGGESTIONS FOR FURTHER RESEARCH

In general, C1 test presents nonstandard results, comparing with literature and the others tests, so it is suggested to repeat it before be used to conclude something.

According to the experience on the present research, when DCPD is used, is better to calculate the crack length by secant method and is not recommended the polynomial method because the voltage-time relationship use to be a high-grade polynomial whose include undesirable curvatures changes that affects the accuracy of FCG calculus. It occurs due to da/dN is a derivative of crack length, calculated from voltage-time relationship and the derivatives amplified any function error.

At the beginning of DCPD tests, happened suddenly change on acquired voltage data. After investigate, the conclusion of the perturbation's origin was magnetic noise from electric vent and induction oven both used for thermo mechanical fatigue test. It is suggested, in case of use DCPD on fatigue test, verify previously the induction noise in the area.

6.7 LIMITATIONS OF THE RESEARCH

The present work found an interesting Dwell carrying effect on AA7050-T7451 FCG, and in order to generate more applicable knowledge further researches must to carry out similar Dwell tests, focusing on the possible crack tip blunt phenomenon.

In order to verify the intergranular corrosion preference and evaluate it quantitatively is important to carry out a research to measure electric conductivity change on the corroded tests specimens as is done when lights strikes an airplane on aeronautical structures workshops.

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8 APPENDICES

8.1 APPENDICE 1: Paris regressions confidence and prediction bands

Figure 126 Test A1

Source: elaborated by the author

Figure 127 Test A2

Source: elaborated by the author

Figure 128 Test A3

Source: elaborated by the author

Figure 129 Test A4

Source: elaborated by the author

Figure 130 Test C1

Source: elaborated by the author

Figure 131 Test C2

Source: elaborated by the author

Figure 132 Test C3

Source: elaborated by the author

Figure 133 Test C4

Source: elaborated by the author

Figure 134 Test E1 COD

Source: elaborated by the author

Figure 135 Test E1 DCPD

Source: elaborated by the author

Figure 136 Test E2 COD

Source: elaborated by the author

Figure 137 Test E2 DCPD

Source: elaborated by the author

Figure 138 Test F1 COD

Source: elaborated by the author

Figure 139 Test F1 DCPD

Source: elaborated by the author

Figure 140 Test F2

Source: elaborated by the author

8.2 APPENDICE 2: a-t CURVES

Figure 141 Crack length during E2 Test

Source: elaborated by the author

Figure 142 Crack length during F1 Test

Source: elaborated by the author