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CRACK GROWTH CURVE CONSTRUCTION OF 7050 T7451 ALUMINUM ALLOY FROM FRACTOGRAPHIC ANALYSIS

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ABSTRACT

Results of crack growth curve of 7050 T7451 aluminum alloy from fractographic analysis is presented on this paper. Purpose of this study is to construct linear portion of crack growth curve (da/dN vs ΔK) by evaluation fracture surface of constant amplitude axial fatigue tests. This approach leads to decrease number of tests, consumed time and raw material usage. On the other hand, it is applicable for components of aerospace vehicles. For this objectives, striation measurements from fracture surface of cylindrical axial endurance test specimens were applied by scanning electron microscope (SEM). Linear portion (Paris and Erdogan Law) of crack growth curve (da/dN vs ΔK) for 7050 T7451 aluminum alloy was constructed by using striation measurements data and axial fatigue test loads. Constructed crack growth curve was compatible with the literature data and crack growth tests of 7050 T7451 results.

INTRODUCTION

Design purposes mechanical tests either static or dynamic have to be done in range of specific material scale to full scale in aerospace industry. They are start with coupon level which is to determine material properties and continue with element level, component level and full scale vehicle tests in order to evaluate design, safety and performance requirements. Mechanical tests are applied for a various analytical data such as S-N curve or crack growth curve (da/dN *vs ΔK).* Although, these curves are mandatory for aerospace vehicle design, every type of curves increase number of tests, consumed time and raw material usage. Therefore, obtaining meaningful data from each test specimen reduce the negative effects. Fractographic analysis is suitable for this purposes. In literature, fractographic analysis of crack growth test under variable amplitude was examined.[Schjive, 1998]. Load time history reconstruction of component under variable load was applied by the help of fractographic examination [Bogdanowicz, Kocańda, & Torzewski, 2009]. Numerical method between crack growth rate and crack depth was proposed and it was validated by striation measurements [Mann, Twite, Watson, & Burke, 2015].Fractography based life assumption of crack initiation and propagation at aircraft components was made.[Wanhill, 2017]. However, none of research focused on crack growth curve construction by measuring striations for specific material data without geometry or combined loading.

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So, this paper provided guidelines that construct to crack growth curve by evaluating fractographic analysis of tested cylindrical specimens for endurance tests without the crack growth tests.

Fatigue Mechanism

Before methodology and data analysis, fatigue in metals and crack growth stages must be explained. Fatigue mechanism starts when crack nucleation and propagation occur as buildup of slip movements in nanoscale under dynamic loading. Some grains at the surface have more tendency to slip movement since their one side is open to environmental conditions such as gaseous (oxygen) or liquid (water). Therefore, these grains are become favorable to plastic deformation. Slip movements occur on surface grains through inner or outer side of the material. After crack initiations stage was completed, crack growth in metals occurs in three stages which was shown in Figure 1.

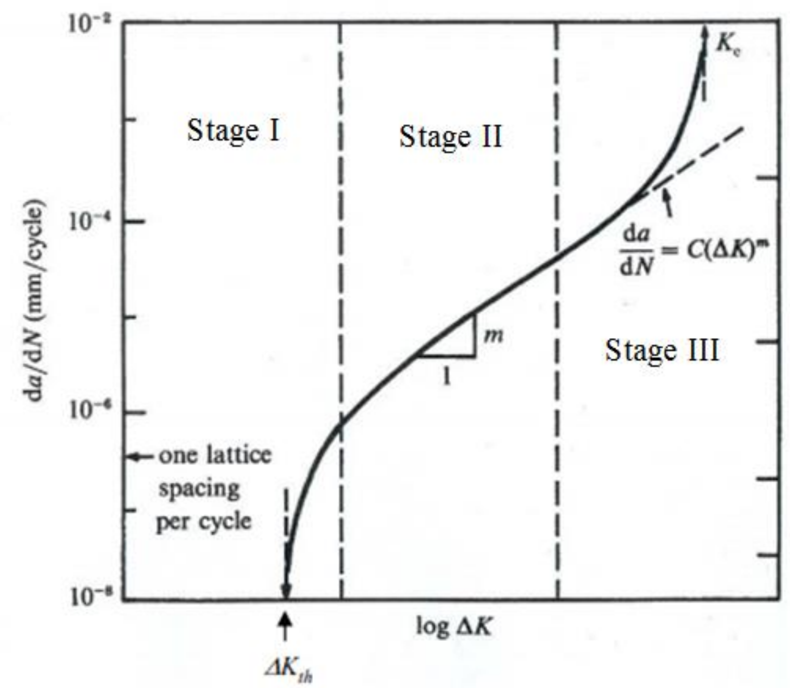

Figure 1. Crack Growth stages

Initiated crack propagates along high shear stress plane in Stage I which is short crack propagation. Propagation of crack slow down by microstructural barriers such as grain boundary or precipitation. During Stage II, stress intensity factor (K) rises and slip movements occurs in different planes at the crack tip. Crack propagation follows perpendicular direction to the loading. Micron scale fatigue striations can be observed during crack propagation in Stage II. [Hattenberg, 2006]. These are proof of fatigue failure which can be find out from fracture surface. However, fatigue striations couldn't be observed throughout crack propagation region. This is resulting from insufficient resolution of scanning method and incapable ductility at crack tip for fatigue striation formation. Crack propagation in Stage II can be explained by a plastic crack blunting which is shown Figure.2. Firstly, load concentrates slip at the sharp crack tip (Figure.2a) to form twin notch at 45^{o} to crack front under tensile loading (Figure.2b). Not only crack elongate by shear loading but also its tip becomes blunt when crack mouth reach the maximum extension (Figure.2c). When loading direction turn to reverse side that is compression, slip movement change reverse direction at end of crack but not at the crack tip (Figure.2d). Fresh crack surfaces are formed under compressive loading due to crash of crack faces (Figure.2e). This loop is repeated until dynamic loading stops or final fracture occurs [Dieter, 1962]. Moreover, linear behavior during this loop in crack propagation stage was firstly proposed by Paris and Erdogan as power rule.

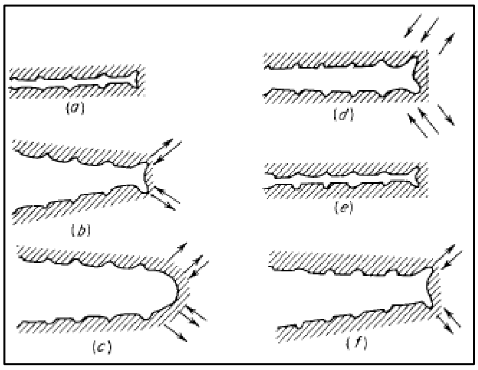

Figure 2. Fatigue striation stages

Accelerated and unstable crack growth occurs during Stage III which is final part of crack propagation. Stress intensity factor reaches fracture toughness value at the end of this stage. Final fracture is observed beyond fracture toughness. Final fracture happen depend on material property either ductile or brittle. In any case, final fracture region is clearly distinct from fatigue crack region. Ratio of the fatigue crack region and final fracture region is directly related with loading level. Fatigue crack region increases with lower fatigue loading. Because crack have to become longer in order to stress intensity factor reaches to fracture toughness.

Basically one striation represent one cycle loading therefore, crack growth (da/dN) behavior could be determined by using striation analysis and stress intensity factor (ΔK) [Broek, 1988].However, only linear portion of crack growth curve which was Stage II in Figure 1 could be plotted depend on striation analysis. Accordingly, linear region of crack growth curve of 7050 T7451 was constructed by analyzing fatigue striation data in this study.

METHOD

Methodology of the research was consist of 3 main steps.

1. Endurance fatigue tests
2. Fractographic Analysis of endurance fatigue test specimens
3. Crack growth tests

Endurance Fatigue Tests

Endurance fatigue tests were force controlled axial fatigue tests under constant amplitude that were conducted to cylindrical specimens in order to construct S-N curve. Cylindrical fatigue test specimen was shown in Figure 3. According to ASTM E-466, cylindrical specimens were manufactured and endurance fatigue tests were conducted. Sinusoidal constant amplitude loading was applied to specimens in fatigue tests until failure.

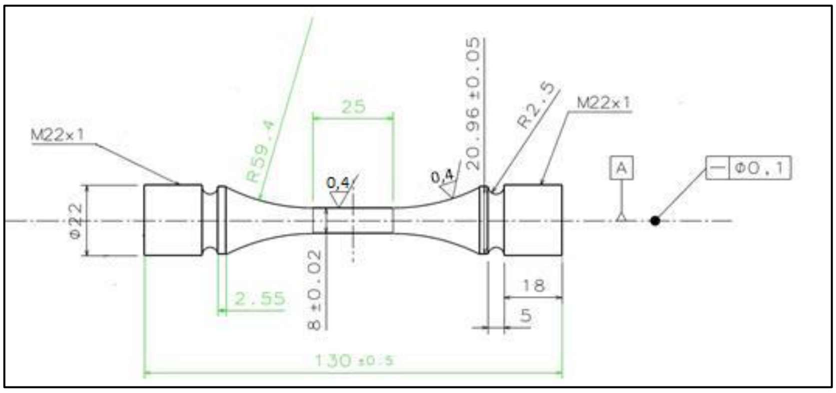

Figure 3. Cylindrical test specimen drawing

Endurance tests was applied at stress ratio (R) equals to zero which specimens were loaded in tension direction then all loads were relieved. Stress levels for the endurance fatigue tests were indicated in Table 1.

$$R = \frac{\sigma min}{\sigma max} \quad \text{Equation (1)}$$

Stress Levels (σmax)
300
240
220
210
170
165
165
150

Table 1. Stress levels of the endurance fatigue tests

Fractographic Analysis of Endurance Fatigue Test Specimens

After specimens were failed at endurance fatigue test, fracture surfaces of them were examined by scanning electron microscopy (SEM). Striation analysis was performed from fracture surfaces by measuring striation width at certain distance away from crack initiation point by SEM. Striation widths were measured at least two different regions from each examined specimen according to Figure 4.

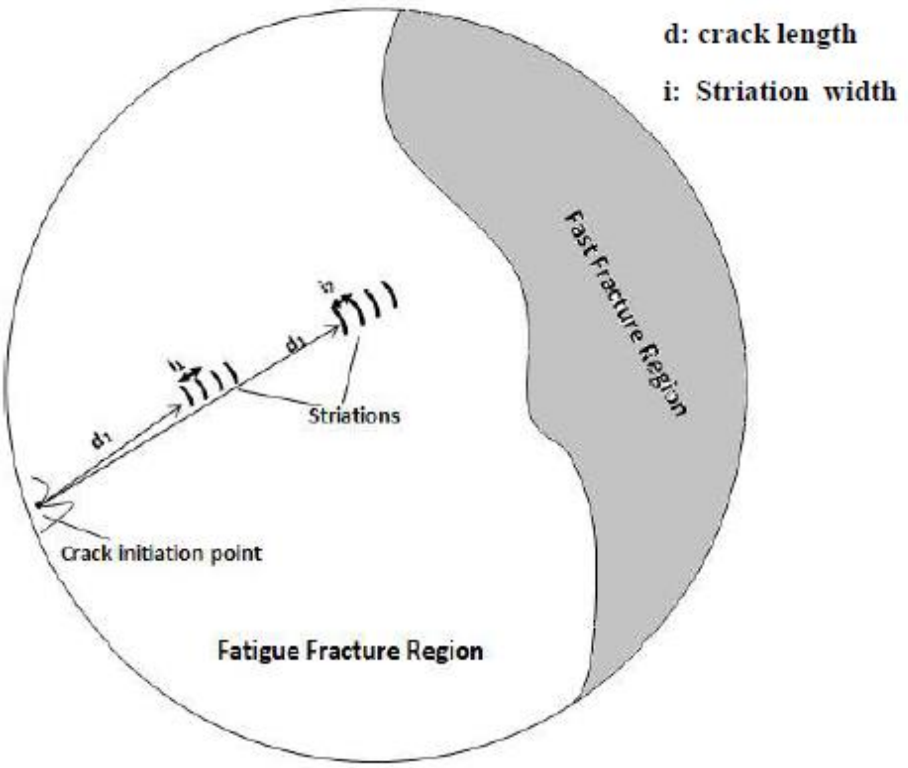

Figure 4. Striation width measurement method

Striation widths and their distance away from crack origin were taken at 19 different regions from 8 specimen`s fracture surfaces. Stress intensity factors (ΔK) were calculated for each striation width according to Equation 2 and 3. After striation analysis and ΔK calculations, stress intensity factor (ΔK) vs da/dN was plotted in order to examine crack growth behavior of 7050 T7451 aluminum alloy.

$$\Delta K = Kmax - Kmin \qquad \text{Equation (2)}$$

$$\Delta K = \sigma_{max}\sqrt{\pi a} - \sigma_{min}\sqrt{\pi a} \qquad \text{Equation (3)}$$

Crack Growth Tests

Crack growth tests were executed to verify fractographic analysis approach, therefore, da/dN vs ΔK curves was constructed depend on both crack growth tests and fractographic analysis. Two single edge crack tension specimens (SET) were tested according to ASTM E-647 as crack growth tests. Besides, geometry, dimension and manufacturing process of the specimen was based on ASTM E-647. Drawing of SET specimen was indicated in Figure 5.

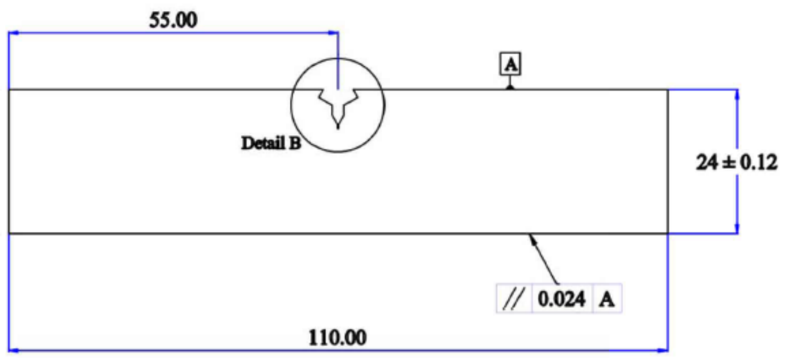

Figure 5. Drawing of single edge crack tension specimens (SET)

Stress intensity factor (ΔK) was calculated by Equation 4 to Equation 7. These equations are valid for 0<α<1.

$$\Delta K = [\Delta P/(B\sqrt{W})]F \qquad \text{Equation (4)}$$

$$F = \alpha^{1/2}\,[1.4 + \alpha][1 - \alpha]^{1/2}\,G \qquad \text{Equation (5)}$$

$$G = 3.97 - 10.88\alpha + 26.25\alpha^2 - 38.9\alpha^3 + 30.15\alpha^4 - 9.27\alpha^5 \qquad \text{Equation (6)}$$

$$\alpha = a/W \qquad \text{Equation (7)}$$

Where;
a: crack length
W: width of the SET specimen

RESULTS & DISCUSSION

After endurance fatigue tests completed with respect to stress levels at Table1, fracture surface of the cylindrical specimens were analyzed by SEM and Digital microscope. Overview of the fracture surface was shown indicated in Figure 6. Crack initiation point is obviously noticeable that was shown with yellow arrow in Figure 6.

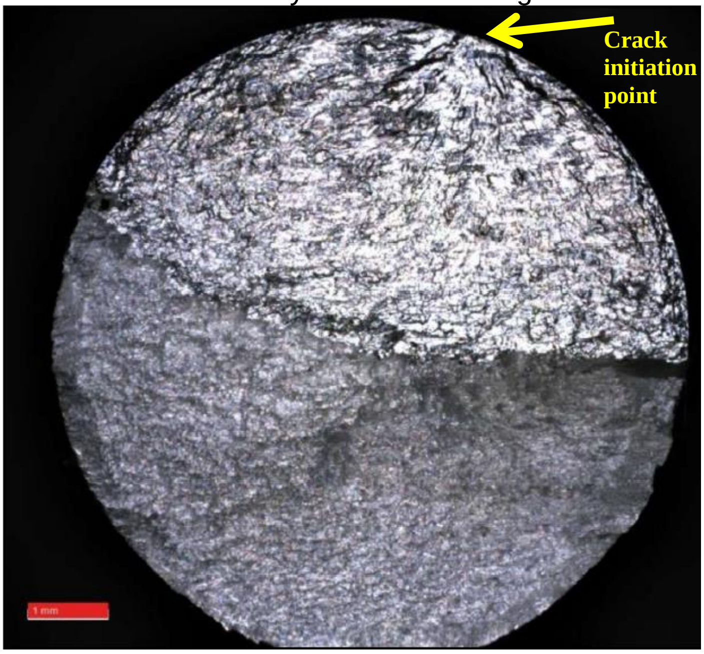

Figure 6. Fracture surface of failed test specimen specimen

Striation widths and distance away form crack initiation points were determined by SEM. At least 2 data were obtained by each specimen with respect to methodology which was indicated in Figure 4. In total, 19 different striation widths and positions from 8 specimen`s fracture surfaces were obtained. Example of striation position at Figure 7 and striation width at Figure 8 were shown.

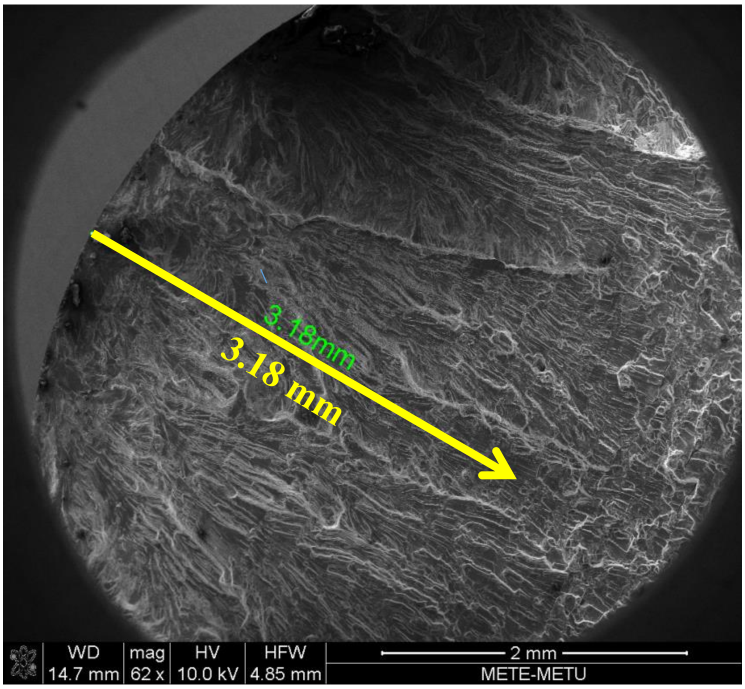

Figure 7. SEM image of distance away form crack initiation points

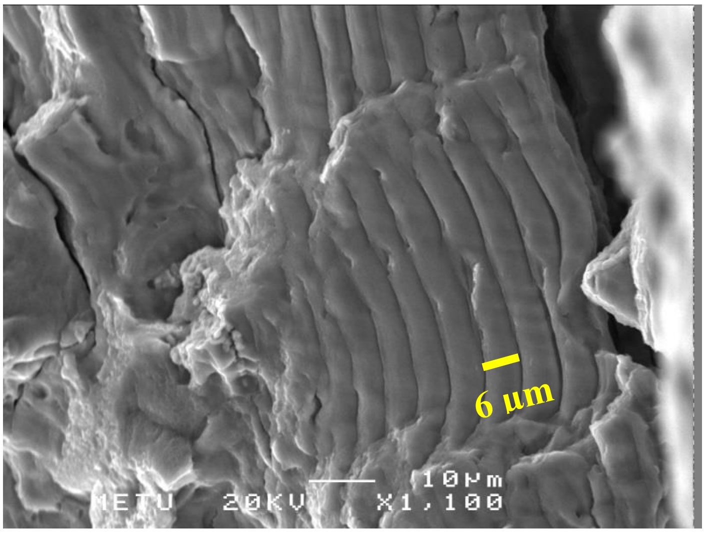

Figure 8. SEM image of straition width

Striations are observable only crack propagation region which is Stage 2 [Totten, 2008].Therefore, the approach by measuring striation width and position is only valid for linear portion of da/dN vs ΔK curve. Furthermore, crack closure effect is not concern during crack propagation region since high enough stress intensity factor (ΔK) [George,2008].

Although, striations occur during crack propagation, their specific visible region 10^{-6} to 10^{-7} m/cycles for aluminum alloys under constant amplitude at air condition [Hattenberg, 2006]. Striations from fracture surface of the specimens were shown in Figure 9.

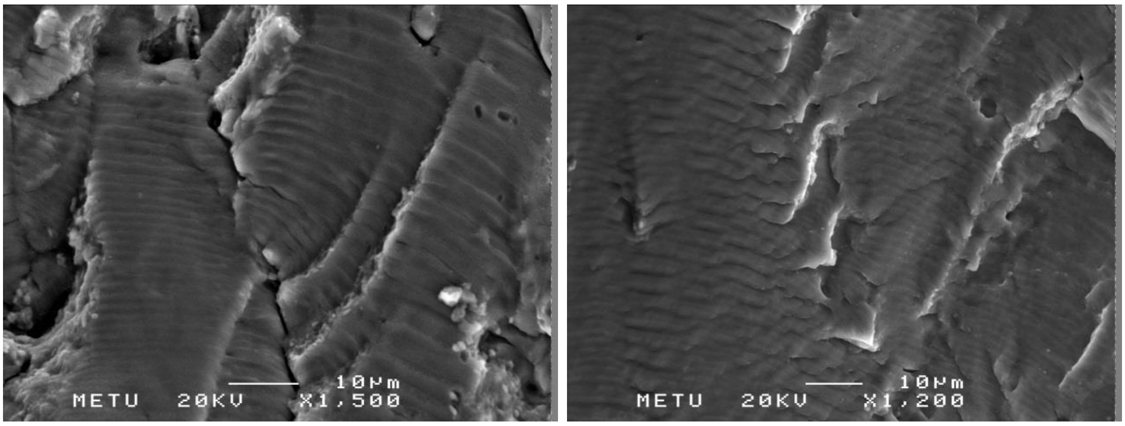

Figure 9 Striations from fracture surfaces

After examination of 8 cylindrical endurance fatigue specimens, stress intensity factor (ΔK) value was calculated for each measurement depend on Equation 2 and 3. All results of fractographic analysis and ΔK calculations were tabulated for plotting da/dN vs ΔK at Table 2.
In order to compare data obtained by striation measurements and calculations, crack growth tests were executed to 2 single edge crack tension specimens (SET) specimens according to ASTM E-647. Crack growth rate (da/dN) was measured by the help of crack gage and data acquisition system. Stress intensity factor (ΔK) was calculated by Equation 4 to 7.

Measurements		Stress (MPa)	ΔK (MPa.√m)
d (mm)	i or da/DN (μm)		
2.34	0.90	165	13.78
3.41	1.16	165	17.40
4.41	3.05	165	19.31
4.83	3.28	165	20.26
2.70	0.50	165	15.20
4.45	1.36	165	19.60
5.16	4.04	165	20.89
2.00	0.75	220	17.44
3.00	5.00	220	21.36
1.74	1.00	300	22.18
2.89	4.50	300	28.59
3.28	6.00	300	30.45
1.80	0.38	210	15.79
3.11	1.38	210	20.76
4.48	3.12	210	24.91
3.23	0.67	150	14.99
4.70	2.00	150	17.89
1.97	0.54	170	13.37
3.80	3.15	170	18.18

Table 2.Sitriation measurements & calculations

After endurance tests, fractographic analysis and crack growth tests, crack growth rate (da/dN) versus stress intensity factor (ΔK) was plotted depending on the striation measurements data and crack growth test results for 7050 T7451 aluminum alloy. Plotted da/dN curve represented only linear portion which is linear region since striation counting can be applied only this region [Totten, 2008].

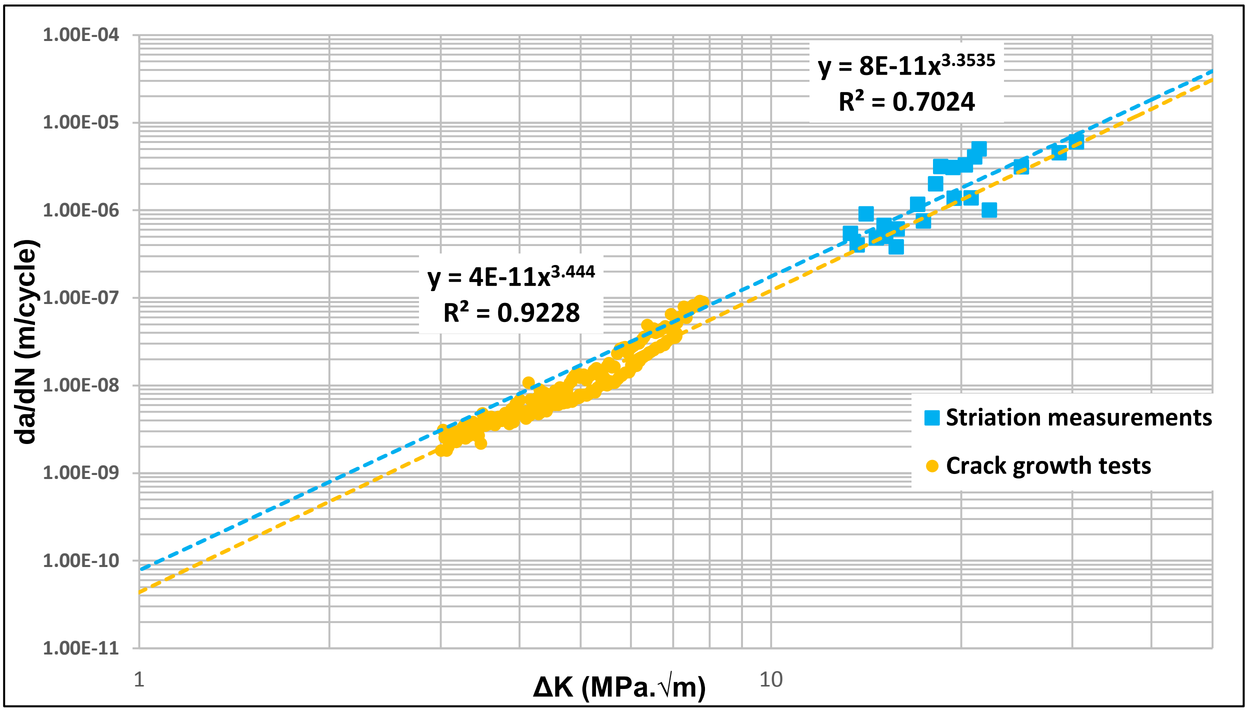

Figure 10. da/dN curves of 7050 T7451 Aluminum alloy

The obtained da/dN vs ΔK curves was compatible with the literature curves [Molent, Barter, & Jones, 2008]. On the other hand, slope of the curve were find out 3.35 for striation analysis. It was solid result because slope of the curve was found 3.44 from crack growth tests which is conventional way to crack growth curve construction. However, coefficient of determinations (R^2) for the striation measurements curve was low which was 0.70 while crack growth test results had 0.92 coefficient of determinations. Striation measurements had high scattering. Since intrinsic property of material and behavior of fatigue loading can affect the striation formation. For example, crack direction and more than one internal crack can be either increase or decrease striation widths. In addition to this, striation widths and position measured from SEM image. Therefore, resolution of the measurement was lower than crack gage.

CONCLUSION

In this study, alternative approach for crack growth curve construction was researched. Fractographic analysis were applied to fracture surface of endurance fatigue tested specimens. Besides crack growth tests were conducted so as to validate the alternative approach. Several advantages were taken with the proposed alternative way in this paper such as reduction in number of tests, consumed time and raw material usage. Four major conclusion were underlined from this study.

- The proposed alternative way for crack growth curve construction by using striation measurements only applicable for crack propagation stage of crack growth which is stage II. Because striations are only visible during crack propagation.
- Crack growth rate (da/dN) versus stress intensity factor (ΔK) curve obtained from striation measurements was compatible with the curve in the literature and the curve obtained from crack growth tests.
- Slopes of the curves were determined 3.35 and 3.44 obtained from striation measurements and crack growth tests respectively. Therefore, error between two curves was found 2.63%.
- Striation measurements had high scattered results since material property, fatigue loading and low resolution of image process cause a scattering. Therefore, coefficient of determinations (R^2) for da/dN vs ΔK curve for striation measurement was found 0.7 while da/dN vs ΔK curve for crack growth test results had 0.92 coefficient of determinations. However, the curve obtained from striation measurements was suitable for design purposes ,because it was more conservative, even if it had high scattering.

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