THE EFFECT OF R-RATIO AND INITIAL ANGLE OF CRACK ON FATIGUE PARAMETERS IN FATIGUE CRACK GROWTH UNDER MIXED MODE I-III

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Abstract:
This study considers the numerical and experimental fatigue crack growth under mixed mode I-III in a holed plate with edge crack (Modified Compact Tension Specimens) which made of aluminum alloy 7017 under simple tensile-tension loading. R-ratio (0.01, 0.02) and first angle of crack $(30^\circ, 45^\circ, 60^\circ)$ are variable. Their effects on Stress Intensity Factor (K_I, K_{III}) and J-Integral (J_I, J_{III}) for both of Fracture mode during the fatigue crack growth has been studied. Also the fatigue crack growth vs. stress intensity factor and J-Integral diagrams has been found and compared to experimental results which show that enhancement in crack angle issues augmentation in mode III and reduction in mode I. In a constant angle, during the crack growth the effect of Mode III will decrease and Mode I will increase. Finally by enhancement in first angle in same crack length, the fatigue crack growth life will increase.

Keywords: Mixed-mode I-III; plate with edge crack; stress intensity factor; J-Integral; fatigue crack growth.

1. Introduction

There is more concentration on the factors with cases of crack mode-I. Although, most of the fatigue crack growth phenomenon place with mixed-mode.one of them is mixed-mode I-III which will be replaced by mode I in a simple case. There are two major factors in fracture of sample under mixed-mode loading including fatigue crack growth life and crack growth path.

There are different standards to find crack growth path under mixed-mode loading [1] and [2]. In these papers the fatigue crack growth standards are studied by using Stress Intensity Factor for modes I, II and III in brittle materials has been studied. Li [3] checked the fatigue crack growth in mixed-mode I-III under simple tensile loading on CT specimen experimentally and the quantities of stress intensity factor was calculated by ANSYS. Yates and Miller [4] introduce a model for fatigue crack growth under mixed-mode I-III. The samples were loaded on four points and crack was place by B angle to the bended plate. The mixed-loading causes bending during torsion. The results show that, the start of crack growth in mode-I is depend on crack tip opening and propagation path. Pook [5] studied the crack behavior in fatigue crack growth in the sample of 3-point bending under mixed-mode I-III. The steel samples show the changes mostly by mode I. At first, the continuous-changes in mode-I has been observed that was accompanied by lightly spinning crack tip. At the end it becomes perpendicular to sample axel. Feng et al [6] used standard which was based on strain energy density. They studied the effect of torsion and tensile mixed-loading on fatigue crack propagation path in every three modes. Kimachi [7] found the fatigue crack growth in Elastic-Plastic materials under torsion-tensile loading experimentally. The results reviewed by J-Integral and finite element method and they show that J-integral is a appropriate way to examine fracture mechanics in mode I-III for elastic-plastic materials. Rozumek and Macha [8] did experiments on fatigue crack growth in Mixed-Mode I-III for Steel 18G2A. Their sample bar was a rectangle (width of 8 mm) with a 60 Degrees crack. They used MZGS-100 to get a mixed-mode. It applies bending and torsion loads at the same time. All experiments have been done by 7.92 and 17.19 N.m torque on AL and Steel respectively. Load ratios were -1 and -0.5 and R=0.To find J-integral values they used 2D finite element method under plane stress in Franc2D. In all experiments they observed that by changing the load rate(torsion to bending) from 0.53 to 1.73 the crack growth rate will increase. Then (changes of stress intensity) ΔK and (changes of J-Integral) ΔJ have been processed and diagram of crack growth of crack growth magnitude vs. number of loading was made. Tanaka [9] used Paris' Law (it works with stress intensity factor K_{eff}) find the crack growth rate. The cylindrical steel samples which were used for fatigue experiment, had circular cracks. The torsion load made these results in the way that changes in effective stress intensity factor and J-Integral was compared.

In this paper Changes in J-integral, Stress intensity factors by variation of crack angle, loading ratio and crack growth rate has been studied.

2. Theoretical Consideration

The description of stress distribution on Mode-I around crack front is:

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\varphi}{2}\left(1 - \sin\frac{\varphi}{2}\sin\frac{3\varphi}{2}\right)$$
$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\varphi}{2}\left(1 + \sin\frac{\varphi}{2}\sin\frac{3\varphi}{2}\right)$$
$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos\frac{\varphi}{2}\sin\frac{\varphi}{2}\cos\frac{3\varphi}{2} \quad (1)$$

For mode III we have:

$$\tau_{xz} = -\frac{K_{III}}{\sqrt{2r}} \sin\frac{\varphi}{2}$$
$$\tau_{yz} = \frac{K_{III}}{\sqrt{2\pi r}} \cos\frac{\varphi}{2} \quad (2)$$

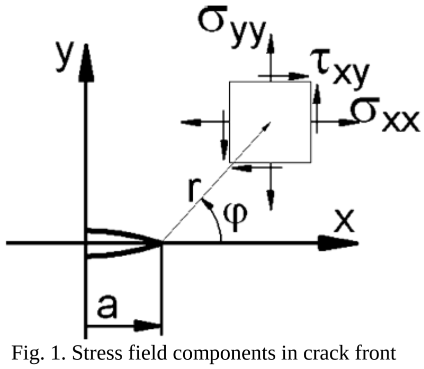

Fig. 1. Stress field components in crack front

Stress intensity coefficients can be found by stress magnitude in different modes. For modes I and III (K_I, K_{III}) can be found from:

$$K_I = \lim_{r\to 0} \sigma_{xx} \sqrt{2\pi r}(\varphi = 0)$$
$$K_{III} = \lim_{r\to 0} \tau_{yz} \sqrt{2\pi r}(\varphi = 0) \quad (3)$$

Fatigue crack growth rate can be calculated by range of effective stress intensity factor in this way [10]:

$$\frac{da}{dN} = C(\Delta K_{eff})^m \tag{4}$$

In the eq.(4) $\Delta K_{eff} = \sqrt{\Delta K_I^2 + \Delta K_{III}^2}$, $\Delta K = K_{\mathbf{max}} - K_{\mathbf{min}}$ and C,m are constant which are found by experiments. For mixed-mode loading (I-III) we have J-integral by [7]:

$$J_{I+III} = J_I + J_{III} \tag{5}$$

The J-integral for mode I and III is defined by:

$$J_I = \frac{1-\upsilon^2}{E} K_I^2$$
$$J_{III} = \frac{1+\upsilon}{E} K_{III}^2 \tag{6}$$

Which υ is Poisson's ratio and E is Young's modulus.
Fatigue crack growth rate in mixed-mode I-III by using J-integral can be calculated by [11]:

$$\frac{da}{dN} = \frac{B(\frac{\Delta J}{J_0})^n}{(1-R)^2 J_{Ic} - \Delta J} \tag{7}$$

Which $\Delta J = J_{\mathbf{max}} - J_{\mathbf{min}}$, J_{Ic} is critical value of the J integral and $J_0 = 1\ Mpa.m$ is initial value of J-integral) in order to create meaningful physical units for coefficient B. B and n determined experimentally.
Specimen and experimental procedure
The specimen is an aluminum plate with edge crack, initial length of 20 mm and 8mm width. Initial crack angle $\theta = (30^\circ, 45^\circ, 60^\circ)$ and R=0.01, 0.2 are variable parameters.
We have a tensile- tension load with magnitude of 10 KN and 5Hz frequency.
The material which used to be in fatigue experiments is aluminum alloy. Aluminum alloys used in aerospace industries. For checking mechanical properties and chemical composition, the sample has been tested by Mythology Lab of Sharif University. To evaluate the chemical composition and finding the equivalent alloy standard we used Quantometric testing and reference standard ASTME 1251-07.The used alloy, chemical composition properties are in table 1.

Table 1. Chemical composition (in wt%) of aluminum alloy

Al	**Si**	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Ni**	**Zn**
Base	0.109	0.217	0.084	0.217	2.34	0.127	0.004	4.51
Ti	**Be**	**Pb**	**Sb**	**Sn**	**V**	**Zr**	**---**	**---**
0.015	0.003	0.005	0.002	0.007	0.004	0.14	---	---

The above chemical composition, is same as aluminum 7017 in American standard AA. We used tensile-test and the reference standard ASTME 8M-09 to fine mechanical properties. They are in table 2:

Tabel 2. Monotonic mechanical properties of aluminum 7017

Yield strength	$\sigma_{YS}(Mpa)$	495
Ultimate stress	$\sigma_{US}(Mpa)$	524
Young's modulus	$E(Gpa)$	70
Poisson's ratio	υ	0.32

Fig. (3) shows the stress-strain diagram for this sample and we can see the built samples with crack specifications in fig. (4).

Fig. 3. Strain-stress diagram for AL 7017

The fracture toughness is $K_{Ic} = 26.2MPa\sqrt{m}$

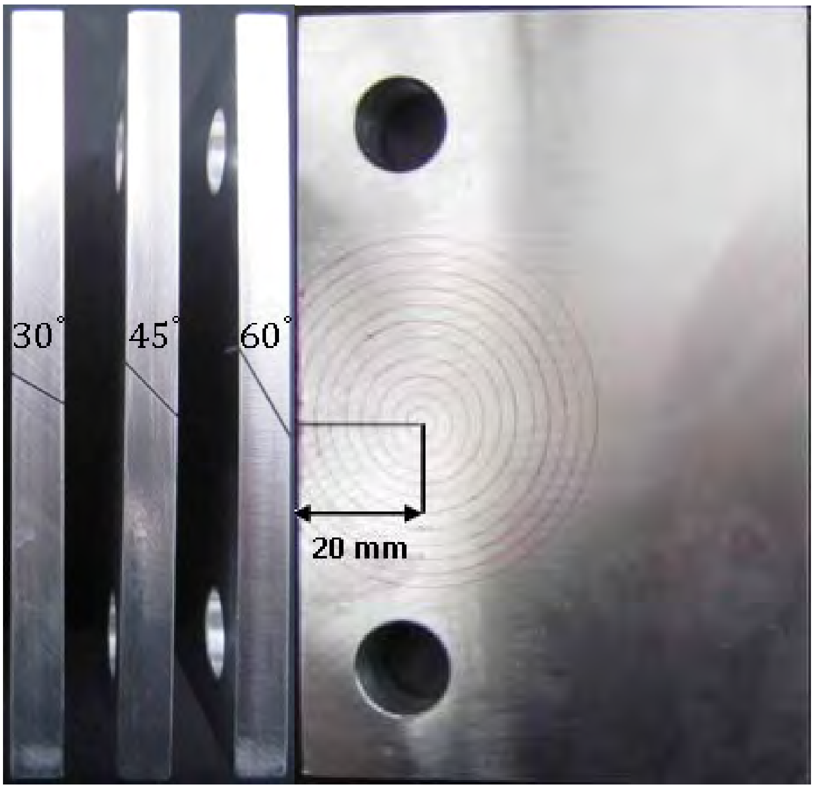

Fig. 4. Specimens test

We can see the results which comes from the experiment for loading ratio R=0.01 in fig (5).The diagram is for Initial crack length Changes vs. number of cycles.

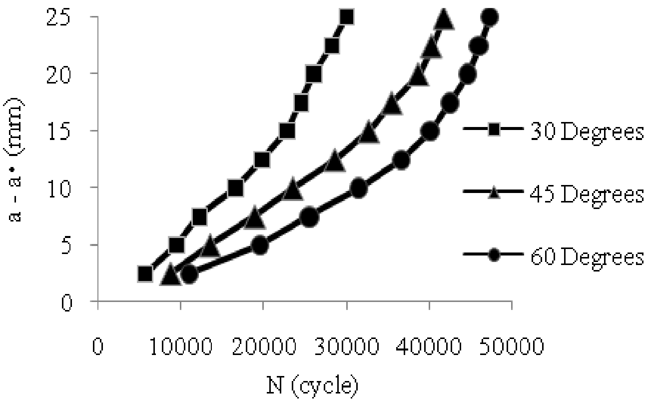

Fig. 5. Experimental results for initial crack length changes vs. number of cycles in different initial crack angles with R=0.01

3. Numerical Modeling

This software has two major parts: OSM is used to be for initial modeling without any crack. Also making crack, model meshing, applying the boundary conditions, crack growth analysis and propagation path calculated by FRANC3D. In order to perform numerical calculations it is necessary to introduce material data such as the yield point, young's modulus, ultimate stress, Poisson's ratio, material density, Critical value into the FRANC3D software.

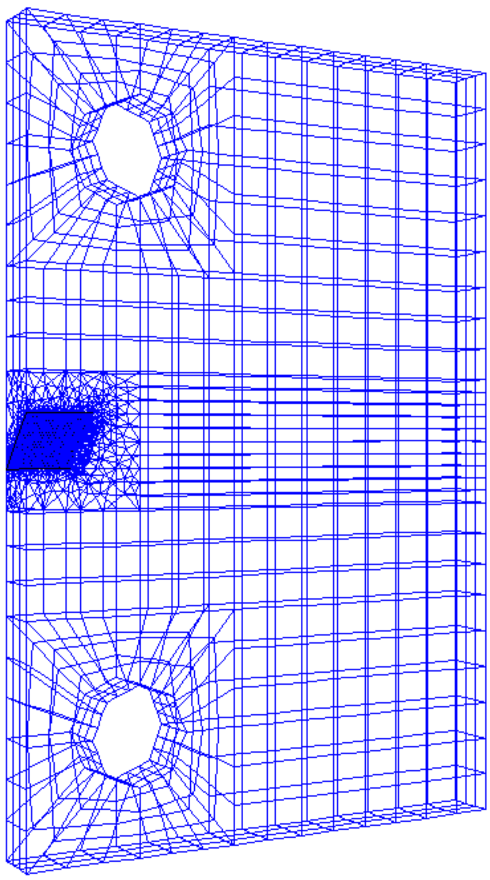

Fig. 6. The cracked modeled with angle of 45°

The mean stress intensity factor K and J-integral values in crack front for mode I-III during 8 stages, one millimeter steps for crack growth has been shown. As we observed during crack growth steps, mode I become dominant compared with mode III.

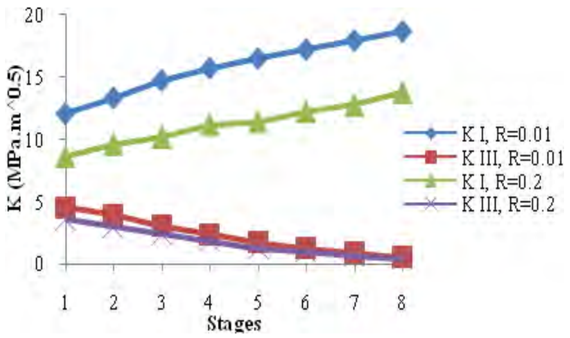

Fig. 7. Stress intensity factor mean for Mode I-III $(\theta = 30^{\circ})$

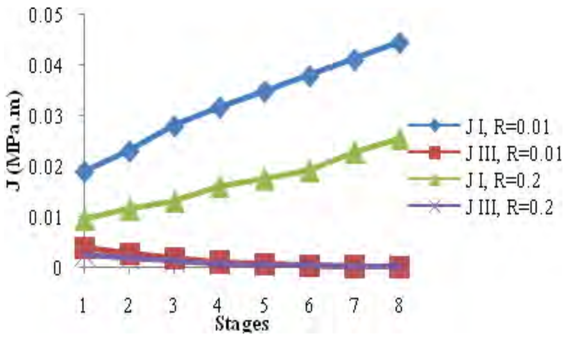

Fig. 8. J-integral mean values for mode I-III $(\theta = 30^{\circ})$

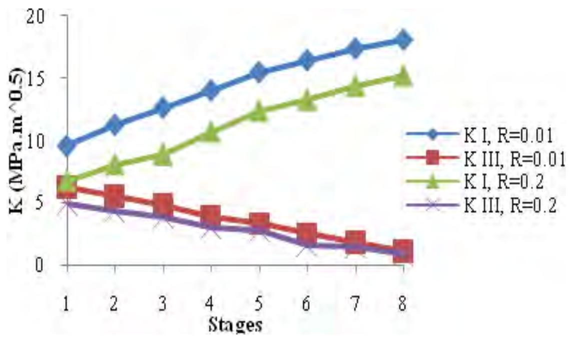

Fig. 9. Stress intensity factor mean for Mode I-III $(\theta = 45^{\circ})$

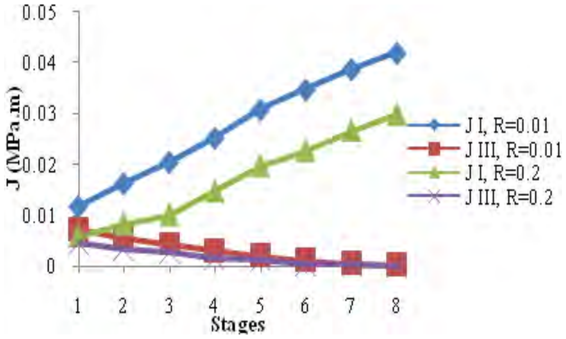

Fig. 10. J-integral mean values for mode I-III $(\theta = 45^{\circ})$

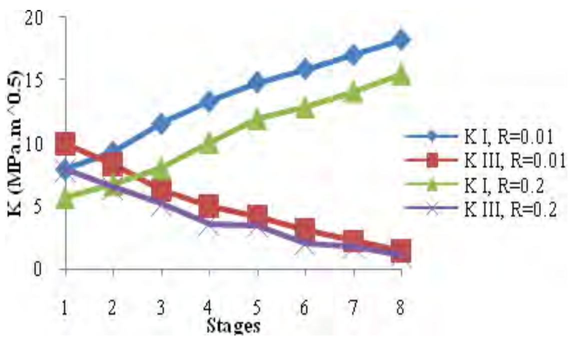

Fig. 11. Stress intensity factor mean for Mode I-III $(\theta = 60^{\circ})$

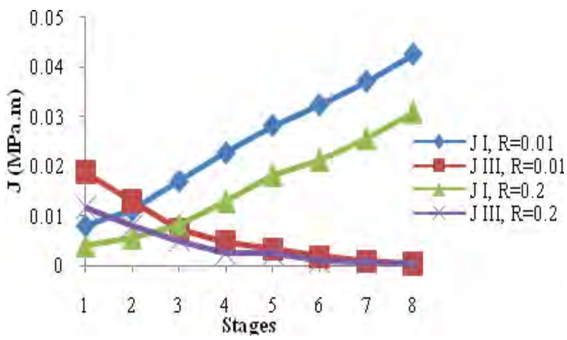

Fig. 12. J-integral mean values for mode I-III $(\theta = 60^{\circ})$

4. Fatigue crack growth

In figures 13 through 18, the fatigue crack growth rate vs. effective stress intensity factor and J-integral in mode I-III has been shown in these diagrams.

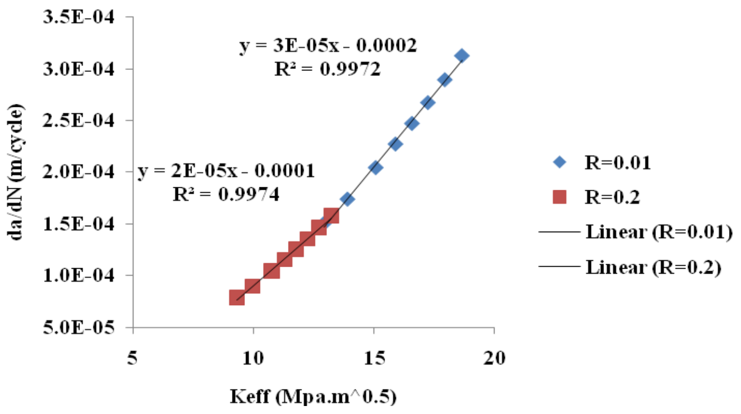

Fig. 13. Fatigue crack growth rate vs. effective stress intensity factor for $(\theta = 30^{\circ})$

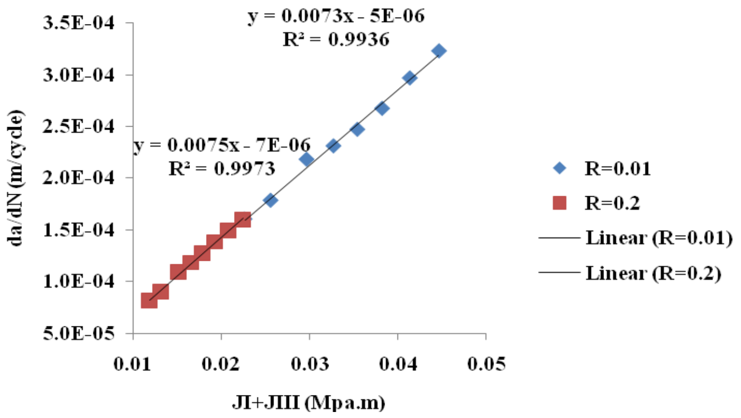

Fig. 14. Fatigue crack growth rate vs. J-integral for $(\theta = 30^{\circ})$

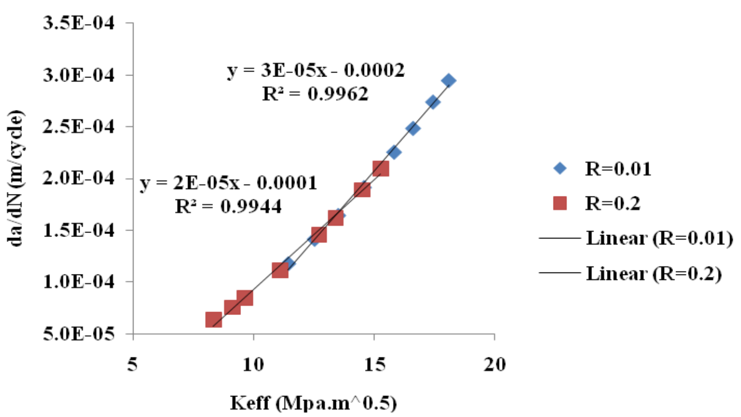

Fig. 15. Fatigue crack growth rate vs. effective stress intensity factor for $(\theta = 45^{\circ})$

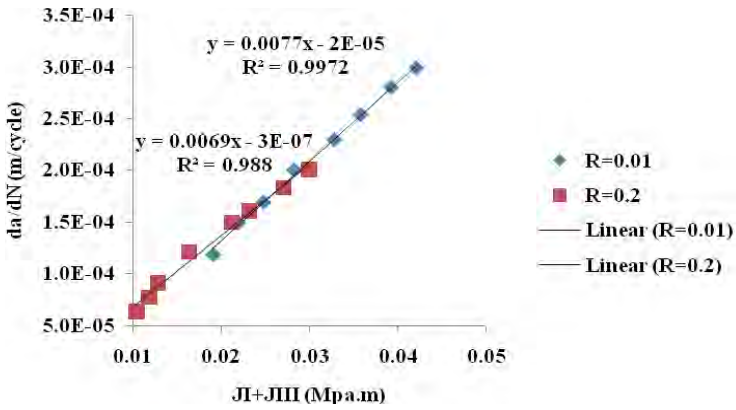

Fig. 16. Fatigue crack growth rate vs. J-integral for $(\theta = 45^{\circ})$

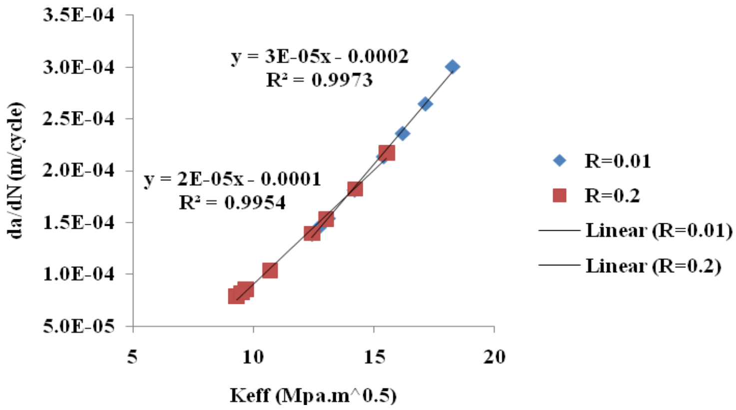

Fig. 17. Fatigue crack growth rate vs. effective stress intensity factor for $(\theta = 60^{\circ})$

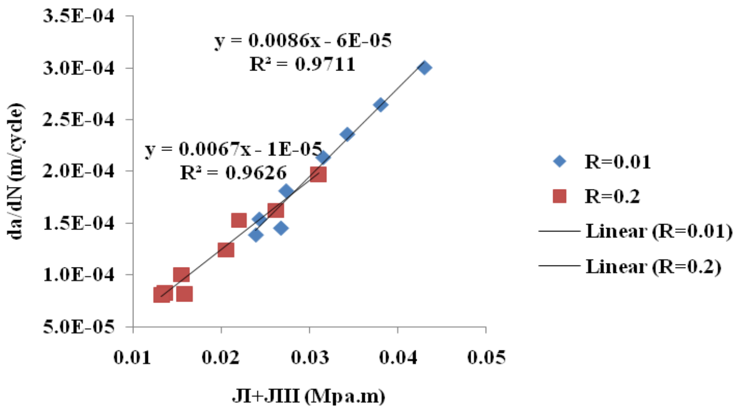

Fig. 18. Fatigue crack growth rate vs. J-integral for $(\theta = 60^{\circ})$

5. Discussion

Based on what we talk about before, we can discuss on these cases:
By more concentration on fig 5 it is obvious that by enhancement in crack angle, the number of cycles for a certain crack growth will increase. This happens because of less effect of mode I and more influence of mode III. On the other hand, we observed that by crack growth the same process happens in all states. Rotation in crack front to become perpendicular to loading and pure mode I causes this phenomenon which does not include any effect of mode III.
The perceptions on changes in mean stress intensity coefficient show that K was more than K most of the time. There is a contrariwise behavior for initial moments of crack growth in angles more than 60°. Nevertheless in all of them, during enhancement of K_I, K_{III} becomes less to reach zero.
Studies on J-Integral show that we can find crack growth rate based on initial crack angle, loading ratios, changes in stress intensity factor and J-integral by using fig 7 through 12.Also in figures 13-18 the crack growth is a linear function of changes in effective stress intensity factor and J-integral. Be careful that in these figures (13-18) the values of ΔK and ΔJ are very small in compare with K_{Ic} and J_{Ic} and they are only for the fist 8 steps of crack growth.

6. Conclusions

1) To define the fatigue crack growth rate in elastic-plastic materials, it is better to use J-integral instead of stress intensity factor
2) During crack growth, (K_I, J_I) will increase and (K_{III}, J_{III}) will decrease. So the crack will growth in the way that Mode I is dominant.
3) By crack angle enhancement, (K_{III}, J_{III}) will increase while (K_I, J_I) are decreasing.
4) Whereas argumentation in crack angle, fatigue cracks growth life will increase.

References

[1] Richard, H. A. (2003): *Theoretical crack path determination*, International Conference on Fatigue Crack Paths, Parma, **15**.
[2] Liu, S.; Chao, Y. J.; Zhu, X. K. (2004): *Tensile-shear transition in mixed mode I/III fracture*, International Journal of Solids and Structures, **41**, pp. 6147-6172.
[3] Li, H. F.; Qian, C. F. (2010): *Experimental study of I + III mixed mode fatigue crack transformation propagation*, Fatigue Fracture Engineering Material Structure, **34**,pp. 53-59.
[4] Yates, J. R.; Miller, K. J. (1989): *Mixed mode (I+III) fatigue thresholds in a forging steel*, Fatigue and Fracture of Engineering Material and Structure, **12**, pp. 259–270.
[5] Pook, L. P. (1985): *The fatigue crack direction and threshold behavior of mild steel under mixed mode I and III loading*, International Journal of Fatigue, **7**, pp. 21–30.
[6] Feng, M.; Jiang, Y.; Ding, F. (2006): *A study of loading path influence on fatigue crack growth under combined loading*, International Journal of Fatigue, **28**, pp. 19-27.
[7] Kimachi, H.; Tanaka, K.; Akiniwa, Y.; Yu, H. (2003): *Elastic-plastic fatigue crack propagation under mixed-mode (I+III) cyclic torsion and axial loading*, International Conference on Fatigue Crack Paths, Parma, **8**.
[8] Macha, E.; Rozumek, D. (2006): *Elastic–plastic fatigue crack growth in 18G2A steel under proportional bending with torsion loading*, Fatigue and Fracture of Engineering Material and Structure, **29**, pp. 135–144.
[9] Tanaka, K. (1983): *The cyclic J-integral as a criterion for fatigue crack growth*, International Journal of Fatigue, **22**, pp. 91–104.
[10] De freitas, M.; Reis, L.; da Fonte, M.; Li, B. (2011): *Effect of steady torsion on fatigue crack initiation and propagation under rotating bending: Multiaxial fatigue and mixed-mode cracking*, Engineering Fracture Mechanics, **78**, pp. 826–835.
[11] Rozumek, D. (2003): *Fatigue crack growth of notched members under bending for different stress ratios*, Material Engineering, Zilina, **10**, pp. 1-8.