EXPERIMENTAL STUDY OF CRACK LENGTH MEASUREMENTS USING ELECTRICAL POTENTIAL DROP METHOD

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ABSTRACT
The paper present some main experimental results on fatigue crack detection using Electrical Potential Drop technique (EPD) under constant stress amplitude. The potential drop electrical circuit was designed and manufactured as well as tested using the flat fatigue specimens of aluminum alloy 7075-T6. The experimental analysis showed that the electrical potential drop circuit capable for detecting the fatigue crack during the test and it gave satisfactory crack length results observation compared to the actual lengths for fatigue long cracks.

Keywords: Constant fatigue crack length, electrical potential drop circuit(EPD), 7075-T6 Al-alloy

INTRODUCTION AND AREVIEW

Several technique can be employed to observe and measure fatigue cracks. The optical microscope [Kunio,1984] for direct observation, the ultrasonic technique which uses the high frequency waves transmitted from a transducer into a test specimen [Klima,1976], The replication technique [De lange,1964] and Electrical Potential Drop measurement (EPD).

The center- cracked panel was monitored using potential drop (EPD)and Johnson with the experimental and it was concluded that the EPD measurements of cracks are well agreed with the results obtained from the experimental and Johuson method [Read,2004]. The direct potential drop technique was adopted to describe and measure the crack growth of fatigue cracks along the major axis of the elliptical detect for titanium alloy by Arnold et al[2004]. They concluded that when the voltage drop the nucleation of crack and its growth appears to initiate and propagate.

Very small surface cracks length and depth were observed using the direct current potential drop (DCPD) sensor. The results indicated high ability of potential drop imaging technique for evaluation the fatigue crack by Masumi S.[2006]

The directional (EPD) method was found to exhibit high sensitivity that allows the detection of elastic and plastic strains as low as 0.05% by Elhoucine Madhi[2011].

Unloading compliance and direct current potential drop (DCPD)was compared by Matthias Verstraete [2012] using 3D elastic-plastic finite element simulations. It was found that the DCPD is a successful method for detecting and measuring the crack length.

Gilbey and pearson [1996] obtained an equation describing the calibration curve of the form :

$$\Delta(Va/Vb) = 9.39 + 2.03a + 4.90a^2 \qquad (1)$$

Where $\Delta(Va/Vb)$ is the potential drop changes and (a) is the crack length. The application of equation (1) showed good agreement for the potential crack length compared to the experimental data.

Farrahi G.H. [1996] presented a calibration curve for three types of cracks for BSL65 copper aluminum alloy ,namely, single edge crack, elliptical centre crack and for double edge crack by the following equations

$$\Delta(Va/Vb) = 4.69a^2 + 2.78a \qquad \text{(2) for single edge crack}$$

$$\Delta(Va/Vb) = 4.31a^2 + 7.58a + 7.66 \qquad \text{(3) for elliptical centre crack}$$

$$\Delta(Va/Vb) = 6.88a^2 - 12.43a + 17.44 \qquad \text{(4) for double edge crack}$$

He concluded that the above equations gave good correlation in comparison to the actual data.

In the present study the Electrical Potential Drop (EPD) method was used. This method based on measurement the drop voltage in the electrical potential between two points fixed to each side of the crack. Our goal is to describe experiments in which the electrical potential drop (EPD) is monitored and the relationship of these potential changes to crack propagation and crack length. Also this article discuss the (EPD) method of crack measurements.

DIRECT CURRENT POTENTIAL DROP TECHNIQUE (DCPD)

The electrical Potential Drop (EPD) method is most Widespread technique for identification crack length in laboratory specimens manufactured from electrically conductive materials such as aluminum alloys. The most common form of this technique, because of the simplicity, is the Direct Current Potential Drop (DCPD) however; it has so high current needs and is sensitive to high levels of noise. The PD method uses two injection probes to apply a constant current to the specimen whilst two separate sensing probes measure the potential drop across the crack and a calibration curve is used to predict the crack length from the EPD figure (1). The calibration curve may be derived by analytical, numerical or empirical methods. This technique depend on the fact that disturbances will occur in the electric potential field about any cut out in current carrying body. The magnitude of the disturbance depending directly on the size and shape of the discontinuity. For the purposes of crack length monitoring the method includes passing a constant current (maintained constant externally, in this case by constant current supply) through a test specimen. With increasing crack length the un cracked cross sectional area of the specimen decreases resulting in an increase in electrical resistance[Tarnowski1 K.,2014]. The thickness of the specimen is significantly affect the output readings of the EPD. Increasing the thickness slightly reducing the ($\frac{V}{V0}$) obtained from the EPD circuit.

The location for the present specimen thickness was fixed to be 3mm of .The crack was designed to be in the same direction of the current passing through the specimen tested [Degeilh R,2013].

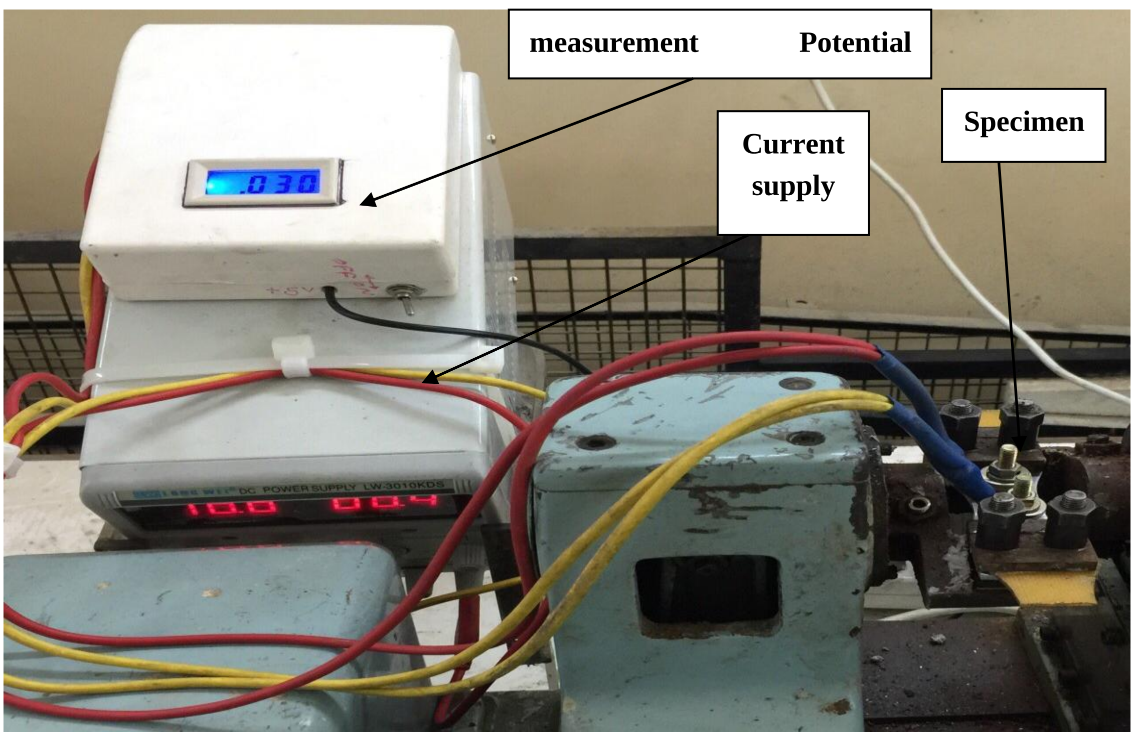

Fig (1) Potential drop system fixed on fatigue specimen

For a constant current flow, the voltage drop across the crack will increase with increasing crack length. The electrical potential drop method measured extremely low voltages. four probes methods used to measure drop voltage between two points. four probes are subjected to the specimens in two additional holes (d=5mm) the distance between them was 20mm shown in figure (3), two probes used to apply direct current

(10A) and others two probes used to measure drop voltage across the crack as shown in the figure (2).

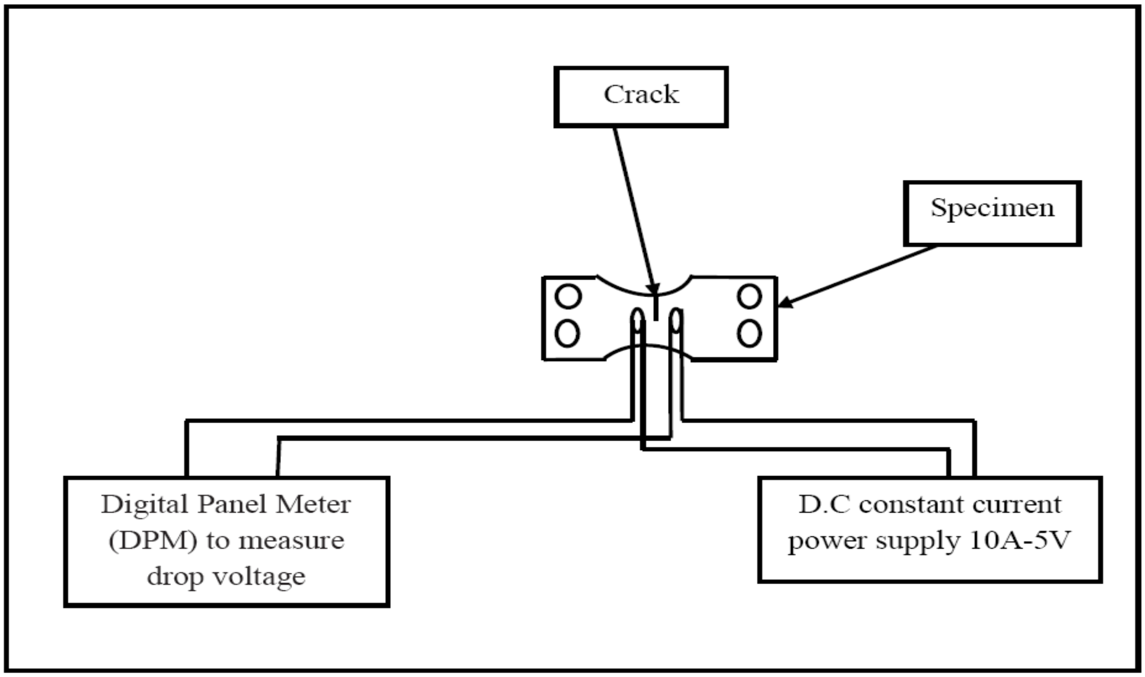

Fig (2) Schematic diagram of EPD circuit

The instruments used to measure drop voltage was:

1- D.C power supply
2- Digital panel meter (DPM): This meter could be a straightforward electronic voltmeter as a result of that it contains in it all the active electronic equipment for a 3.5 digit panel meter (DPM) in a single chip. It had been designed to interface directly onto a liquid crystal display (LCD). That the chip contains seven segment decoders, display drivers, clock and a reference voltage as well as the necessary analog to digital (A/D) circuitry to convert the input voltage to a digital form.

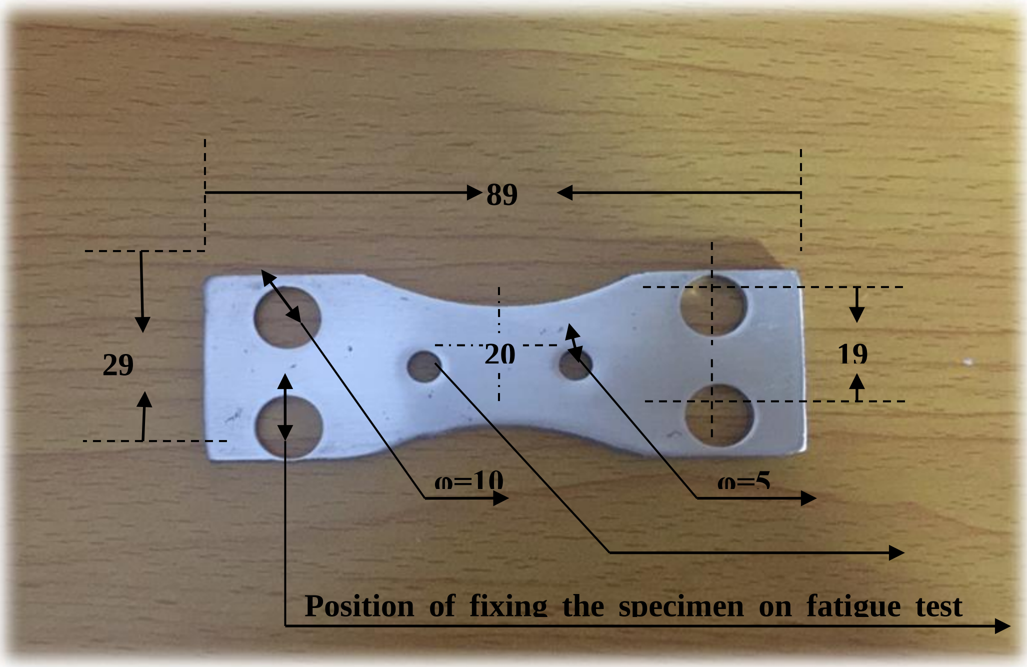

Fig (3) Reverse cyclic bending fatigue test specimen of 3mm constant thickness (all dimensions in mm) according to ASTM D3479M-96standard.

EXPERIMENTAL WORK

The aim of the experimental work is to detect and measure the crack length using EPD and compared it with the experimental results. The flow chart below explained the step of the experimental work.

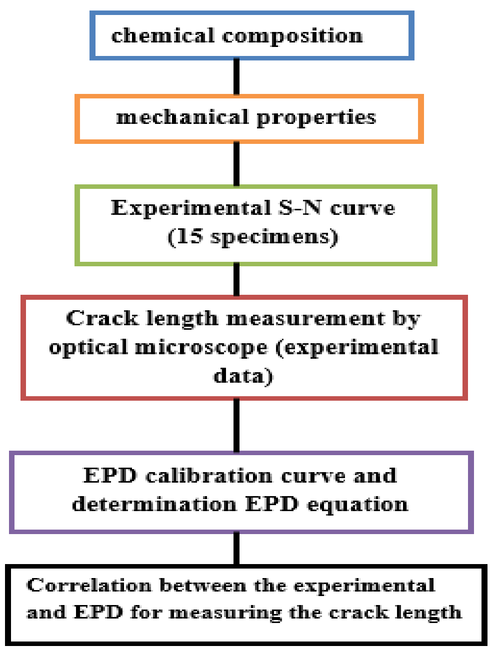

Fig (4) Flow chart of the experimental work

MATERIAL AND TEST SPECIMENS

The material under investigation was 7075-T6 Al-alloy in the form of rolled sheets with chemical composition in weight percentage as given in table(1). The experimental examination of chemical analysis was done using spectrum analyses at the State Company for Inspection & Engineering Rehabilitation (S.I.E.R), laboratories and engineering test department Baghdad/Iraq. The mechanical properties are presented in table(2). All specimens were machined for both sides so as to be parallel to the rolling direction.

Table (1) Chemical composition of 7075-T6 in wt%

Component	% Si	% Fe	% Cu	% Mn	% Mg	%Cr	% Zn	%Ti	% other	%Al
Standard ASTM E1251-11	≤ 0.4	≤ 0.5	1.2-2.0	≤ 0.3	2.1-2.9	0.18-0.28	5.1-6.1	≤ 0.2	≤ 0.15	Rem.
Experimental (S.I.E.R)	0.26	0.24	1.81	0.11	2.15	0.183	5.52	0.028	0.089	Rem.

The tensile test specimen is illustrated in figure (5) according to (ASTM D-638-I) standard

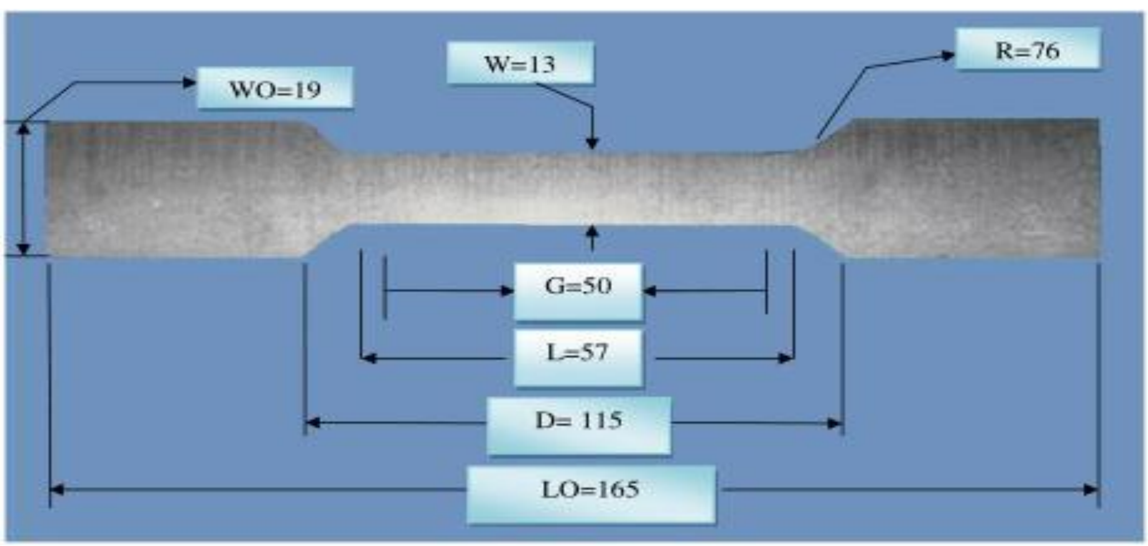

Fig (5) Standard tensile test specimen

Table (2) Mechanical properties of 7075- T6

Mechanical Properties	Experimental	Standard (ASTM B557M - 15)
Hardness , Rockwell B	90	87
Ultimate Tensile Strength	502 MPa	572 MPa
Tensile Yield Strength	406 MPa	503MPa
Elongation at Break	12%	11%
Modulus of Elasticity	74 GPa	71.7 GPa
Poisson's Ratio	0.33	0.33
Fatigue Strength*	186 MPa	195 MPa

*Fatigue Strength 186MPa measured at 10^7 cycles

RESULTS AND DISCUSSIONS

stress calculations

The applied stress was calculated from angle of twist (Θ) in degree based on the dimensions of the fatigue test rig,[AL-Qaisy,2015]. For more details, see appendix(a).

S-N curve predictions

The specimens were tested under constant amplitude fatigue bending were conducted in stress control with a stress ratio R= -1 at room temperature. 15 specimens are tested to estimate S-N curve. The experimental S-N curve data of 7075-T6 Al alloy is given in table (3) and plotted in the figure (6).

Table (3) Experimental S-N curve data

Specimen Number	1,2,3	4,5,6	7,8,9	10,11,12	13,14,15
Degree (Θ^{o})	6	8	10	12	**14**
Deflection ±δmax (mm)	1.05	1.55	1.85	2.35	**3.05**
Applied stress, σ_f (MPa)	172.782	255.262	304.856	387.746	**504.407**
No.of cycle to failure, Nf	170000 190000 185000	300001 280001 129000	50000 66000 34000	35000 44000 26000	**20000** **11000** **15500**

No. of average cycle to failure, Nf_{av}	181667	129000	50000	35000	**15500**
***Basquin equation**	σ_f=23902$Nf_{av}^{-0.39}$				
***R²**	**0.942**				

* Basquin equation derived from S-N plot by excel program.

***R²** is the correlation coefficient and is a hand measure of the goodness of fit [Mustafa,2014].

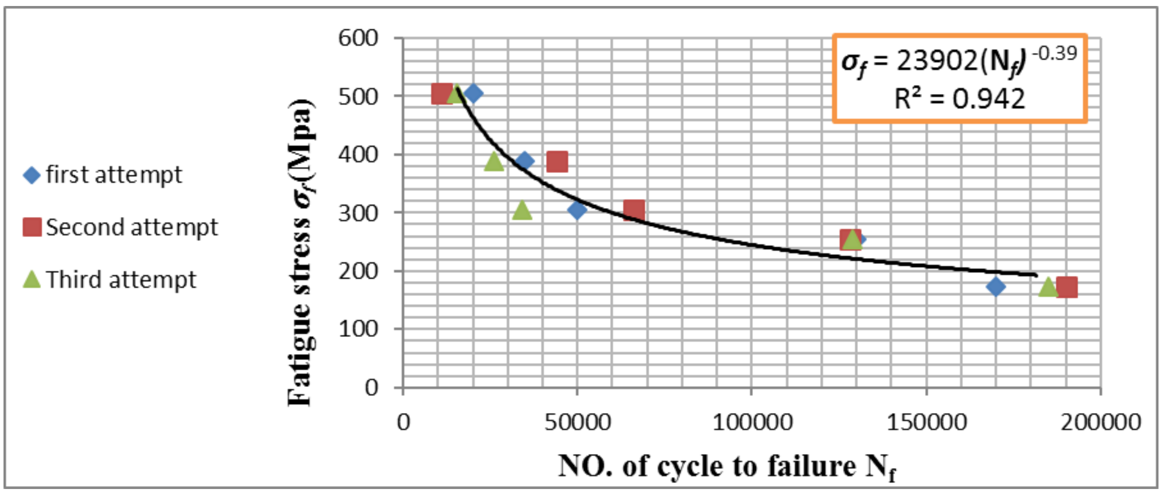

Fig (6) Relationship between applied stress and No. of cycle to failure (N_f)

experimental calibration curve

The working principle of the potential drop method is that any surface crack in a conducting specimen will causes a perturbation in the flow of electric current around the crack, generating a measurable difference in the potential across the crack. In this method, a constant current is flow through a specimen. When the crack extends in length the minimum width of specimen or the minimum cross-sectional area of the specimen decrease with an increase in the current path resistance and potential. In the present work, the experimental calibration curve results are presented as potential drop ratio against surface crack length. Potential drop ratio are characterized by the term (V/V_o). The parameter (V/V_o) is the ratio of actual potential drop and the reference one. The parameter (V/V_o) was selected in such away so as to minimize the error due to noise and vibration. The results of experimental calibration curve are presented in table

(4) while Fig.(7) shows the average experimental calibration curve (average of three readings). Therefore, this figure gives scatter and this scatter may be due to the shape of the crack, noise and vibration. The best fitting of the experimental calibration curve may be described by equation (5) with correlation factor R^2 = **0.991**.

$$(V/V_o)=0.004(a/t)^2-0.001(a/t)+1.016 \quad (5)$$

Table (4) Calibration curves results

a/t	(V/V0)1	(V/V0)2	(V/V0)3	(V/V0) Average of three readings
0.667	1.025	1	1.024	1.016333
1.334	1.025	1	1.024	1.016333
2	1.051	1	1.048	1.033
2.667	1.051	1.0222	1.048	1.040333
3.334	1.0769	1.0222	1.073	1.057
4	1.0769	1.0444	1.097	1.072333
4.667	1.102	1.0444	1.121	1.089
5.334	1.128	1.0666	1.146	1.113333
6	1.179	1.1111	1.17	1.153333

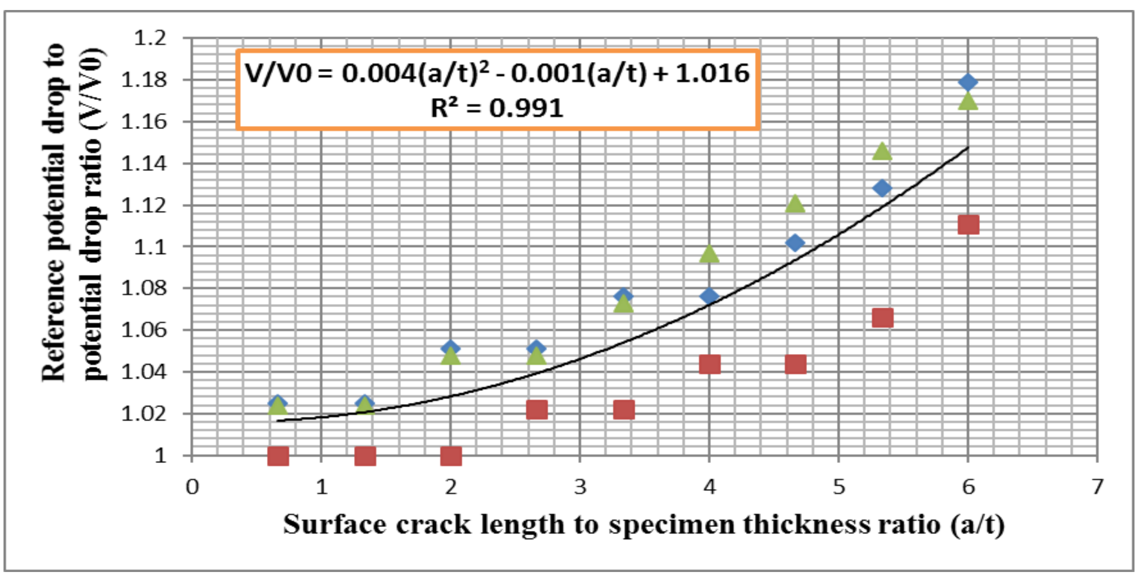

Figure (7) Experimental calibration curves

Degeilh et al [2013] made a comparison of calibration curves from potential drop and optical calibration one. They found that good agreement between the two curves mentioned above. The current work is now compared to the calibration curve of Ref [Degeilh] as given in figure (8).

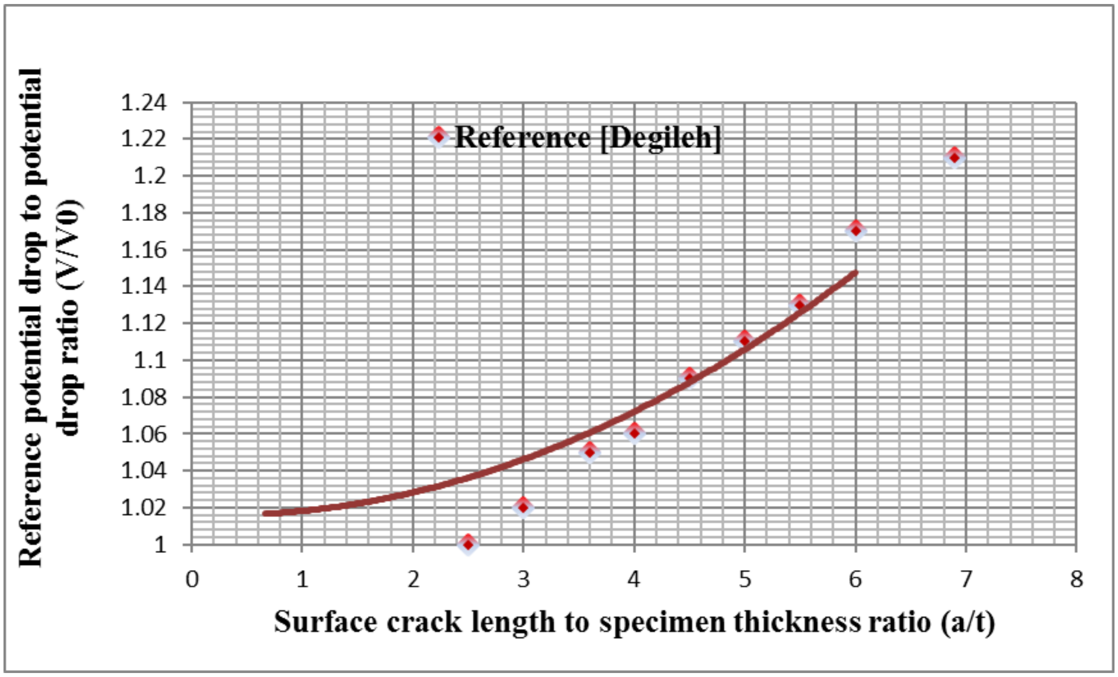

Fig (8) Comparison between calibration curve in this work and other in reference [Degeilh]

The method has been shown to yield accurate results when compared with available experimental work of the previous work.

It is observed that the estimation of crack lengths using the present calibration curve showed much better agreement compared with the actual crack length measured on the testing specimens.

EPD method as a tool for crack length

The experimental S-N curve data of 7075-T6 Al alloy can be illustrated in table (4) with the final reading of V/Vo .

Table (5) Correlation between actual crack length and crack calibration

Applied stress σ_f	**No. of average cycle to failure** $\mathbf{Nf_{av}}$	**V/Vo**	**EPD prediction (crack length) at failure mm Equation(5)**	**Actual crack length at failure mm**
172.782	181667	1.16	18.3	19
255.262	129000	1.14	16.8	18
304.856	50000	1.12	15.6	16.2
387.746	35000	1.10	14.1	14.5
504.407	15500	1.06	10.2	11

The results of the above table show that the amount of any further change in PD is related to the extent of crack growth. In general, the predicted crack length is somewhat closed to the measured crack length. Lowes and Fearnehough [1971] examined C-M structural steel using PD technique to detect the crack length. They observed that the predicted length always less than the observed crack length in experiment, This finding is achieved in the present experiment work. Also the above results gives an indication about the applied stress level. Increasing the applied stress reducing the final crack length or reducing the output EPD method reading.

Conclusions

1-The electrical potential drop technique gave rapid method of providing calibration for measuring fatigue crack length

2- The electrical potential calibration curve allowing accurate determination of fatigue crack length using EPD method.

3- Experimental measurement of crack length showed that most cracks were detected after 25% of the total fatigue life so that the remainder of the fatigue life > 75% was dominated by long crack or crack propagation.

4- The calibration equation that related to the potential drop was obtained based on experimental work. This equation may be described by

$$\mathbf{V/V0 = 0.004(a/t)^2 - 0.001(a/t) + 1.016} \qquad \mathbf{(6)}$$

The EPD calibration equation has been successfully used to measure the crack length of the flat bending fatigue specimens.

5-The predicated cracks using EPD always less than the actual crack length.

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Appendix (A)

Evaluation of maximum bending stress for fatigue testing machine model (AVERY 7305)

In order to provide a known bending stress in a cantilever, several variables have to be considered simultaneously. The simple theory of a cantilever is as follows, figure (A-1)

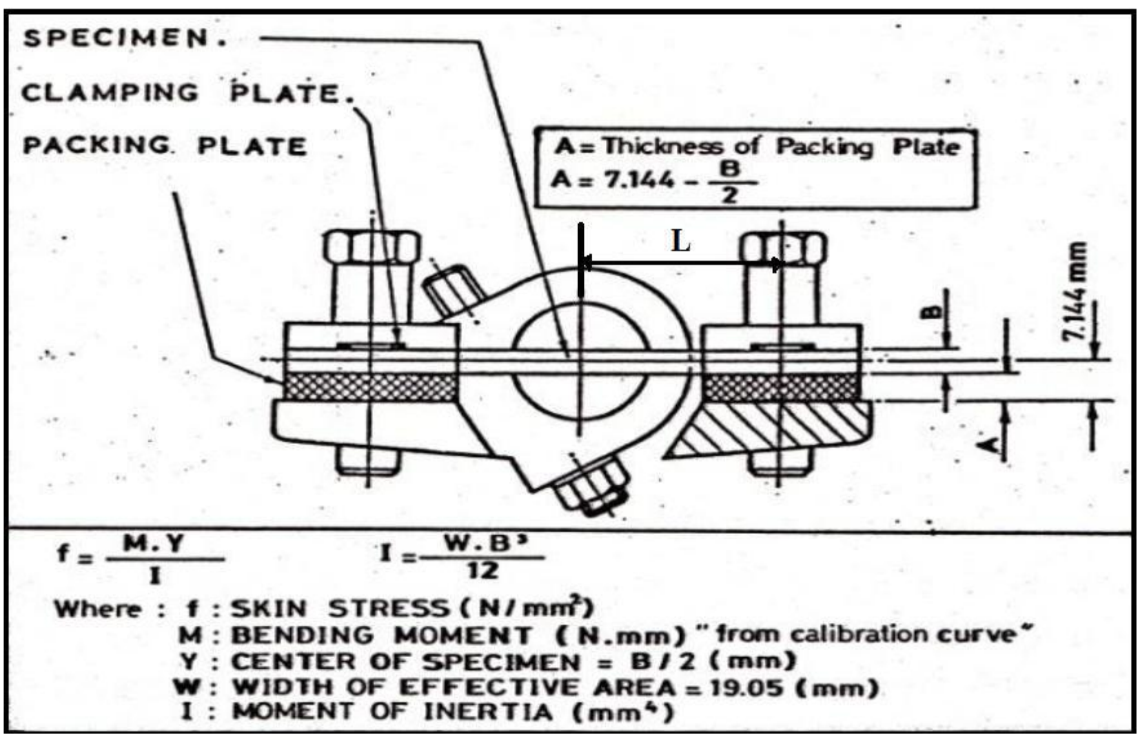

Fig (A-1): Schematic representation of fixing method, and how to calculate maximum bending moment

Maximum Bending Moment M = WL **(A-1)**

Where, W is load on free end and L is the strip cantilever long in mm

Maximum Bending Stress $\sigma_{max} = \frac{M.Z}{I}$ **(A-2)**

Where, z is the vertical distance measured from the neutral axis.

For cantilever free end deflection is $\delta = \frac{W.L^3}{3EI}$ **(A-3)**

Substituting (A-1) in (A-3) gives $\delta = \frac{M.L^2}{3E.I}$ **(A-4)**

Substituting (A-2) in (A-4) gives $\delta = \frac{\frac{\sigma.I}{Z} L^2}{3EI}$ **(A-5)**

Where, $Z = h/2$**, and then** $\delta = \frac{\sigma.L^2}{\frac{3}{2} E.h} = \frac{\sigma.L^2}{1.5\ E.h}$ **(A-6)**

when determining the maximum bending moment. A further modification, is necessary to take into account the curvature of the cantilever and reduction in length given

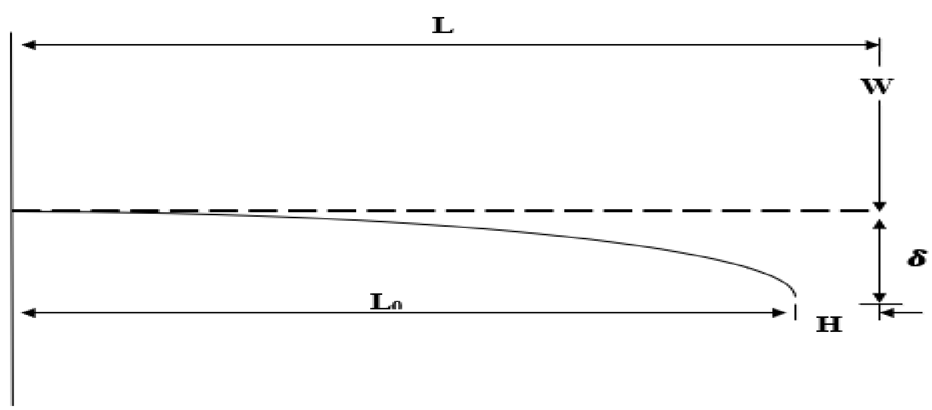

Fig (A-2):-Schematic representation of curvature of the cantilever

Where :

$$\boldsymbol{H} = \frac{1}{2}\int_0^L \left(\frac{dy}{dx}\right)^2 dx \qquad \textbf{(A-7)}$$

Assuming the curvature can have approximated by:

$$Y = \delta\left(1 - \cos\frac{\pi x}{2L}\right) \text{ Then , } \frac{dy}{dx} = \frac{\delta\pi}{2L}\sin\frac{\pi x}{2L} \qquad \textbf{(A-8)}$$

By substituting (A-8) in (A-7) and integrating it, then ;

$$\mathbf{H} = \frac{\delta^2\pi^2}{16L} = \frac{0.61685\delta^2}{L} \qquad \textbf{(A-9)}$$

Maximum Bending Moment is thus :

$$\boldsymbol{M} = \boldsymbol{W}(\boldsymbol{L} - \boldsymbol{H}) = \boldsymbol{W}\boldsymbol{L}_0 \qquad \textbf{(A-10)}$$

When L_0 =L-H

$$\text{Then ,}\boldsymbol{L} = \frac{1}{2}\boldsymbol{L}_0 + \sqrt{0.25L_0^2 + 0.61685\delta^2} \qquad \textbf{(A-11)}$$

This enables (L_0) to be calculated ;

$$(2L - L_0)^2 = L_0^2 + 2.465\delta^2$$

$$4L^2 - 4LL_0 + {L_0}^2 = L_0^2 + 2.465\delta^2$$

$$4L^2 - 4LL_0 + = 2.465\delta^2$$

$$\textbf{Then , } L_0 = \frac{4L^2 - 2.465\delta^2}{4L} \qquad \textbf{(A-12)}$$

If L=45mm,Then;

$$L_0 = \frac{8100 - 2.465\delta^2}{180} \qquad \textbf{(A-13)}$$

Which can be written in the form of maximum deflection as;

$$\delta^2_{max} = \frac{8100-180L_0}{2.465} \quad \textbf{(A-14)}$$

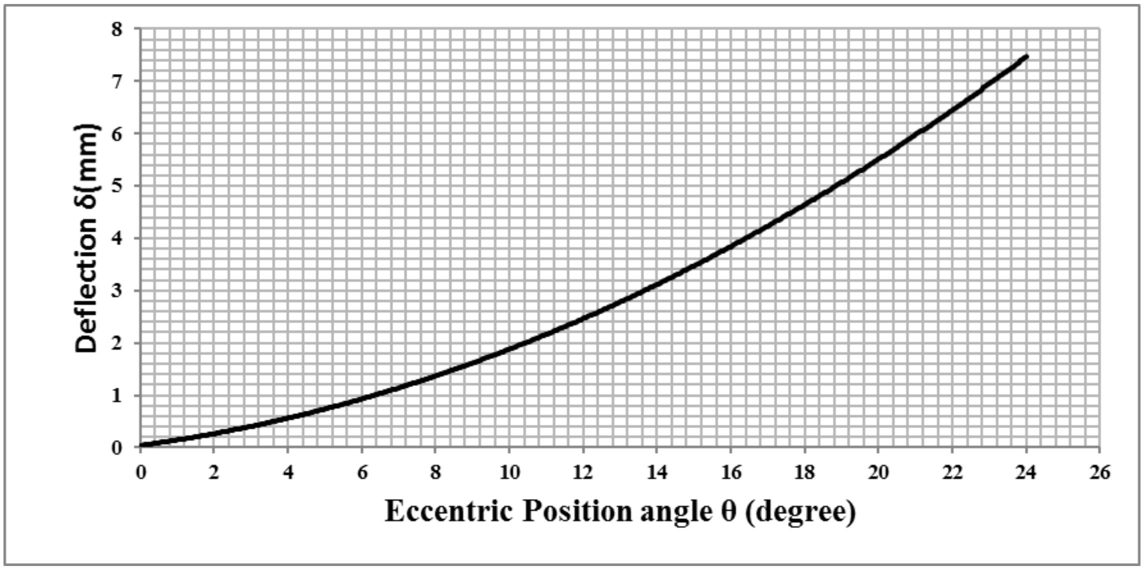

Fig (A-3): Calibration curve between bending deflection and eccentricposition angle of AVERY machine for aluminum alloy

The maximum bending stress can be calculated from:

$$\sigma_{max} = \frac{1.5Eh\,\delta_{max}}{L_\circ^2} \quad \text{(A-15)}$$

whilst the specimen thickness (h=3mm) and Modula's of Elasticity (E) for the aluminum alloy 7075-T6= 74 GPa , substituting this values in equation (A-15)

Table (A-1):- Maximum bending stress value for Aluminum alloy (7075-T6)

θ(degree)	δ_{max} (mm)	$L_\circ$ (mm)	σ_{max} (MPa)7075-T6
0	0	0	-
2	0.25	44.999	41.112
4	0.5	44.996	82.234
6	1.05	44.984	172.782
8	1.55	44.967	255.262
10	1.85	44.953	304.856

12	2.35	44.924	387.746
14	3.05	44.872	504.407
16	3.85	44.797	638.861
18	4.65	44.703	774.830
20	5.55	44.578	930.020
22	6.35	44.447	1070.329
24	7.55	44.219	1285.777