JOURNAL OF TECHNIQUES

Journal homepage: http://journal.mtu.edu.iq

RESEARCH ARTICLE

A new Track of Fatigue crack growth in Aluminum Alloy (2219) under Cyclic Stresses

Abdullah Dhayea Assi

Middle Technical University\Institute of Technology\ Baghdad

Corresponding author E-mail: drabdullah_dhayea@mtu.edu.iq

Article Info.

Article history:

Received
05 August 2020

Accepted
12 November 2020

Publishing
31 December 2020

Abstract

A study of new Track of Fatigue crack growth in aluminum alloy (2219) under cyclic stresses has been made. It was found out that this crack grow and propagate in three phases, the first phase though the grain size (micro-structure short cracks(MSC)), second phase cross the boundary of the grain size to about 1mm in length (physically short cracks (PSC)) and the third phase up to the final fracture (Length cracks(LC)). In addition, two programs were designed on MATLAB to perform the compute calculations to collect the results. The first program to calculate the practical constants and the second to make the calculations required to complete the work schedules. The stress and the parameters effecting the growth of these cracks in each phase were studied. A model consisting of three formulas was established from the experimental results. Each formula describes the behavior of the cracks in the particular phase. The comparison showed that the proposed model is safer than the experimental results for the designed parts of aircraft.

Keywords: Fatigue Crack Growth (FCG), AA (2219), Cyclic Stresses, MATLAB.

1. Introduction

In practice, many parts of machines and machines are exposed to thousands or may reach millions of Repeat Stress cycles. In general, the materials used in making these parts may fail when exposed to a certain number of repeated stress cycles even if the value of the maximum stress is much lower from the stress that causes it to break [1] (Vikram and Kumar, 2013).

The emergence of the industrial revolution at the beginning of the year 1800 AD led to the emergence of rotating and repeating machines and equipment so that the moving parts that fail due to the repeated loads became very familiar. This phenomenon was observed when a railway project was designed and implemented by relying on static relations represented by Hooke's law and tensile tests where values were the stress tests for the minerals used in the project at that time are much higher than the actual stress values, i.e. by 1.5 as a safety factor. But after completing the design and putting these rails in service, they appeared after days of cracks in them and started to grow in some parts where the failure occurred. Therefore, designers resorted to studying this phenomenon in a large and deep way. Hence the phenomenon of fatigue, which was named by the French (Pancelet), in 1839 AD [2]. Failure from repeated stress cycles is called fatigue failure [3].

Literature review concerned with studying this phenomenon on the basis that it represents the growth of cracks and their progression until failure occurs without taking into account the behavior of these cracks. Hence Paris et. al, was among the first researchers in this field (Paris) [4] where he described the relationship of crack growth and its speed with a factor called stress intensity factor (K) Since this parameter describes the distribution of stresses at the top of the crack, so the stress coefficient in the case of a rapid fracture of the engineering part is called the fracture toughness. As for the critical stress intensity factor (Kc), it depends on the type of metal, the length of the crack, the engineering stress, temperature and thickness of the engineering part. And he concluded that these cracks increase their speed as they progress in service, and that the relationship he created is represented by the following equation, which is called (Paris Equation):

Symbols			
AA2219	Aluminum Alloys 2219	S-N	Stress – No. of Cycles
σ_f	Fatigue stress at failure (MPa)	ΔK	The range stress intensity factor ($MPa.m^{.5}$)
SIF	Strength improvement factor (%)	σe ,σ_{EL}	Fatigue Endurance limit stress (MPa)
N_f	No. of cycles to failure (cycle)	Δσ	The stress range (MPa)
Ra	Average roughness (μm)	ASTM	American Society for Testing and Materials
R	Stress ratio	SIER	State Company for Inspection and Engineering Rehabilitation
BHN	Brinell hardness number (*g/mm²*)		

$$\frac{da}{dN} = C(\Delta K)^m \qquad \text{..............(1)}$$

Where:

da/dN = the crack speed (or crack growth rate).

ΔK = The range stress intensity factor

C,m = Constants that depend on the material used and the value of (m) ranges between (2-4) for most materials, including aluminum alloys [5].

In addition to the importance of studying different stresses on the life of fatigue, several studies were conducted that addressed the effect of different stresses, including studies carried out by researchers as follows:

Salmi & Mohamed (2019) [6], this study examines the influence of the load ratio and temperature on the propagation rate of long cracks on the outer surface. The propagation of a fatigue crack in ABAQUS was therefore automatically simulated using an identified Paris law of 2024 T3 aluminum alloy. Therefore, the study of these components' fatigue resistance in such conditions becomes essential to predict the service life and safety of the components.

Mudasir et. al. (2019) [7], in this research work, a widely used Aluminum alloy AA2219-T87 was TIG welded using AA2319 as a filler material. The relationship between stress intensity factor (ΔK) and crack ratio (a/W) for different values of the crack length in base metal and the welded zone is presented. The results obtained provide a base for the development of Structural Health Monitoring systems for the propagation of crack growth in such components.

Hongjun et.at. (2018) [8], this paper provides an overview of the fatigue mechanism, influencing factors, crack growth rate, and fatigue life assessment. It is found that the fatigue performance of friction stir welded joints can be affected by welding process parameters, test environment, stress ratio, residual stress, and weld defect. The optimized process parameters can produce high quality weld and increase the weld fatigue life.

Haftirman et. at. (2018) [9], the effect of thickness on FCG has been investigated for aluminum alloys such as a high-strength aluminum alloy (A7075-T6), a medium strength alloy (A6063-T6), and A2024-T351. The fatigue tests on all those materials with different thicknesses. These tests were run under constant amplitude load for each different thickness and materials. It is concluded that FCG decreases significantly with increasing thickness, and the crack initiates very fast on surface material.

Abdullah Dhayea & Sliman (2011) [10], This research is concerned with the study of the effect of tempering on the fatigue strength of medium carbon steel (CK 45), by using different heat treatments including quenching in water. The fatigue tests have been done under constant amplitude stresses with a stress ratio (R=-1). Two models have been proposed to assess fatigue lives of quenched and tempered medium carbon steel at different tempering temperatures. The first model was derived from the FCG rate equation (da/dN) while the second model was extracted from the stress intensity factor equation (ΔK).

The aim of this research was to focus on studying the growth of fatigue cracks in aluminum alloy 2219 based on the three phases (short, physical and long). Because this alloy has wide practical applications, especially in the manufacture of fuel tanks for aircraft, as well as in the manufacture of pipeline networks for fuel inside the aircraft, pharmaceutical applications and food containers, due to the advantages of this alloy of light weight and good resistance to chemical corrosion. In addition to another important target, which is the design of modern engineering programs by MATLAB for the purpose of completing calculations with high accuracy and great speed that exceeds traditional methods of completing these calculations.

2. Experimental work

2.1 The Specimens Preparing

The metal used was obtained from the local market in the form of round bars measuring (2 * 100) cm. These bars were cut into six pieces to obtain six specimens that were run on a CNC lathe in order to obtain high accuracy. Figure 1 represents the dimensions of the specimen used for fatigue testing as per American Standard (ASTM).

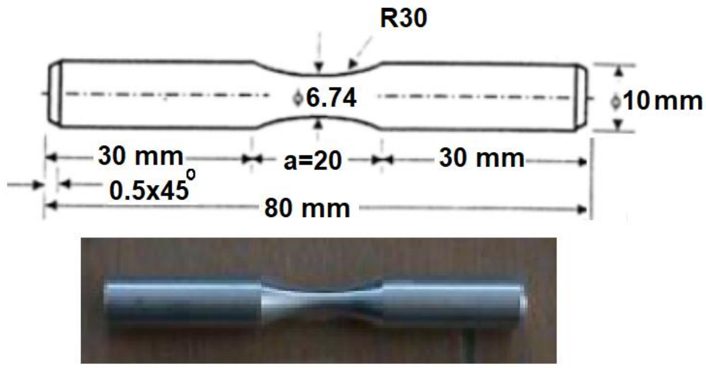

Fig. 1: Fatigue Specimens (ASTM)

2.2 Microstructure

The microstructure of the alloys is illustrated by the following stages:

1- Smoothing was performed on fatigue test specimens after the operation process using Emery Papers or the so-called silicon carbide polishing paper with different grades of smoothness (ASM grades 220, 320, 400, 600, 800, 1000,1200,2000).

2- The polishing process was then carried out using an alumina solution with its own cloth to polish the surface of the test specimens with two degrees, the first was with a degree of smoothness (µ5) and the second with a degree of smoothness (µ3).

3- Using diamond paste degree (µ1) then moderate degree (0.25µ).

4- Use a demonstration solution consisting of hydrofluoric (HF), hydrochloric acid (HCI), nitric acid (HNO3), and distilled water.

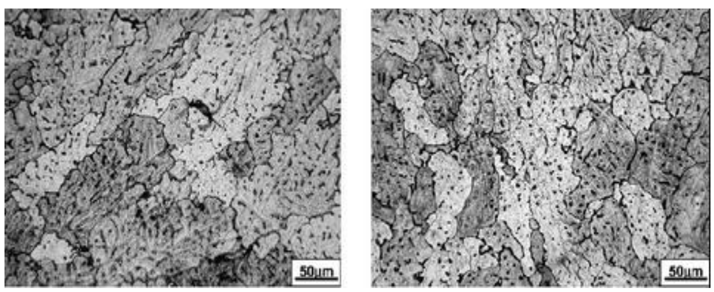

Fig. 2: The microstructure of AA 2219

2.3 Surface Roughness

The purpose of smoothing the specimens with a softening paper of graded smoothness in order to reduce the surface roughness and thus reduce the stresses on the surface. Surface roughness was measured for six specimens. Five readings were taken and rate was extracted as shown in Table (1).

Table 1 Roughness rate for fatigue test specimens

Specimen No.	Ra(µm)
1	0.24
2	0.22
3	0.23
4	0.25
5	0.21
mean	0.23

2.4 Average Grain Size Diameter Calculation

The linear intercept method was used in measuring the grain size of the specimens, where the grain size was measured by calculating the number of granules located within a known length line on the microscopic structure reflected on a screen in the microscope device, then the length of the line is taken in millimeters and divided by the number of granules located within the line to obtain The average diameter of the granule, and five or more regions are taken from the microscopic structure, then the five readings are taken to obtain sufficient accuracy in measuring the diameter of the granule, knowing that the granules located at the ends of the straight line (first and last) are calculated as half of a granule, and it has been found that the diameter of the granule of the specimens is as follows

The average grain diameter after obtaining the granular size of the specimen is calculated from the equation(2) [11]:

$$D_{average} = \frac{L}{n * MG} \quad ....(2)$$

Where: L = Represents the length of the line used (any length can be used).
n = The number of intersections for the above line with the grain boundary.
MG = Magnification used to show the microstructure of the material.
The diameter of the grains was calculated at the end of (1000) grains and the diameter rate was (200) microns.

2.5 Chemical Composition

Table (2) shows the chemical analysis of the aluminum alloy 2219 used in the research. It was conducted at the State Company for Inspection and Engineering Rehabilitation(SIER).

Table 2 The chemical composition of AA2219

AA2219 %	Si	Fe	Cu	Mn	Mg	Ti	Al
Standard [12]	0.02	0.3	5.8-6.8	0.2-0.4	0.02	0.02-0.1	Balance
Experimental (SIER)	0.18	0.28	6.1	0.23	0.02	0.04	Balance

2.6 Mechanical properties of AA2219

Six specimens were examined on INSTRO (225) tensile tester by capacity 150 KN and the readout rate was taken. Also the hardness on a Brinell Hardness Machine was checked if I took six readings and extracted the average readings for the alloy.

Table 3 The mechanical properties of AA2219

Mechanical Properties	AA2219
Ultimate tensile strength (MPa)	350
Yield stress (MPa)	240
Elongation%	13
Brinell hardness number (BHN)	75

2.7 The Fatigue Testing Machine

Avery Type 7305 rotary fatigue test was used at a speed of 1420 rpm in the center of the measurement and quality control device in order to test the specimens, knowing that 3 specimens were tested for each level of stress and extraction of the rate in order to get rid of the scattering that occurs in the fatigue test, and this is the common context It is based on fatigue tests.

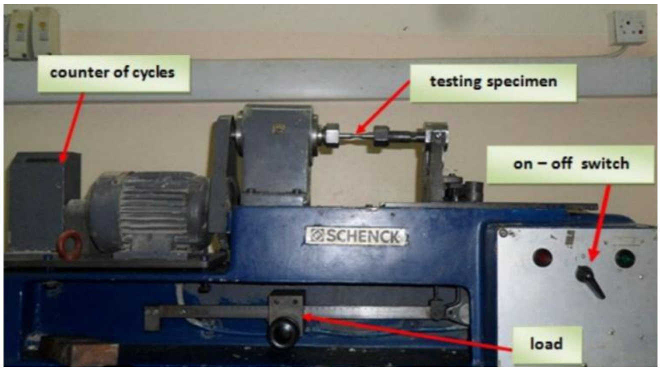

Fig. 3: The Fatigue Testing Machine (Avery Type 7305**)**

Fig. 4: Fatigue Specimens before & after Fatigue testing

2.8 Track surface cracks

The replication technique was used to extract the lengths of the cracks where the crack length was calculated on the basis of the average length and from the following equation [13]:

$$a_{av} = \frac{a_{i+1} - a_i}{2} \qquad .....(2)$$

Then calculate the crack speed from the equation [13]

$$\frac{da}{dN} = \frac{\Delta a}{\Delta N} = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \qquad .....(3)$$

3. Results and experimental calculations

Six specimens were exposed to different stresses, three specimens were examined, and one crack was monitored in each specimen. The results were as shown in Table (4).

Table 4 Specimens and Stresses Loaded on it

Specimen No.	Stress σ (MPa)	stress range Δσ (MPa)	No. of failure cycles N_f (cycle)
1	200	400	6500
3	160	320	150000
4	140	280	370000
5	120	240	600000
6	100	200	No fail

3.1 The Fatigue Curve *(S-N Curve) or Wohler Curve*

The designer should know when to change the mechanical part subject to frequent and variable periodic stresses (dynamic loads), i.e. know the age of the part in advance in order to avoid sudden failure or sudden breakage, so the researchers tended to build a relationship between loads or repeated stresses (number of cycles) Failure of a piece or part, and this relationship is called the SN curve or Wohler curve and takes the following mathematical form [14]**.**

$$\sigma_f = A N_f^{\alpha} \qquad ....(4)$$

The formula for the life curve has been reached through the results in Table (4) by designing Program No.1 with MATLAB as shown in Figure (A1) in appendix -A to obtain the constants (A & α), as it gives the equation for the curve directly as in the output of the program which appears in Figure (A2) in appendix -A and by applying the data below:
x = N_f = [6500 25000 150000 370000 600000];
y = σ_f = [200 180 160 140 120];

So we get the values of the constants (A = 504.7558 & α = -0.10228) so the formula is:

$$\sigma_f = 504.7558 * N_f^{-0.10228} \qquad ....(5)$$

It is clear from the above equation that this curve has no relationship to cracks and their disposal, as a certain limit can be extracted from the above equation in which the fracture cannot occur and this limit is called the Fatigue limit. For the purpose of extracting this limit, it was agreed that the number of turns is equal to 10^7 when This limit, especially in non-ferrous metals and alloys, such as aluminum and its alloys.

Therefore, the age of the specimen under the fatigue limit for ferrous metals is endless, while for non-ferrous metals up to 10^8 or more, as is evident in Figure (5) [15], therefore it is preferable to study the behavior of cracks and their growth, especially for ferrous metals such as aluminum because there is no specific fat limit under it. Age is infinite, hence attention should be paid to the behavior of cracks and know when to stop and what is the factor that causes them to grow after they stop. This research was focused on the behavior of cracks and how to address their growth and what are the means that make them stalled or what is known as blind cracks.

From the above equation we conclude that the fatigue limit for the alloy used is 97MPa.

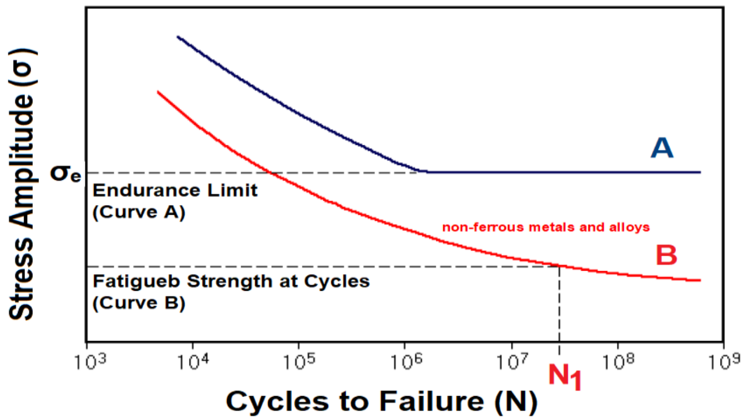

Fig. 5: Typical Wohler Curve [15]

3.2 Stress Intensity Factor

The stress intensity factor (K) was calculated by applying the following equation [6].

$$K = \sigma\sqrt{\pi c} \qquad \text{..............(6)}$$

Where: σ = Stress (MPa)
c = Half crack length (m)

It is possible to estimate the extent of the Critical Stress Intensity Factor under which the cracks cannot grow and are considered idle cracks, by replacing the Endurance limit (σe) or fatigue limit instead of (σ) and the half-diameter of the grain instead of half the length of the crack (c) in equation (6) it becomes as follows [6]:

$$K_c = \sigma_e\sqrt{\pi\frac{D}{2}} = 96\sqrt{\pi\frac{200*10^{-6}}{2}}$$

$$K_c = 1.7 MPa\sqrt{m} \qquad \text{..............(7)}$$

The value of the alloy used was (Kc) ($1.7 Mpa\sqrt{m}$). It should be noted here that the grain diameter and the crack length are used in unit (µm), whereas, stress is in units (MPa) which is equivalent (N/mm²).

3.3 Track Fatigue Cracks

The phases of the cracks are divided into three zones, as is evident from the experimental results in Table (8,9,10):
a - From zero to the grain diameter, i.e. (200µm), it is (MSC), i.e. (Micro structurally Short Crack).
b - From the grain diameter to one millimeter (PSC), meaning (Physically Short Crack).
c - more than (1mm) is (LC), meaning (Long Crack).

Table 5 Experimental results and their division into the three phases of the first fatigue specimen

Specimen No.= 1	Stress Range $\Delta\sigma = 400$ MPa	No. of Cycles to Failure $N_f = 6500$ cycle
Phase Crack	Crack Length *a* (µm)	No. of Cycles N
MSC	60	1404
	140	1873
	200	2497
PSC	200	2783
	380	3226
	1000	3668
LC	1100	4006
	1320	4943
	1500	5710
	1680	6023
	1800	6322
	Broken	**6500**

Table 6 Experimental results and their division into the three phases of the **second** fatigue specimen

Specimen No.= 2	Stress Range $\Delta\sigma = 360$ MPa	No. of Cycles to Failure N_f =25000 cycle
Phase Crack	Crack Length *a* (µm)	No. of Cycles N

MSC	48	18379
	112	19030
	200	19682
PSC	200	20394
	700	21091
	1000	21470
LC	1080	21848
	1210	22606
	1400	23394
	1590	24030
	1770	24212
	Broken	**25000**

Table 7 Experimental results and their division into the three phases of the third fatigue specimen

Specimen No.= 3	Stress Range $\Delta\sigma$ =320 MPa	No. of Cycles to Failure N_f = 150000 cycle
Phase Crack	Crack Length *a* (µm)	No. of Cycles N
MSC	40	123020
	120	125550
	200	128080
PSC	200	130610
	680	131950
	1000	133240
LC	1160	135860
	1390	138580
	1510	141300
	1620	144210
	1700	147120
	Broken	**150000**

Using experimental results in tables (5,6,7) for each region (microscopic, physical and long) and using MATLAB to design program No. (2) as it appears as Figure (A3) in appendix –A to organize tables and integrate equations and to be a reference for researchers and graduate students because the table dictates The resolution is very cumbersome and takes a lot of time. The results of the program are shown in figures (A4,A5,A6) according to the three specimens.

Table 8 experimental accounts and dividing them into the three phases of the first fatigue specimen

Specimen No. 1		Stress Range ($\Delta\sigma$) 400 MPa		No. of Cycles to Failure (Nf) 6500 cycle		
Crack Phase	Crack Length *a* (µm)	No. of Cycles N (cycle)	Crack Length Range Δa (µm)	No. of Cycles Range ΔN(cycle)	Crack Growth Rate $\Delta a/\Delta N$(**10^{-5}**) µm/cycle	Average Crack Length a_{av}(µm)
MSC	60	1404	60	1404	4273.5	30
	140	1873	80	469	17058	100
	200	2497	60	624	9615.4	170
PSC	200	2783	0	286	0	200
	380	3226	180	443	40632	290
	1000	3668	620	442	140277	690
LC	1170	4006	170	338	50296	1085
	1380	4943	210	937	22412	1275
	1540	5710	160	767	20860	1460
	1680	6023	140	313	44728	1610
	1800	6322	120	299	40134	1740
	Broken	**6500**	**Σ=1800**	**Failure**	-	-

Table 9 Experimental accounts and dividing them into the three phases of the second fatigue specimen

Specimen No. 2		Stress Range ($\Delta\sigma$) 360 MPa		No. of Cycles to Failure (Nf) 25000 cycle		
Crack Phase	Crack Length *a* (µm)	No. of Cycles N (cycle)	Crack Length Range Δa (µm)	No. of Cycles Range ΔN(cycle)	Crack Growth Rate $\Delta a/\Delta N$(**10^{-5}**) µm/cycle	Average Crack Length a_{av}(µm)
MSC	48	18379	48	18379	261.17	24
	112	19030	64	651	9831	80
	200	19682	88	652	13497	156
PSC	200	20394	0	712	0	200
	700	21091	500	697	71736	450
	1000	21470	300	379	79156	850

LC	1180	21848	180	378	47619	1090
	1290	22606	110	758	14512	1235
	1450	23394	160	788	20305	1370
	1580	24030	130	636	20440	1515
	1770	24212	190	182	104400	1675
	Broken	**25000**	**Σ=1770**	**Failure**	-	-

Table 10 Experimental accounts and dividing them into the three phases of the third fatigue specimen

Specimen No. 3		Stress Range (Δσ) 320 MPa		No. of Cycles to Failure (N_f) 150000 cycle		
Crack Phase	Crack Length *a* (μm)	No. of Cycles N (cycle)	Crack Length Range Δ*a* (μm)	No. of Cycles Range ΔN(cycle)	Crack Growth Rate Δa/ΔN(**10^{-5}**) μm/cycle	Average Crack Length a_{av}(μm)
MSC	40	123020	40	123020	32.515	20
	130	125550	90	2530	3557.3	85
	200	128080	70	2530	2766.8	165
PSC	200	130610	0	2530	0	200
	680	131950	480	1340	35821.0	440
	1000	133240	320	1290	24806.0	840
LC	1160	135860	160	2620	6106.9	1080
	1390	138580	230	2720	8455.9	1275
	1510	141300	120	2720	4411.8	1450
	1620	144210	110	2910	3780.1	1565
	1700	147120	80	2910	2749.1	1660
	Broken	**150000**	**Σ=1700**	**Failure**	-	-

4. Analysis and Discussion of the Results

4.1 Analysis and discussion of microscopic short cracks (MSC)

The highest value of these cracks is the diameter of the grain (200μm), and thus the relationship between ($D-a_{av.}$) and the crack speed (da / dN) has been found (200μm). Note the tables (8), (9) and (10). Because when the value of (a) reaches (D), the crack speed is equal to zero, meaning that the crack length has reached the grain boundaries. And therefore it stops even for a very brief period. Through the results of the lengths of the cracks and the number of turns indicated in the tables above, a relationship was built by assuming that the crack speed is related to ($D - a_{av.}$) As follows [12]:

$$\frac{da}{dN} = A_2 * \Delta\sigma^{\alpha_2} * \left(D - a_{av.}\right)^{\alpha_1} \qquad ....(8)$$

To facilitate the solution of this equation, we reduce it as follows:

$$\frac{da}{dN} = A_1\left(D - a_{av.}\right)^{\alpha_1} \qquad ....(9)$$

Where:

$$A_1 = A_2 \Delta\sigma^{\alpha_2} \qquad ....(10)$$

Through the results in tables (8), (9) and (10), the value of A1 and α1 can be found for each specimen separately and by preparing a program using MATLAB.

Table 11 A1 & α1 values for the three specimens

First Specimen		Second Specimen		Third Specimen	
A_1	$\alpha 1$	A_1	$\alpha 1$	A_1	$\alpha 1$
$1.1*10^{-6}$	3.8	$2.23*10^{-7}$	-6.4	$3.77*10^{-8}$	-4.3

For simplicity, the mean value of α1 was taken, and we found it equal to (-2.3). We prepared the same program to find out the relationship between stress range (Δσ) and the above three (A1) values, as in the following table

Table 12 Values of A1 & Δσ for the three specimens

First Specimen		Second Specimen		Third Specimen	
A_1	Δσ (MPa)	A_1	Δσ (MPa)	A_1	Δσ (MPa)
$1.1*10^{-6}$	400	$2.23*10^{-7}$	360	$3.77*10^{-8}$	320

By Using Equation (10) And Applying the Same Program That Was Prepared with MATLAB, the constants were found and follows:
$A_2 = 5.6*10^{-46}$ & $\alpha_2 = 15.1$

By Substituting Equation (10) By (9) We Obtain:

$$\frac{da}{dN} = 5.6*10^{-46} * \Delta\sigma^{15.1}\left(D - a_{av.}\right)^{-2.3} \quad \ldots\ldots\ldots\ldots\ldots\ldots(11)$$

Since this area is limited between the length of the crack zero to the diameter of the grain mμ200, therefore, these values represent the integration limits for equation (11), and therefore we get the final equation that represents the fatigue life at this stage:

$$\int_0^D \frac{da}{\left(D - a_{av}\right)^{-2.3}} = 5.6*10^{-46} * \Delta\sigma^{15.1} \int_0^{N_{f1}} dN \quad \ldots\ldots\ldots\ldots\ldots\ldots(12)$$

$$\int_0^D \left(D - a_{av}\right)^{2.3} da = 5.6*10^{-46} * \Delta\sigma^{15.1} \int_0^{N_{f1}} dN \quad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

$$N_{f1} = \frac{D^{3.3}}{3.3*5.6*10^{-46} * \Delta\sigma^{15.1}} = 2.672*10^{42} * \Delta\sigma^{-15.1} \quad \ldots\ldots\ldots\ldots\ldots\ldots(14)$$

Where, Δσ units are MPa and Nf1 in cycles represents the specimen life in the first region. The above equation describes the behavior of cracks emerging in the first grain, where it becomes clear that the main factors affecting the speed of the cracks da / dN are:

a- The value of (D) or the grain size, where the higher the value of (D), the higher the crack speed, and therefore it is preferable for the diameter of the grain to be small to reduce the crack speed and thus increase the life of the specimen or part, and this corresponds to the stated source [6].

b-The higher the stress, the higher the crack speed. Therefore, it is preferable that the stresses close to the fatigue limit of the material. In the case of making the stresses too high, the effect of the above equation is almost neglected because the small cracks end suddenly and do not affect them, and this corresponds to the stated source [7].

4.2 Analysis and discussion of physical short cracks (PSC) in the second region

The mathematical formula in this region is:

$$\frac{da}{dN} = B * \Delta\sigma^{\beta} * a_{av} \quad \ldots\ldots\ldots\ldots\ldots\ldots(15)$$

In the same way as before in the first region and using the same program, these constants were found as follows: **B = 1.24*10^-41^** **&** **β = 14.54**

Thus, we examine the formula for the crack speed or the rate of cracks growth in the second region:

$$\frac{da}{dN} = 1.24*10^{-41} * \Delta\sigma^{14.54} * a \quad \ldots\ldots\ldots\ldots\ldots\ldots(16)$$

By integrating this equation from 200μm to 1000μm we get the final equation for the life of fatigue in the second region:

$$N_{f2} = \frac{\ln(1000) - \ln(200)}{1.24*10^{-41} * \Delta\sigma^{14.54}} = \frac{\ln\frac{1000}{200}}{1.24*10^{-41} * \Delta\sigma^{14.54}} = \frac{1.61}{1.24*10^{-41} * \Delta\sigma^{14.54}}$$

$$N_{f2} = 1.3*10^{41} * \Delta\sigma^{-14.54} \quad \ldots\ldots\ldots(17)$$

Where, Δσ units are MPa and Nf_2 in cycles represents the specimen life in the second region.

4.3 Analysis and discussion of long cracks (LC) in the third region

These cracks have no correlation with the grain size of the material, while the effect of the cyclic stress is extreme, the same method was used in the previous regions to create an equation describing the movement of these cracks as follows [6]:

$$\frac{da}{dN} = E * \Delta\sigma^{\beta_2} * a_{av}^{\beta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots(18)$$

To facilitate the solution of this equation, we reduce it as follows:

$$\frac{da}{dN} = F * a_{av}^{\beta_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots(19)$$

Where:

$$F = E * \Delta\sigma^{\beta_2} \quad ....(20)$$

Through the results in tables (8), (9) and (10), the value of β1 and F can be found for each specimen separately and by preparing a program using MATLAB, the following was found:

Table 13 The values β_1 & F for the three specimens

First Specimen		Second Specimen		Third Specimen	
$F*10^{-6}$	β_1	$F*10^{-6}$	β_1	$F*10^{-6}$	β_1
2147	0.842	666.9	0.701	75.6	0.737

For simplicity and high accuracy, a mean value of β1 was taken, and we found it equal to (**0.76**).
We prepared the same program to find out the relationship between stress range (Δσ) and the above three (F) values as in the following table:

Table 14 The values Δσ & F for the three specimens

First Specimen		Second Specimen		Third Specimen	
$F*10^{-6}$	Δσ (MPa)	$F*10^{-6}$	Δσ (MPa)	$F*10^{-6}$	Δσ (MPa)
2147	400	666.9	370	75.6	320

By using equation (20) and applying the same program with MATLAB, constants were found as follows: $\mathbf{E=2*10^{-42}}$ **&** $\mathbf{\beta_2 = 15}$

$$\frac{da}{dN} = E * \Delta\sigma^{\beta_2} * a_{av}^{\beta_1} \quad ....(21)$$

$$\frac{da}{dN} = 2*10^{-42} * \Delta\sigma^{15} * a_{av}^{0.76} \quad ....(22)$$

By integrating this equation from 1000μm to 6740μm which represents the specimen diameter at the fracture region, we obtain the final equation for the fatigue life in the third region:

$$\int_{1000}^{6740} \frac{da}{(a_{av})^{0.76}} = 2*10^{-42} * \Delta\sigma^{15} * \int_{0}^{N_{f3}} dN \quad ....(23)$$

$$\int_{1000}^{6740} (a_{av})^{-0.76} * da = 2*10^{-42} * \Delta\sigma^{15} * \int_{0}^{N_{f3}} dN \quad ....(24)$$

$$N_{f3} = \frac{\left((6740*10^{-3})^{0.24} - (1000*10^{-3})^{0.24}\right)}{0.24*2.5*10^{-42} * \Delta\sigma^{15}} = \frac{580.8*10^{-3}}{0.24*2.5*10^{-42} * \Delta\sigma^{15}}$$

$$N_{f3} = \frac{2.42}{2*10^{-42} * \Delta\sigma^{15}} = 1.21*10^{42} * \Delta\sigma^{-15} \quad ....(25)$$

Where, the units of Δσ are MPa and that the Nf3 in cycles represents the specimen life in the third region.

The above equation describes the movement of long cracks when the 1mm crack crosses and leads to specimen failure, in this paper, we are satisfied with five surface crack readings for the following reasons:

1- High difficulty following cracks under the microscope.

2- Monitoring and measuring cracks takes a lot of time.

3- When the cracks are about 2-3 mm old, the fusion process will begin.

4- It is clear from the above equation that long cracks are not affected by the microscopic structure of the material and when the stresses are high, they are effective.

Thus, we obtain the total life of fatigue that represents the life of the specimen extracted from the model proposed in this research for the three regions as follows:

$$\mathbf{N_{ft} = N_{f1} + N_{f2} + N_{f3}}$$

Where, $\mathbf{N_{ft}}$ is the total number of courses, which represents the life of the specimen extracted from the model proposed in this research.

Many researchers [9,7,6] and others have placed a limit on the behavior of small cracks associated with the grain Size Parameter where the boundaries of the small cracks end when the crack reaches the end of the first grain boundary as shown in figure (6).

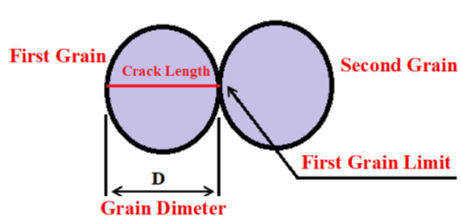

Fig. 6: A schematic diagram of the boundaries of microscopic cracks

They considered that what is after this is a long crack, that is, two stages for the growth of the crack, as in the schematic figure (7a).

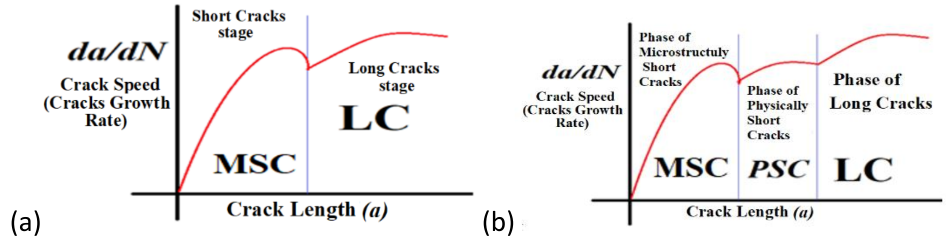

Fig. 7: (a) relationship of crack speed to crack length, (b) shows three stages of fatigue cracks growth in AA 2219

But in this research, the lengths of the cracks were divided into three regions as follows: -

i. From zero to the grain diameter, it is (MSC), that is (Microstructuly Short Cracks).
ii. From the grain diameter to one millimeter (PSC), meaning (Physically Short Cracks).
iii. more than (1mm) is (LC), meaning (Long Cracks).

This means that the short cracks stage is classified into two phases, after which it will be the third phase that represents the long cracks, as shown in Figure (7b).

In order to confirm and understand more accurately the importance of this regions, two models from reference [4], Paris and Forman, were applied to the samples used in this research as shown in table (15), and compare the results of the proposed model with the experimental results on the one hand, and the results obtained from the Paris model [4] and the Foreman model [4] on the other hand, where the results obtained from the proposed model took the safest side. Thus, it is clear that the current model gives a safer estimate, especially for this alloy, from which aircraft tanks and fuel pipeline networks inside the planes are made. The current model provides a suitable safety factor at a rate (3.2), which encourages the designer to use it, as table (15) shows the results FCG of the proposed model for three-stage by calculating the total life (Nf1+ Nf2+ Nf3) compared with the experimental results, Paris model and Forman model.

Table 15 The three-stage results of the proposed model for FCG compared to experimental results, Paris model [4] and Forman model [4].

Specimen No.	Stress (MPa)	Experimental Nf	N_{f1}	N_{f2}	N_{f3}	N_{ft}	Paris model[4]	Forman model[4]
1	200	6500	1370	1906	1127	4403	6680	6470
2	180	25000	6724	8816	5473	21013	26250	25600
3	160	150000	39815	48873	32028	120716	154000	153000

By doing this, it proves to us that neglecting the second stage (PSC) leads to an estimate of fatigue life for FCG is not safe, especially in important structures such as airplanes, because in this designs, the designer must take the safety optimum in order to avoid disasters.

5. Conclusions

The FCG in AA (2219) was divided into three phases (MSC, PSC & LC) instead of two phases (MSC & LC), and mathematical model was proposed for FCG of each phase and calculating the life of each stage, where an identification new variables to be introduced in the FCG model. The new variables take into account the second phase cross the boundary of the grain size to about 1mm in length (physically short cracks (PSC)), it is obvious that neglecting the effect of this stage in fatigue calculations under any loading can lead to completely invalid life predictions where in stage ii phase the failure mode changes from inter-granular to trans-granular as the stress level increases. Using this new modeling it is possible the derivation of the a-N and S-N curves for different initial crack size and optimizing aluminum alloy selection for fracture resistant aluminum engineering structures and also will lead to a higher stability condition for the aircraft tanks designer when using the proposed model.

1- Physically short cracks (PSC) are the same conditions as short fatigue cracks grow under the range of stress intensity factor less than the threshold and the concepts of linear elastic fracture mechanics cannot be applied in this case.

2- Neglecting the effect of second stage (physically short cracks (PSC)) in fatigue calculations under any loading can lead to completely invalid life predictions. The same was not possible with the Paris equation and the modified Forman equation, indicating that generalization of this model is not as straightforward as for the proposed equation. The obtained results qualify the proposed model as a promising tool to describe the complete FCG curves of aluminum alloys and other structural metallic materials.

3- The rate of the FCG increases as the length of the crack increases until it approaches the grain limit, which represents the major obstacle to growth, then the growth rate decreases, and after exceeding this obstacle, the growth begins to accelerate.

4- The growth of short fatigue cracks depends on the cyclic stresses projected, the length of the crack and the grain size, while the growth of the long fatigue cracks depends on the cyclic stresses projected and the crack length.

5- Estimation the life of the specimen subject to cyclic stresses, were compared with the experimental results, the Paris model and the Foreman model and gave a more safety condition, which will lead to a higher stability condition for the aircraft tanks designer when using the proposed model.

6- The use of MATLAB programs in calculating FCG tables reduced effort and time as well as the high accuracy of results.

References

[1] N. Vikram and K. Raghuvir,“Review on Fatigue-Crack Growth and Finite Element Method.”International Journal of Scientific & Engineering Research 4 (4): 833–43 , 2013.
[2] L.C. Singal, S. G. Rajwinder and M. J. Aishna, “Fatigue Mechanical Life Design-A Review.” International Journal of Engineering Research and General Science 5 (2): 247–51, 2017.
[3] F. K. Fajdigag, “Numerical Analysis of Surface Fatigue Crack Groth Using FEM Method.” Int. Design Conf., 527–32, 2000.
[4] A. B. Abdessalem, “Model selection, updating and prediction of fatigue crack propagation using nested sampling algorithm”, 23ème Congrès Français de Mécanique, Lille, 28 au 1er September 2017.
[5] R. I. Stephens, "Metal Fatigue in Engineering", Second Edition, Aweiley- Interscience Publication, John Wiley and sons, INC, 2011.
[6] A. Salmi & S. M. El-Amine, “Crack growth study under thermo-mechanical loads: parametric analysis for 2024 T3 aluminum alloy”, Vol 13 No 50 , October 2019.
[7] I. Mudasir, O. Faisal,E. Hassan, U. Mudaser, E. Marco, B.Saeed & G. Paolo, “Effect of Natural Aging and Fatigue Crack Propagation Rate on Welded and Non-Welded Aluminum Alloy (AA2219-T87)”, Advances in Science and Technology Research Journal (ASTRJ), Volume 13, Issue 3, September 2019, pages 129–143.
[8] L. Hongjun, G. Jian and L. Qinchuan,“Fatigue of Friction StirWelded Aluminum Alloy Joints”, Appl. Sci. 2018, 8, 2626; doi:10.3390/app8122626.
[9] A. Haftirman, W. Haris , J. Andika, and N. A. Yahadi,” Effect of thickness on FCGof Aluminum alloys”, IOP Conf. Series: Materials Science and Engineering 343 (2018).
[10] D.A. Abdullah & H. O. Salman " The effect of tempering on the fatigue Behavior for medium carbon steel", the Iraqi Journal For Mechanical and Material Engineering, Vol.11, No.4, 2011.
[11] S.L. Sabater, Fundiciones ,SABATER FUNDIMOL,Catalogo,2004-2014.
[12] D. A. Abdullah & H. J. Al-Alkawi, " Design Effect of The Welded Joints On Fatigue Strength For Low Carbon Steel Metal (ST- 52- 3) ", Engineering and Technology Journal,vol.25,No.1,2007, pp 9-23.
[13] International Alloy Designation and Chemical Composition Limit for Wrought Aluminum and Wrought Aluminum, registration recorded series, pp3,2017.
[14] O. A. Hatamleh ,"Laser and shot peening effects on fatigue crack growth in friction stir welded 7075-T7351 aluminum alloy joints", International journal of fatigue, Vol.29, No.3, pp. 434-421, 2007.
[15] L. H. Al Najar, L. S. Al-Ansari, Mohammed Wahab Al-Jibory, "The Effect of Load Magnitude on Fatigue Life and Thermal Behavior of Notched Fatigue Specimen" , Journal of University of Babylon, Engineering Sciences, Vol.(26), No.(1): 2018.
[16] D. Gross & S. Thomas, "Fracture Mechanics with an Introduction to Micromechanics”, Second Edition, Springer-Verlag Berlin Heidelberg 2011.

Appendix-A

CF.m

```
function CF   % Curve Fitting (CF)
clc ,clear ,close all
disp('                    Curve Fitting (CF)                    ')
disp('***************************************************')
syms x y
x = input('inpu The Values of x = ');
y = input('input The Values of y =');
n=length(x);sx=0;sx2=0;sy=0;sxy=0;r=2;
for i=1:n
sx=sx+log10(x(i));
sx2=sx2+(log10(x(i)))^2;
sy=sy+log10(y(i));
sxy=sxy+log10(x(i))*log10(y(i));
end
sum=[sx,sx2,sy,sxy ];A=[n sx ;sx sx2 ];b=[sy;sxy];
X=inv(A)*b;Lao=X(1);
disp('-----------------------------------------------------------')
X(1)=10^(X(1));
ao=X(1);
a1=X(2);
disp(['  Log ao =',num2str(Lao)])
for i=1:r
disp([' a',num2str(i-1),' = ',num2str(X(i))])
end
disp('------------ The equation of this Proplem is :-------------')
disp('   ')
disp(['             y = ',num2str(ao),' * x^',num2str(a1)])
disp('-------------------------------------------------------------')
```

Figure (A1) the MATLAB program No. (1) for calculating practical constants using the best curves

Command Window

```
                    Curve Fitting (CF)
***************************************************
inpu The Values of x = [6500  25000  150000  370000  600000];
input The Values of y =[200   180   160   140   120  ];
-----------------------------------------------------------
  Log ao =2.7031
 a0 = 504.7558
 a1 = -0.10228
------------ The equation of this Proplem is :-------------

          y = 504.7558 * x^-0.10228
-----------------------------------------------------------
```

Figure (A2): Output of Program No. (1) using the results of table (4) to find the constants of the fatigue life formula

```
clc,clear,close all
SNo = input('   inpu The No. of Specimen :n = ');
a = input('     inpu The Crack Length of a = ');
N = input('     inpu The The No. of Cycles= ');
n=length(a);sda=0;k=n-1;
for i=1:n
 if i <= k
 da(i)=a(i+1)-a(i); sda=sda+da(i); dN(i)=N(i+1)-N(i);
 aav(i)=(a(i+1)+a(i))/2;
 end
 end
sumda=sda; final=a(n);digits(5);daN=da./dN;daN=vpa(daN);daN=daN*100000;
disp('------------------------------------------------------------------')
disp('       Experimental Procedure and Results of Crack Growth ')
disp('------------------------------------------------------------------')
disp(['  The Specimen No. = ',num2str(SNo)])
disp(['  a =[',num2str(a),']'])
disp(['  N =[',num2str(N),']'])
disp('------------------------------------------------------------------')
disp(['  The Value of sum crack Length Range = [',num2str(sda),']'])
disp(['  The Value of final crack Length = [',num2str(final),']'])
disp('------------------------------------------------------------------')
disp('                        Results Taple')
disp('------------------------------------------------------------------')
disp('   da              dN             da/dN*10^-5             aav')
disp('------------------------------------------------------------------')
for i=1:n
 fprintf('%4d  %16.5g  %16.5g  %16d\n', da(i),dN(i), daN(i),aav(i))
 disp('------------------------------------------------------------------')
end
```

Figure (A3) MATLAB program No. (2) to organize the schedule for crack tracking

```
--------------------------------------------------------------------------
Experimental Procedure and Results of Crack Growth for Specimen No.= 1
--------------------------------------------------------------------------
 The Value of sum crack Length Range = [1800]
 The Value of final crack Length = [1800]
---------------------------------------------------------------------
                      Results Taple
---------------------------------------------------------------------
  da             dN            da/dN*10^-5            aav
---------------------------------------------------------------------
 60            1404            4273.5                 30
---------------------------------------------------------------------
 80             469             17058                100
---------------------------------------------------------------------
 60             624            9615.4                170
---------------------------------------------------------------------
  0             286                 0                200
---------------------------------------------------------------------
180             443             40632                290
---------------------------------------------------------------------
620             442        1.4028e+05                690
---------------------------------------------------------------------
170             338             50296               1085
---------------------------------------------------------------------
210             937             22412               1275
---------------------------------------------------------------------
160             767             20860               1460
---------------------------------------------------------------------
140             313             44728               1610
---------------------------------------------------------------------
120             299             40134               1740
---------------------------------------------------------------------
```

Figure (A4) applying the program to the experimental results of the first fatigue sample from Table (5)

Experimental Procedure and Results of Crack Growth for Specimen No.= 2

The Value of sum crack Length Range = [1770]
The Value of final crack Length = [1770]

Results Taple

da	dN	da/dN*10^-5	aav
48	18379	261.17	24
64	651	9831	80
88	652	13497	156
0	712	0	200
500	697	71736	450
300	379	79156	850
180	378	47619	1090
110	758	14512	1235
160	788	20305	1370
130	636	20440	1515
190	182	1.044e+05	1675

Figure (A5): Applying the program to the experimental results of the second fatigue sample from Table (6)

Experimental Procedure and Results of Crack Growth for Specimen No.= 3

The Value of sum crack Length Range = [2400]
The Value of final crack Length = [2400]

Results Taple

da	dN	da/dN*10^-5	aav
80	1.728e+05	46.296	40
90	57600	156.25	125
30	76800	39.062	185
0	35200	0	200
450	54400	827.21	425
350	54400	643.38	825
90	41600	216.35	1045
430	1.152e+05	373.26	1305
280	94400	296.61	1660
300	38400	781.25	1950
300	36800	815.22	2250

Figure (A6) applying the program to the experimental results of the third fatigue specimen from Table (7)