STUDY OF FATIGUE CRACK GROWTH IN 6063-T6 ALUMINUM ALLOY

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ABSTRACT

The present study relates to investigate the crack propagation behavior of 6063 T6 Al Aluminum Alloy under fatigue loading. The experimental as well as analytical analysis was done and for crack growth rate for 6063-T6 Aluminum Alloy. All analysis was done on Side edge notch specimen. A program was developed on Matlab® to calculate crack growth rate and effective stress intensity range ratio based on polynomial algorithm. That gave a very good agreement between them. The effective stress intensity range ratio (U) was found to depend on stress ratio (R). Variation in load range affects the crack growth rate. For constant load range its variation was negligible, constant C was almost constant at variable load range. Variation of maximum load affects constant C.

Keywords: Fatigue, 6063-T6 Al Alloy, Fracture, Analytical Analysis, Crack Closure

1. INTRODUCTION

The phenomenon of metal fatigue is very old and is related with mechanical failure of the components subjected to cyclic loading. Fatigue failure is a major problem encountered by designers. Generally it occurs in the machine components and structures which are associated with dynamic loading i.e. the load on a component changing with time. Although fatigue failure is important in almost all the design problems, yet the designing of the components of some machines like an aircraft, space vehicle, turbine, engine, rails & bridges are most critical (BROEK, 1982; ZHENG, 1983; ELBER, 1970).

According to ASTM (1976) fatigue is defined as "the process of progressive localized permanent structural change occurring in the material subjected to the conditions which produce fluctuating stresses and strain at some point or points and which may culminate in crack or complete fracture after a sufficient number of fluctuations" (FOREMAN; MEARNEY; ENGLE ,1967; WALKER, 1970; NIRPESH; RAGHUVIR, 2013; NIRPESH; RAGHUVIR, 2015).

Fatigue failures are generally caused due to some stress raisers as a crack initiates from these stress raisers. (PEARSON, 1972; ELBER, 1971; NIRPESH; SAKSHI; RAGHUVIR, 2014) There are three most important factors which cause the fatigue failure to take place:

- Cyclic loading

- Points of stress concentration

- Residual tensile stresses

2. METHOD

The crack growth rate experiments have been carried out by various researchers on a wide range of materials using different specimen geometries (PARIS; ERDOGAN, 1963; BROEK, 1982; ZHENG, 1983; ELBER, 1970; NICCOLLS, 1976; KUMAR; GARG, 1988A; KUMAR; GARG, 1988B; ASTM, 1967).

Studies have shown that the crack propagation is a complex phenomenon. Literature reveals that crack growth rate (CGR) can be related to ΔK, ΔK_Θ etc. these relationships are empiricalin nature. The CGR constants C, m etc. of different models are considered to be material constants. In addition to materials they depend upon loading parameters $\Delta\sigma$, σ_m and R.

A number of researchers tried to relate these constants with the loading parameters for 6061-T6 and 6063-T6 Aluminum alloys.

Here are the main steps of the work carried out:

(1) A program is written using MAT Lab to calculate the maximum stress intensity factor K_m, stress intensity range ΔK, effective stress intensity range ΔK_Θ and crack growth rate$\frac{da}{dN}$.

(2) The program thus developed is used on different sets of data (a-N) for 6061-T6 & 6063-T6 alloys. There is two types of data:

   (a) When maximum load was kept constant

   (b) When load range was kept constant

(3) The curves are plotted for N Vs a, N Vs $\frac{da}{dN}$, ΔK Vs $\frac{da}{dN}$ and $\Delta K\Theta$Vs $\frac{da}{dN}$, for both the materials.

(4) The constants of the crack growth rate are evaluated for the following models:

   (a) Paris and Erdogan model

   (b) Elber model

   (c) Walker model

   (d) Foreman model

(5) Co-relations are developed between CGR constants and loading parameters.

3. ANALYSIS

The aim of our study is to see the effect of loading parameters on the crack growth rate constants. The first thing is to fit the models in our data and evaluate the constants. It was planned to analysis models for the given type of loading conditions.

1. Maximum load was kept constant and the load ratios were increased.

2. Load range was kept constant and load ratios were increased.

3.1. Materials used

The material used is 6063-T6 Al alloys. The chemical composition of the materials as per manufacturer's catalogue is given in Table no (1).

Table 1: Chemical composition of the material

Materials		Elements					
		Cu	Mg	Si	Fe	Mn	Others
6063-T6	Max	0.10	0.90	0.8	0.70	0.60	0.4
	Min	-	0.40	0.30	-	-	-

Table 2: Mechanical properties of the materials

Material	Properties					
	σ_y kg/mm^2	σ_u kg/mm^2	σ_f kg/mm^2	$E \times 10^6$ kg/mm^2	Elongation %	Reduction in area %
6063-T6	14.95	18.26	33.62	5.12	10.7	45.67

3.2. Fatigue tests

6063-T6 Al-alloy

1. P_m = 820 Kg

2. ΔP = 585 Kg

The details of the experiments are given in Table no (3).

There are 9 experiments in all; tests S1 – S5 were conducted by keeping maximum load constant. Remaining S6-S9, were conducted at constant load range.

Fatigue tests were carried out on the side edged notched specimens of about 180mm x 50mm x 3mm initially with a notch of 6 mm. During the tests crack initiated

from this edge readings of number of cycles were taken at a regular interval of 0.5 mm crack length.

Table 3

S.No	Tests	R	P_m Kg	P_n Kg	ΔP Kg	N_f
Tests for 6063-T6 Al-Alloys
1.	S1	0.0	820	0	820	61470
2.	S2	0.2	820	164	656	83380
3.	S3	0.3	820	246	574	116000
4.	S4	0.35	820	287	533	137660
5.	S5	0.45	820	369	541	199760
6.	S6	0	585	0	585	479690
7.	S7	0.2	731.25	146.25	585	143030
8.	S8	0.4	975	390	585	96990
9.	S9	0.6	1462.5	877.5	585	76970

3.3. Program development

A program was developed for calculating the crack growth rate, maximum stress intensity factor, stress intensity range and effective stress intensity range, which were later used for model fitting.

Following data was used as input in the program, which is written in MATLAB R2012a:

1.   No of readings of (a-N) in a set N_p

2.   Crack length (a).

3.   Number of cycles (N)

4.   Maximum load of the cycle (P_m)

5.   Minimum load of the cycle (P_n)

6.   Width of the specimen (w)

First we calculate (R) & (U) (FOREMAN; MEARNEY; ENGLE ,1967; PEARSON, 1972)

$$R = \frac{P_n}{P_m} \qquad (3.1)$$

$$U = 0.69 + 0.5R + 0.12R^2 \qquad (3.2)$$

To find out the crack growth rate "seven point successive incremental polynomial method" was adopted. Following form of equation was formed:

$$a_1 = d_1 + d_2 N_1 + d_3 N_1{}^2 + d_4 N_1^3 + d_5 N_1^4 + d_6 N_1^5 + d_7 N_1^7$$

$$a_2 = d_1 + d_2 N_2 + d_3 N_2{}^2 + d_4 N_2^3 + d_5 N_2^4 + d_6 N_2^5 + d_7 N_2^7$$

$$a_3 = d_1 + d_2 N_3 + d_3 N_3{}^2 + d_4 N_3^3 + d_5 N_3^4 + d_6 N_3^5 + d_7 N_3^7$$

$$a_4 = d_4 + d_2 N_4 + d_3 N_4{}^2 + d_4 N_4^3 + d_5 N_4^4 + d_6 N_4^5 + d_7 N_4^7$$

$$a_5 = d_1 + d_2 N_5 + d_3 N_5{}^2 + d_4 N_5^3 + d_5 N_5^4 + d_6 N_5^5 + d_7 N_5^7$$

$$a_6 = d_1 + d_2 N_6 + d_3 N_6{}^2 + d_4 N_6^3 + d_5 N_6^4 + d_6 N_6^5 + d_7 N_6^7$$

$$a_7 = d_1 + d_2 N_7 + d_3 N_7{}^2 + d_4 N_7^3 + d_5 N_7^4 + d_6 N_7^5 + d_7 N_7^7$$

The general form of the equation is as follows:

$$a_i = d_1 + d_2 N_i + d_3 N_i{}^2 + d_4 N_i^3 + d_5 N_i^4 + d_6 N_i^5 + d_7 N_i^7$$

$$(3.3)$$

The basic principal to solve these equations is the Gauss elimination method back substitution is used to solve them. For each set of seven readings values was found of constants d_1-d_7 which gave the value of crack growth rate (da/dN)

$$\frac{da}{dN} = d_2 + 2d_3 N_i + 3d_4 N_i^2 + 4d_5 N_i^3 + 5d_6 N_i^4 + 6d_7 N_i^5$$

$$(3.4)$$

After calculating the first value of crack growth rate, da/dN value was increased from 0-1 to 2-8 and the above process repeated for second value of da/dN. Thus calculated the values of da/dN until i= N_p. here N_p is the number of reading in a test.

For calculating maximum stress intensity factor K_m, stress intensity range ΔK_e (UΔK) following equations were used:

$$K_m = \left(\frac{P_m}{A}\right)(a)^{\frac{1}{2}}\{f\} \qquad (3.5)$$

$$\Delta K = \left(\frac{\Delta P}{A}\right)(a)^{\frac{1}{2}}\{f\} \qquad (3.6)$$

$$\Delta K_e = U(\Delta K) \qquad (3.7)$$

Where

$$f = [1.99 - 0.41\left(\frac{a}{w}\right) + 18.7\left(\frac{a}{w}\right)^2 - 38.48\left(\frac{a}{w}\right)^3 + 53.85\left(\frac{a}{w}\right)^4]\Delta K_e = U(\Delta K)$$

Output of the program is given as follows:

1.   Stress intensity range ratio (U)

2.   Maximum stress intensity factor (K_m).

3.   Stress intensity range (ΔK).

4.   Effective stress intensity range (ΔK_e)

3.4.   Curves drawing

Computer program was run for various test data. From the output curves were drawn. The scheme of the curves is given below.

(a)   Number of cycles Vs Crack length

(b)   Number of cycles Vs crack growth rate.

(c)   Stress intensity range Vs crack growth rate.

(d)   Effective stress intensity range Vs crack growth rate.

 A.   Maximum load constant

1. N Vs a

2. N Vs CGR

3. Log ΔK Vs log CGR

4. Log ΔK_e Vs log CGR

B.   Load range constant

1. N Vs a

2. N Vs CGR

3. Log ΔK Vs log CGR

4. Log ΔK_e Vs log CGR

3.5.   Model fitting

3.5.1. Model fitting for 6063- T6 Aluminum alloy:

It is also carried in the two stages i.e.

(A)   Maximum load constant

(B)   Load range constant.

(A)   Maximum load constant: From Figure 1 and 2 we observed that with increasing load ratios life of components and crack initiation stage increased while the crack growth rate decreased.

ΔK Vs CGR & ΔK_e Vs CGR curves are drawn for second stage of crack growth rate given by Figure 3 and 4. Lines of best fit have been drawn, from each set of readings, from which CGR constants were evaluated for different models as below:

1. Paris model: - A decrement in the value of constant m is observed. Constant C was found to have a little variation.

2. Elber model: - The values of constant m were found to be nearly equal to the values of its counterpart in Paris model. The values of constant C are found to increase if we compare them with that of the Paris model, which are constant.

3. **Walker model:** - The values of constant m have the same variation as it is in Paris and Elber model, but they are somewhat less in comparison to that of Paris model. The values of constant C are having very low variation almost negligible. Constant n increased consistently.

4. **Foreman model:** - The values of constant m are equal to the values of constant m in Paris model. Constant C is high in comparison to the values of C in other models.

(B) **Load range constant**: From Figure 5 and 6 this was observed that with increasing load ratio life of components & crack initiation stage decreased while the crack growth rate is found to increase.

ΔK Vs CGR &ΔKe Vs CGR curves were drawn for second stage of crack growth rate given by Figure 7 and 8. Lines of best fit have been drawn from each set readings, from which CGR constants were evaluated of different models as below:

1. **Paris model:** - Constants m are found to have very low variations and constant C are found to decrease steadily.

2. **Elber model:** - In this model the value of constant m have been found to have very low variation, for analysis purpose its value may be taken as constant. The value of constant C decreased consistently.

3. **Walker model:** - It shows that the value of constant m has little variation, and is less in comparison to other models. The constant C was found to decrease continuously. Exponent n has steady increment.

4. **Foreman model:** - In this model the value of constant m is same as that of Paris model. Value of C decreased consistently, it has higher values in comparison to other models.

3.6.   Relationship of CGR constants

After evaluating the crack growth rate constants of different models a relationship was developed involving constant C and constant m. The constant m is found to have a relationship with stress range $\Delta\sigma$, constant C bears a relationship with maximum stress σ_m. Relationship of C and σ_m can be expressed in the form as follows:

$$\sigma_m + S_1(\log C) + S_2 = 0 \qquad (3.8)$$

Here $S_1 \& S_2$ are constants which were evaluated by drawing the curve between maximum stress σ_m & constant C on semi log scale for each model.

Relationship between stress range $\Delta\sigma$ and constant m is found to be as follows:

$$\Delta\sigma + T_1(m) + T_2 = 0 \qquad (3.9)$$

Again $T_1 \& T_2$ are constants which are evaluated by drawing the curve between stress range $\Delta\sigma$ and constant m on linear scale. Constants T_1, T_2, S_1 and S_2 are given in chapter four.

6063-T6 AL ALLOY
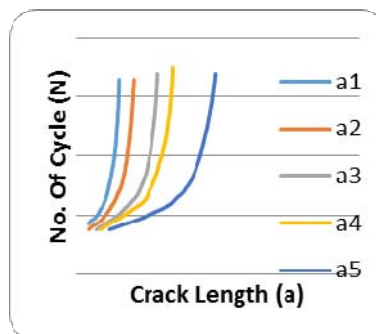
Maximum Load = 820 kg

Crack Length vs Number Cycle

Figure 1: Number of Cycles Vs Crack Length

TEST	S1	S2	S3	S4	S5
R	0	0.2	0.3	0.35	0.45

6063-T6 AL ALLOY

Maximum Load = 820 kg

Crack Growth Rate Vs Number of Cycle
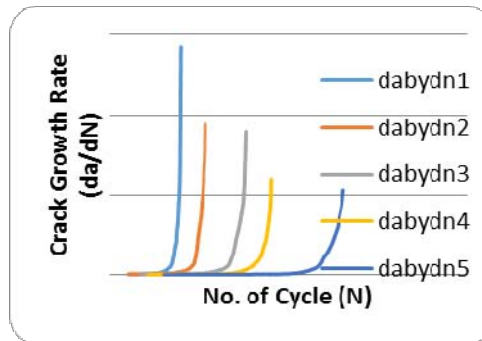
Figure 2: Number of Cycles Vs Crack Growth Rate

Test	S1	S2	S3	S4	S5
R	0	0.2	0.3	0.35	0.45

6063-T6 AL ALLOY

Maximum Load = 820 kg

Log Crack Growth Rate Vs Log Stress Intensity Range
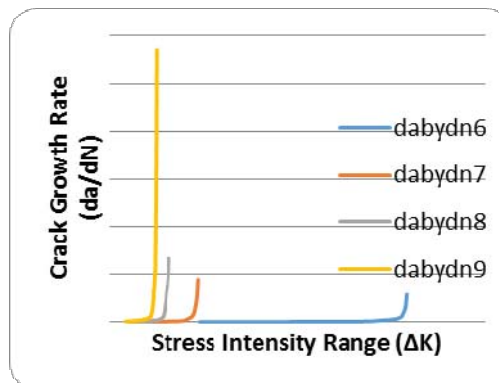
Figure 3: Stress Intensity range Vs Crack Growth Rate

Test	S1	S2	S3	S4	S5
R	0	0.2	0.3	0.35	0.45
U	.69	.79	.84	.87	.93

6063-T6 AL ALLOY

Maximum load = 820 kg

Log Ccrack Growth Rate Vs Log Effective Stress Intensity Range

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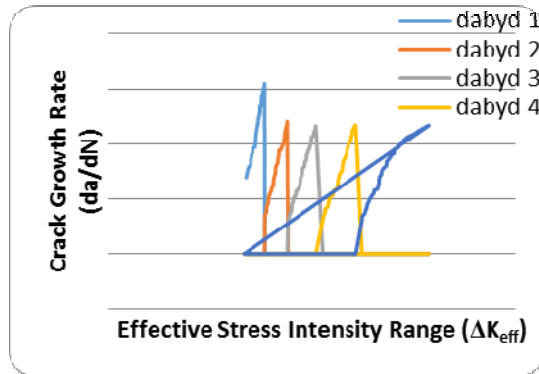
Figure 4: Effective Stress Intensity range Vs Crack Growth Rate

Test	S1	S2	S3	S4	S5
R	0	0.2	0.3	0.35	0.45

6063-T6 AL ALLOY

Load range = 585 kg

Crack Length Vs Number of Cycle
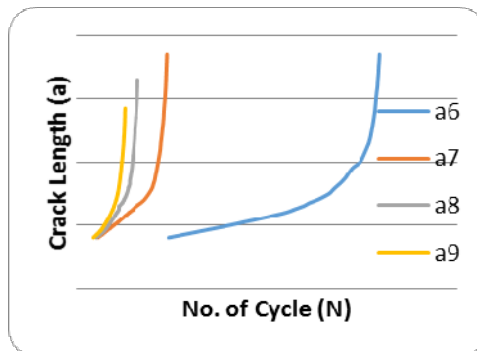
Figure 5: Number of Cycles Vs Crack Length

Test	S6	S7	S8	S9
R	0	0.2	0.4	0.6

6063-T6 AL ALLOY

Load Range = 585 kg

Crack Growth Rate Vs Number of Cycle
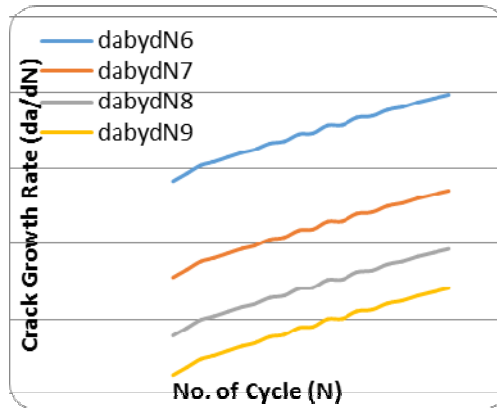
Figure 6: Number of Cycles Vs Crack Growth Rate

TEST	S6	S7	S8	S9
R	0	0.2	0.4	0.6

6063-T6 AL ALLOY

Load Range = 585 kg

Log Crack Growth Rate Vs Log Stress Intensity Range
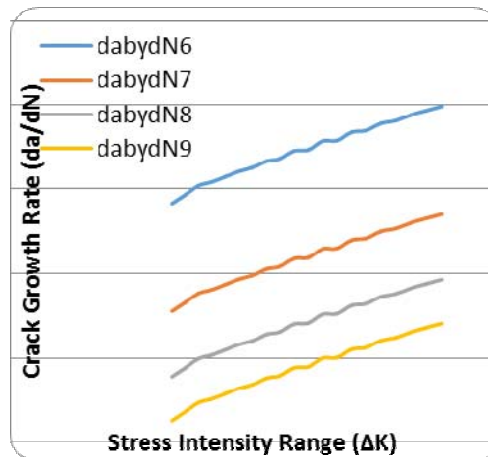
Figure 7: Stress Intensity range Vs Crack Growth Rate

Test	S6	S7	S8	S9
R	0	0.2	0.4	0.6

6063-T6 AL ALLOY

Load Range = 585 kg

Log Crack Growth Rate Vs Log Effectivestress Intensity Range
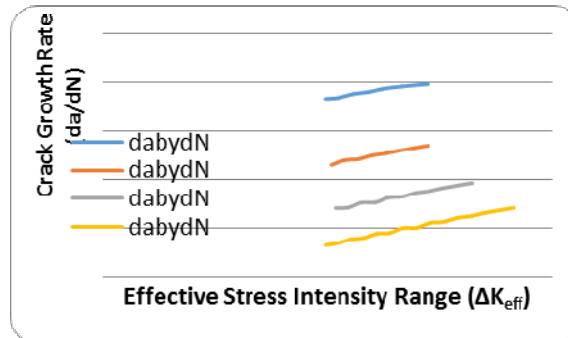
Figure 8: Effective Stress Intensity range Vs Crack Growth Rate

Test	S6	S7	S8	S9
R	0	0.2	0.4	0.6
U	.69	.79	.90	1.03

4. RESULTS & DISCUSSION

To evaluate constants C & m the maximum stress Vs log C and stress range Vs m curves were used.

Constant C was plotted on log scale with maximum stress on linear scale. Slopes & intercepts give constants S_1 and S_2 respectively. Straight line passing through maximum number of points has been drawn for each model. Slope of the lines gives constant T_1 & intercepts of the lines gives constant T_2. The constants evaluated are given in Table no (4) for different models.

Table no 4: Constants for 6063-T6 Al Alloy

Model	$\sigma_m + S_1(\log C) + S_2 = 0$		$\Delta\sigma + T_1(m) + T_2 = 0$	
	Constant S_1	Constant S_2	Constant T_1	Constant T_2
Paris	3.70	30.85	-3.25	6.49
Elber	2.95	21.89	-3.46	7.19
Walker	3.11	25.29	-2.08	1.68
Foreman	4.18	6.66	-3.25	6.49

5. CONCLUSIONS

Variation in load range affects the crack growth rate constant m, i.e. constant m had the higher variation when load range was varying. For constant load range its variation was negligible constant C was almost constant at variable load range.

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Variation of maximum load affects constant C, i.e. constant C in found to vary with maximum load. At constant maximum load it is found to be almost constant.

Walker model modifies the constants m of Paris model, by introducing a new constant n. This constant n is the exponent of maximum stress intensity K_m modification introduced in constant C is negligible.

Foreman model modifies the constant C of Paris model by introducing the fracture toughness K_f of the material. It does not affect constant m.

Elber model introduces a slight modification in Paris model for both constants C & m.

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APPENDIX A

Symbols	Description
a	Crack length
A	A constant
B	Specimen thickness
C	Constant of crack growth equation
d1, d2, d3…d7	Constants of seven point method
$\frac{da}{dN}$	Crack growth rate
D	A constant
E	Young's modulus of elasticity
f	A variable factor
K	Stress intensity factor
K_C	Fracture toughness of the material
K_m	Maximum stress intensity factor of a cycle
K_n	Minimum stress intensity factor of a cycle
K_o	Optimum stress intensity factor of a cycle
K_t	Threshold stress intensity factor
ΔK	Stress intensity range
ΔK_Θ	Effective stress intensity range
m	Exponent of crack growth rate equation
n	Exponent of crack growth rate equation
N	Number of cycles
N_f	Number of cycles to failure
N_p	Number of readings in a set of readings
p	A ratio $\frac{\Delta\sigma}{\sigma_p}$

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P	Simple load
P_a	Average load in a cycle
P_m	Maximum load in a cycle
P_n	Minimum load in a cycle
ΔP	Load range in a CAL cycle
R	Stress ratio in CAL cycle $(\frac{P_m}{P_n})$
S_1	Relationship constant
S_2	Relationship constant
T_1	Relationship constant
T_2	Relationship constant

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