

Fatigue crack growth measured by the Electric Potential Drop Conceptual Upgrade

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1.- History

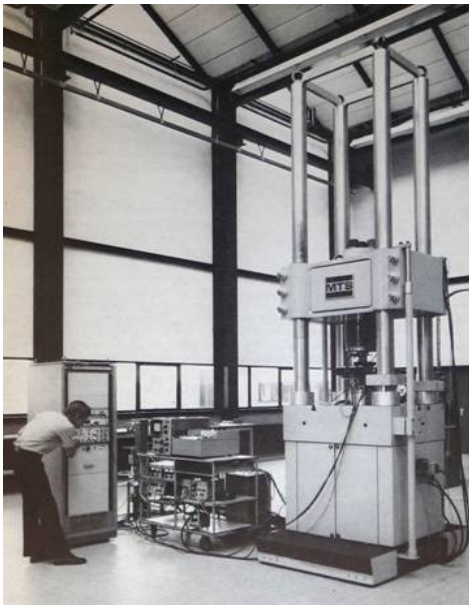


Fig. 1. Fatigue test set-up

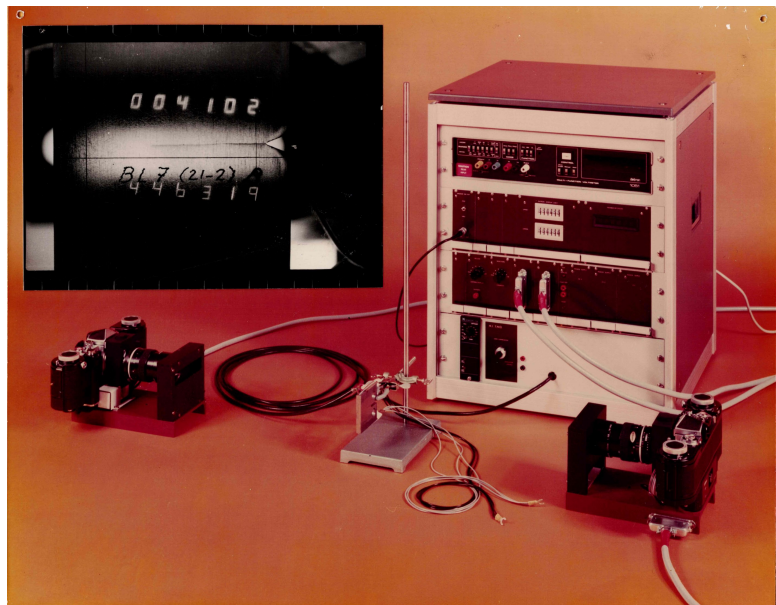


Fig. 2. Crack length measurement instrument

Fig. 1. and 2. Research done in the mid 70's, as a part of the Bros project. Safety of nuclear reactor vessels. Focused on the cold water inlet nozzle. Influence of temperature changes at cold water refill. Financed by the Dutch Ministry of Economic Affairs. The fatigue test instrumentation aimed at the accurate measurement of the crack growth as a function of the cyclic load count. Results are published in the Bros Project Final Reports.

Additionally, the instrumentation was published in *'Fatigue Crack Growth Measurements by Combined Optical and Electric Potential Drop Observations'*, D. Slagter and M. A. Lont. 1980. [1]

At the end of the Bros project I had some ideas about conceptual upgrades for the Electric Potential Drop fatigue crack growth instrumentation. For instance: - Position of the potential points, - Use of the Johnson-Tada expressions, and - Simplification of the electronic circuits. But, no time, no plan, or budget. Then, after years, I started a project at home on the proposed conceptual upgrades. With fatigue crack growth simulated by a saw cut crack.

2.- Introduction

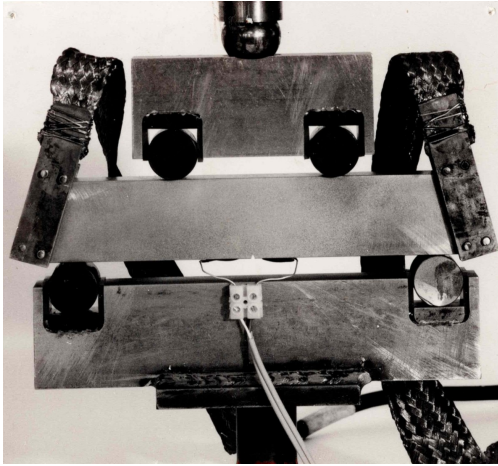


Fig. 3. Four point bend specimen



Fig. 4. Stepwise interrupted fatigue crack growth

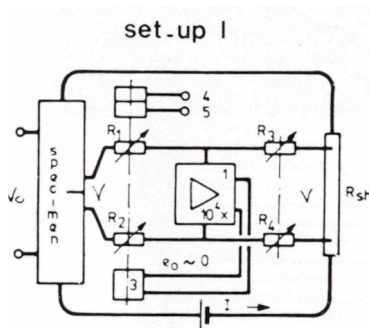


Fig. 5. The Thompson bridge as used in tests shown in Fig. 1.

A fixed pair of ten-turn resistors, hand positioned. And a moving pair of ten-turn resistors, with a servo controlled position. Balanced by a Keithley 155 null detector.

Additional two ten-turn resistors are mounted on the servo controlled axis to record the bridge position. And to trigger photographic recording at equal bridge position intervals. Moreover photographic recording at equal load cycle intervals. [1]

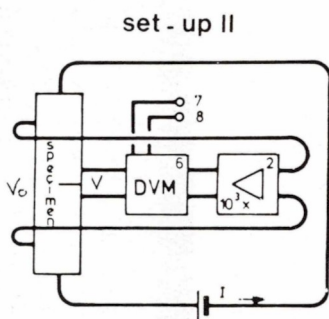
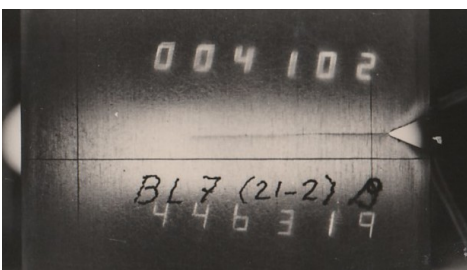


Fig. 6. The Electric Potential Drop method as used in the crack length measurement instrument shown in Fig. 2.

V1 (Johnson-Tada) measured with a Datron digital multimeter. V2 (Johnson-Tada) amplified by a Newton instrumentation amplifier, used as external potential reference for the Datron digital multimeter. Photographic recording similar to set-up I. In fact $V1/V2$ was measured. [1]

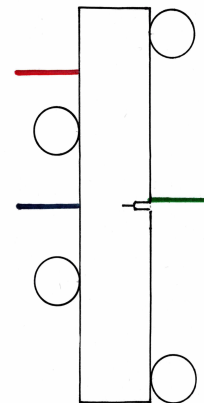
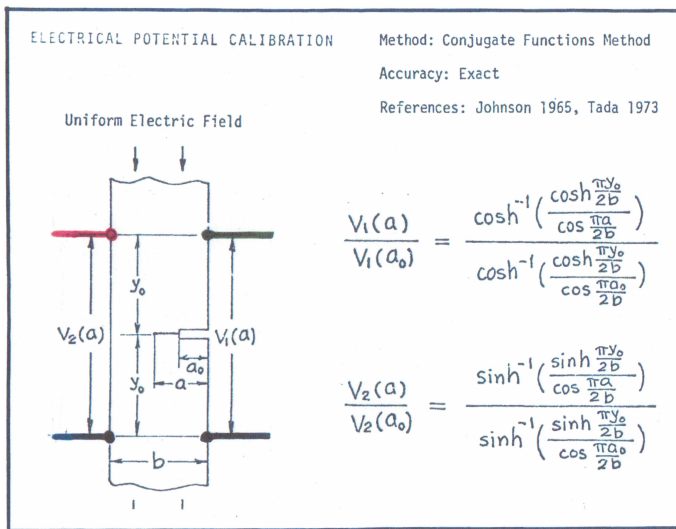


- Datron display of $V1/V2$,
- Line shaped flashlight, triggered at maximum load,
- Fatigue crack,
- Marks to ease the measurement of the crack length,
- Specimen identification,
- Number of load cycles.

Fig. 7 Photographic recording of a fatigue crack [1]

The accuracy of the crack length photographic recording is limited. Poor visible specimen edges and crack tip. And the difference between the surface and the inner crack length as shown in Fig. 4.

3.- Johnson-Tada expressions



To reduce influence on offset and noise the two black potential points are combined and welded at the symmetry axis.

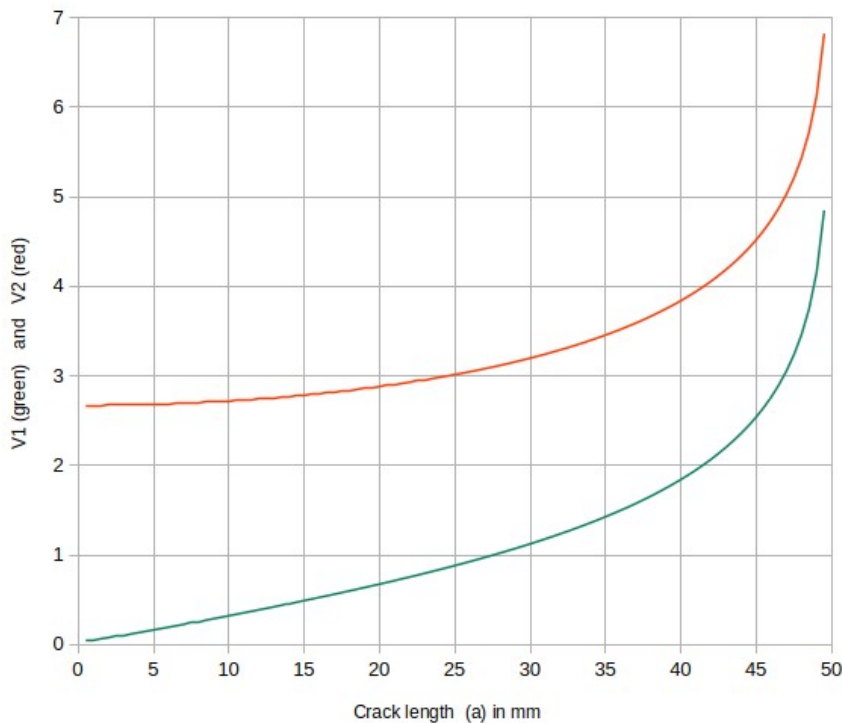
The electric potential drops divided by two. But now single ended signals with a shared common point.

Fig. 8. Johnson-Tada expressions [2, 3, 4]

Spreadsheet analysis of Initial Data, Analog Solution, and Digital Solution.

- To avoid ambiguity y_0 renamed as y_1 for $V_1(a)$, and y_2 for $V_2(a)$,
- Specimen: $b = 50$ mm, (a) in mm, $y_1 = 1,5$ mm, $y_2 = 85$ mm,
- Crack length divided into 100 points.

Fig. 9. Initial Data



Calculation of $V_1(a)$ and $V_2(a)$

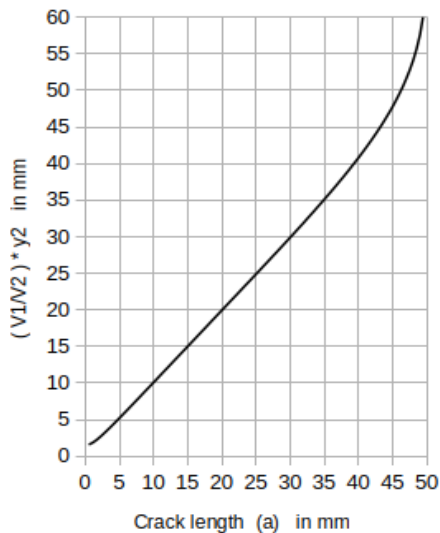


Fig. 10a. Analog Solution

As mentioned at Fig. 6. set-up II, the Datron digital multimeter displays in fact $V1/V2$. And actual tests showed a close to linear relation between (a) and $V1/V2$.

By spreadsheet trial and error the best locations of the potential points ($y1 = 1,5$ mm and $y2 = 85$ mm) were established. And a nearby one to one relation between (a) and $V1/V2$ by multiplying the value of $V1/V2$ with $y2$.

Result: (a) is very close to $(V1/V2) * y2$.

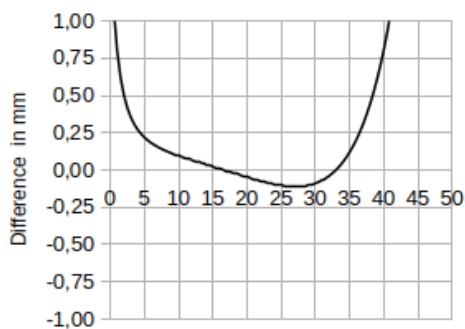


Fig. 10b. The difference $(V1/V2) * y2 - (a)$ at a twenty times enlarged vertical scale

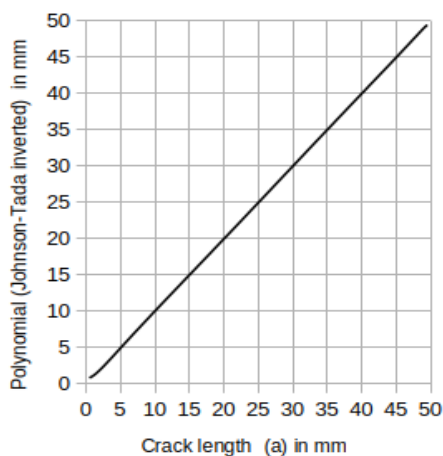


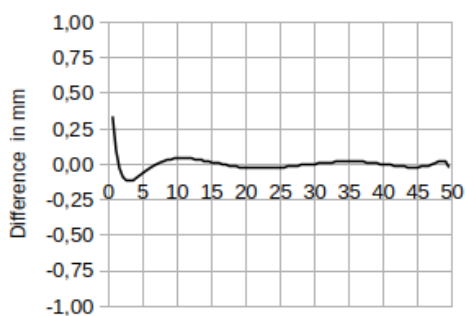
Fig. 11a. Digital Solution

First: Define, with the Johnson-Tada expressions, an array of $x = (a/b)$ and $y = (V1/V2)$, 100 points.

Then: Substitute the Johnson-Tada expressions by an inverted polynomial expression. Solved by least square curve fitting. [5]

$$x = C0 + C1*y + C2*y^2 + C3*y^3 + C4*y^4 + C5*y^5$$

(Inverted position of x and y in the polynomial expression.)



Result:

$$(a) = (-,021594 + 2,116616 * y - 3,128100 * y^2 + 10,920500 * y^3 - 16,445064 * y^4 + 7,512652 * y^5) * b$$

Fig. 11b. The difference **inverted polynomial** - (a) at a twenty times enlarged vertical scale

4.- Electronic circuits

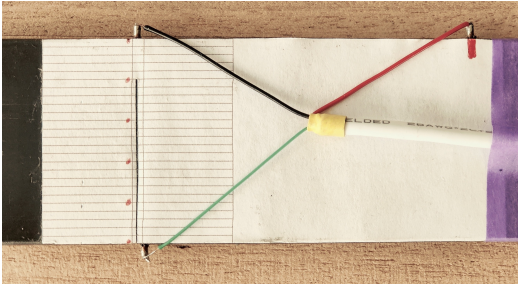
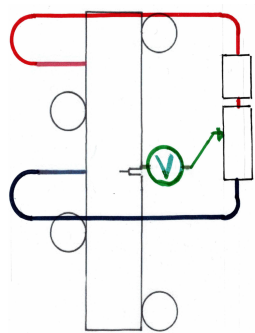
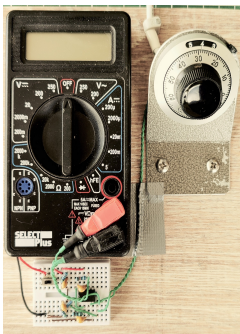


Fig. 12. Photo of a saw cut specimen with the three wire potential points. Signals single ended.

Stud welds on the specimen edges to connect the potential points to a shielded USB 2.0 cable. On the surface of the specimen a paper sticker with 2 mm marks fastened.

4.1.- Electronic circuit Analog Solution



Redefine the axes in Fig. 10a. into the dimensionless form $((V1/V2) * y2) / b$ versus a/b , it is the same image. Recall the vertical axis to $V1 / (V2 / (y2/b))$.

With $y2/b$ is 1,7, adjust the resistor R2 to 0,7 of the full value of potentiometer R1. Which gives analog the division of $V2/(y2/b)$. Then the position of the potentiometer R1 is very close to the value of a/b in Fig. 10a. Both in the range 0-1. R1 positioned by zero-ing the null detector V.

Fig. 13. Digital multimeter, LTC 1050 (gain 4700) and ten-turn potentiometer R1

Advantage

Passive electric components. Simple to build, quick hands-on experience.

Observation of the agile behavior of the microvolt level null detection.

Fatigue load cycle termination by the null detector's polarity at a certain crack length.

Drawback

Manual zero-ing. Limited correction of offset and noise. Difficult computer data acquisition.

4.2.- Electronic circuit Digital Solution

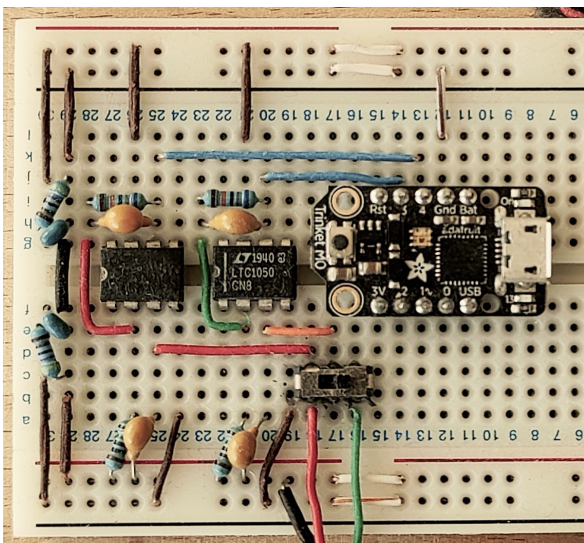


Fig. 14. Photo of the electronic circuit.

< 10 V regulated power supply connection [6]

< Artificial ground [7]

<<< Two LTC 1050 amplifiers [8]

<< Dotstar [9] < Trinket M0, USB [10]

<< Slide switch [11]

< Artificial ground [7]

< 0 V regulated power supply connection [6]

< Potential leads common, V2, V1

5- Experimental verification

Three specimen are prepared for tests:

- A Red, standard steel specimen dimensions 300, 50, 5 mm,
- B Green, standard steel specimen dimensions 1000, 50, 5 mm,
- C Blue, stainless steel specimen dimensions 1000, 50, 6 mm.

The electric current through the specimen is supplied by a Delta Electronics Power Supply SM1540. The current adjusted with dummy specimen and Dotstar. [9] The required current depends on tested material, the specimen thickness and the LTC 1050 gain. For these three specimen about 8 A.

Each crack saw cut over 4 to 40 mm lengths in increments of 2 mm.

With attention paid to a saw cut with a linear and perpendicular crack front.

Crack length is measured with the electronic circuit Digital Solution.

Each crack length sampled 4 times, each sample individually calibrated for offsets and gains. [12]

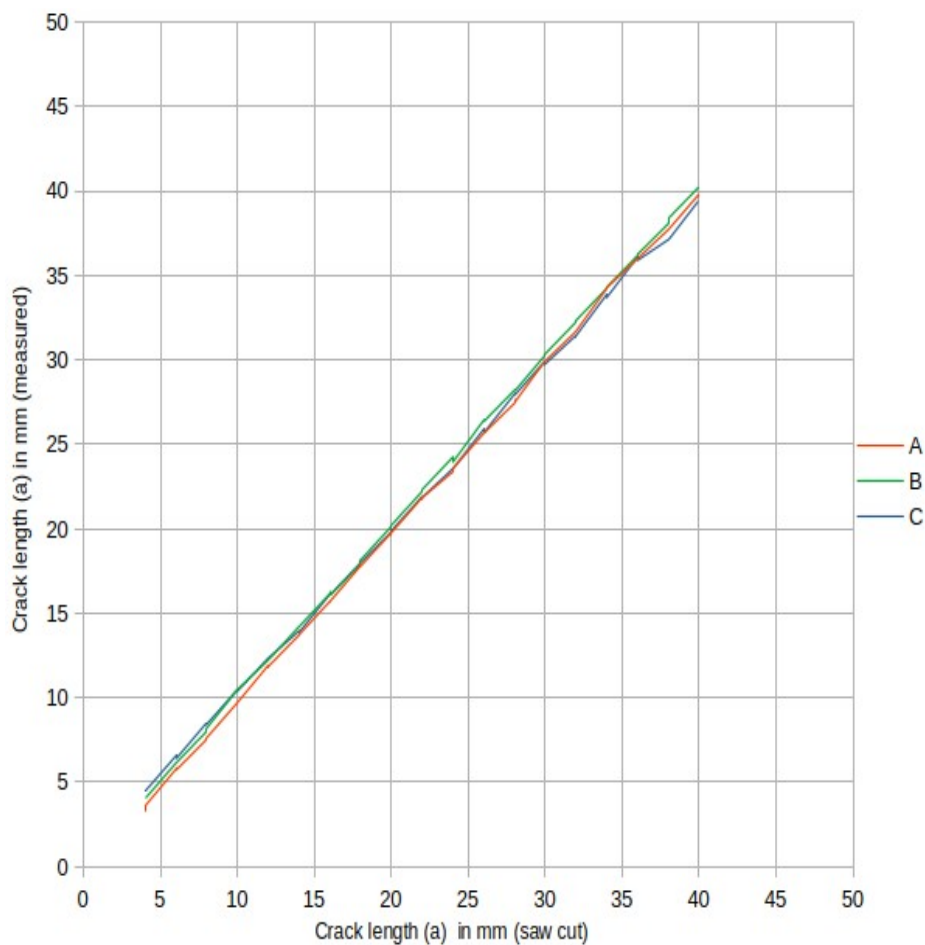


Fig. 15. Experimental verification, all samples.

First impression:

- the position of the potential points reduced the influence on offset, and noise,
- the inverted polynomial expression substitute for the Johnson-Tada expressions is effective, and
- the electronic circuit is simplified, with continual tuning of gain.

The Electric Potential Drop method measuring fatigue crack growth, Conceptual Upgrade, is beneficial.

6.- Result analysis

Additional to the the first impression a more detailed analysis of the experimental verification.

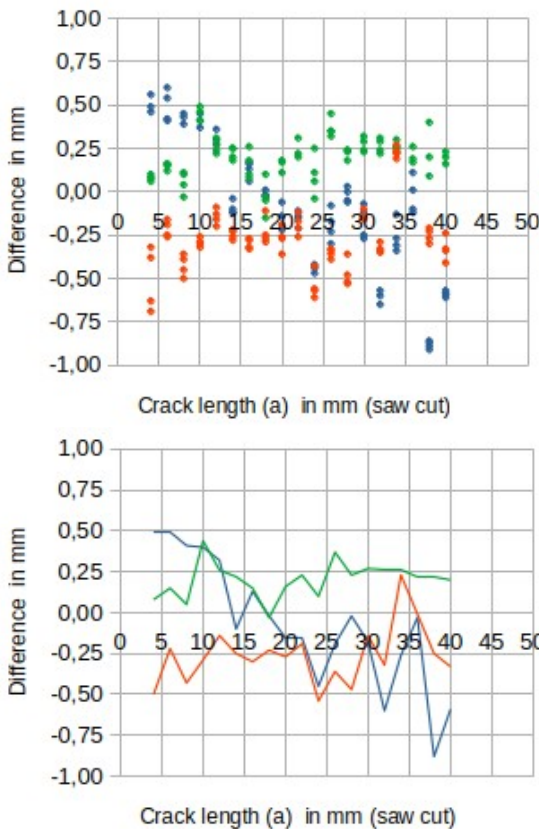
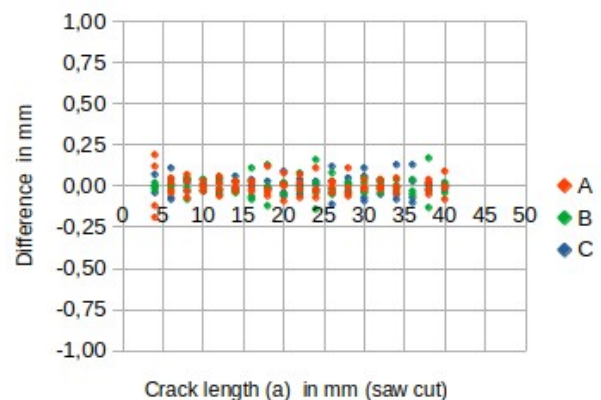


Fig. 16a.

The **measured crack length – saw cut crack length** at a twenty times enlarged vertical scale. For the analysis this figure is split into two different views:

I. Fig. 16b. Average the four samples for each 2 mm increment. It shows **mean-samples – (a)**. Trend of the difference.

II. Fig. 16c. Subtract the trend from all samples. It shows **samples – trend**. Noise on the difference.



I. Fig. 16b. Trend of the difference

II. Fig. 16c. Noise on the difference

Summary of accuracies (Don't cumulate $\pm$ values.)

- 1.- Mathematical: Fig. 11b. Polynomial fifth degree. $\pm 0,03$ mm.
- 2.- Electronic circuit: Fig. 16c. Repeated identical samples, noise. $\pm 0,15$ mm.
- 3.- Saw cut crack length: (Crack tip, visual observation. Sticker with 2 mm increments, positioning. Non linear and non perpendicular crack front.) Vertical offset in Fig. 16b. $\pm 0,25$ mm.
- 4.- Uniform electric field: (Specimen A length 300 mm and B 1000 mm.) Inaccuracy neglected.
- 5.- Specific electric resistance: Inaccuracy neglected.
- 6.- Thermoelectric effects: (On V1 and V2 due to the symmetrical set-up largely compensated. Temperature gradient in steel limited by the high thermal conductivity.) Inaccuracy neglected.
- 7.- Agile behavior of microvolt level signals. Constrained by individual calibration of each sample.

The vertical offset of specimen A and B in Fig. 16b. may be explained by point 3.- Accuracy of saw cut crack length. With this amended in Fig. 16b. the accuracy established at $\pm 0,15$ mm.

I have no explanation for the irregularities of specimen A. and B. and in particular specimen C. These irregularities and the agile behavior of the microvolt level signals needs more attention.

But overall:

The Electric Potential Drop method, Conceptual Upgrade, measuring fatigue crack growth, is beneficial.

A.- Explanatory notes

- [1] Fatigue Crack Growth Measurement by the Combined Optical and Electrical Potential Drop Observations. D. Slagter and M. A. Lont. 1980. pp 272-284.

Compiled with 19 other publications on the subject in: The measurement of crack length and shape during fracture and fatigue. Editor C. J. Beevers. Engineering Materials Advisory Services, EMAS LTD. ISBN 0 9506820. Warley, West Midlands UK, 1980.

- [2] Calibrating the Electric Potential Method for Studying Slow Crack Growth. H. H. Johnson, Materials Research & Standards, 5 No 9, 442-445, Cornell University, Ithaca, New York US, 1965.

- [3] The Stress Analysis of Crack Handbook, H. Tada, P. C. Paris & G. R. Irwin, Del Research Corporation, Hellertown, Pennsylvania US, 1973.

- [4] Notation $\cosh(x)^{-1}$ and $\sinh(x)^{-1}$ stands for $\operatorname{arccosh}(x)$ and $\operatorname{arcsinh}(x)$.

- [5] Least square curve fitting by matrix math.

Available on platform Ubuntu, application Calc, function LINEST.

Function input line: $\{=LINEST(E14:E114 ; F14:J114 ; 1 ; 0)\}$,

x = E14:E114, y = F14:J114 consecutive columns of y, y^2 , y^3 , y^4 , y^5 .

- [6] Connection to a 10 V regulated power supply AC/DC Adapter Model 3122.

- [7] Artificial ground, split 10 V into -5 V and 5 V.

- [8] Two LTC 1050 Precision Zero-Drift Operational Amplifiers.

V1: $R1 = 146,5 \Omega$ and $R2 = 698,7 \text{ k}\Omega$, result gain 4769.

V2: $R1 = 146,4 \Omega$ and $R2 = 704,5 \text{ k}\Omega$, result gain 4812.

(Single ended input, chopper LTC 1043 in the LTC 1050 Product Specification not necessary.)

- [9] Dotstar current indications.

V2 as supplied to Trinket ADC

(a) 4 mm

(a) 40 mm

0,000 V ----Yellow---- 0,075 V ----Blue---- 2,267 V ----Green---- 3,250 V ----Red---- 3,300 V.

- [10] Trinket M0 Single Board Computer.

ADC Analog to digital conversion of V1 and V2.

Dotstar multicolor led light, used to indicate the electric potential limits.

CircuitPython version 3.1.1 (Don't upgrade, USB handshake problem.)

USB connected to Raspberry PI 4G 4B with Ubuntu Raspberry PI OS (64-bit) as host.

Sample display on Raspberry PI Thonny Integrated Development Environment shell.

CircuitPython source code to control the measurement and to calculate the crack length. [B]

- [11] Slide switch V1 = V1 (right position) or V1 = V2 (left position).

- [12] Sampling the crack length with calibration of offsets and gains, Digital Solution.

Repeat:

Switch current off, set slide switch to V1 = V2,

Observe consecutive values for zero offsets, if reasonable values switch current on,

Observe consecutive values for gains adjustment, if reasonable values slide switch V1 = V1,

Wait a number of cycles until sampled values are stable, then record measured crack length.

B.- CircuitPython source code

```
"""
Fatigue crack length measured by the Electric Potential Drop. Conceptual upgrade.

Components:
- Raspberry PI 4G 4B with Ubuntu Raspberry PI OS (64-bit) used as host.
- Thonny Integrated Development Environment
- Trinket M0, CircuitPython version 3.1.1 (Don't upgrade, USB handshake problem.)
- CircuitPython source code (rules of open software).

Dick Slagter, 29-05-2026 (C)
"""

# Connect libraries
import board
import adafruit_dotstar as dotstar
from digitalio import DigitalInOut, Direction, Pull
from analogio import AnalogIn
import time

# Initialize DotStar
dot = dotstar.DotStar(board.APA102_SCK, board.APA102_MOSI, 1, brightness = 0.20)
dot[0] = ( 0, 0, 0 )

# Switch off onboard internal red led
led = DigitalInOut(board.D13)
led.direction = Direction.OUTPUT
led.value = 0

# Analog input on D3 and D4
pin_d3 = AnalogIn(board.D3)
pin_d4 = AnalogIn(board.D4)

# Define globals
V1_adj = 0.0 # Zero adjustment of specimen crack side potential
V2_adj = 0.0 # Zero adjustment of specimen back side potential
V1_gain = 4769.0 # Gain defined by 146.5 Ohm and 698.7 kOhm
V2_gain = 4812.0 # Gain defined by 146.4 Ohm and 704.5 kOhm
V1 = 0.0 # Specimen crack side potential
V2 = 0.0 # Specimen back side potential
b = 50.0 # Specimen width
a = 0.0 # Crack length according to V1/V2 calculated with inverted polynomial
count = 0 # Sample counter
reduce = 10 # Number of samples skipped before sample write to Thonny IDE shell

# Read voltages on D3 and D4, average samples, calculate V1 and V2, and (a)
def sample_data ():

    loop = 91 # Sample time trimmed to one second
    delay = 0.005 # Balance time for ADC before each sample

    V1 = 0.0
    V2 = 0.0

    for i in range ( 0, loop ):

        time.sleep ( delay )
        ADC_V1 = pin_d3.value * ( 3.3 / 65536 ) # Sample ADC on D3
        V1 = V1 + ADC_V1 # Cumulate samples

        time.sleep ( delay )
        ADC_V2 = pin_d4.value * ( 3.3 / 65536 ) # Sample ADC on D4
        V2 = V2 + ADC_V2 # Cumulate samples

        if ( ADC_V2 > 3.250 ) or ( ADC_V1 > 3.250 ):
            dot[0] = ( 255, 0, 0 ) # Red, current too high

        elif ( ADC_V2 > 2.267 ):
            dot[0] = ( 0, 255, 0 ) # Green, current normal

        elif ( ADC_V2 > 0.075 ):
            dot[0] = ( 0, 0, 255 ) # Blue, current low

        else:
            dot[0] = ( 255, 255, 0 ) # Yellow, no current
```

```

V1 = V1 / loop          # Calculate V1 at ADC in Volt
V2 = V2 / loop          # Calculate V2 at ADC in Volt

V1 = ( V1 / ( V1_gain * 1.0E-6 ) ) - V1_adj    # Calculate V1 at specimen in muVolt
V2 = ( V2 / ( V2_gain * 1.0E-6 ) ) - V2_adj    # Calculate V2 at specimen in muVolt

if V2 > 10.0:

    a = ( - 0.021594
          + 2.116616 * ( V1/V2 )
          - 3.128100 * ( V1/V2 )**2
          +10.920500 * ( V1/V2 )**3
          -16.445064 * ( V1/V2 )**4
          + 7.512652 * ( V1/V2 )**5 ) * b # Calculate crack length with V1, V2 and b

else: a = 0.0

return V1, V2, a

# Keep track of the time with a time stamp
def time_stamp():

    str = ["          "]
    ds, secs = divmod( count, 86400 )          # Split to days and seconds
    hs, secs = divmod( secs, 3600 )            # Split to hours and seconds
    mins, secs = divmod( secs, 60 )            # Split to minutes and seconds
    str = '{:02d}:{:02d}:{:02d}'.format(hs, mins, secs)

    return str

# Show data on Thonny IDE shell
def print_data ( show ):

    trigger, skip = divmod (count, reduce )    # Reduce number of lines written to shell
    if ( skip == 0 ) or ( count in range ( 11 ) ): # Start with 10 consecutive samples without skip

        if ( show == "test" ) and ( count == 10 ): print ( " " )

        print (
            show,
            ", ", time_stamp (),
            'Sample:',
            "    %5.1f" % V1,
            ",    %5.1f" % V2,
            ",    %8.2f" % a,
            'Check:',
            "    %4.1f" % V1_adj,
            ",    %4.1f" % V2_adj,
            ",    %2.4f" % ( V1_gain / 4769.0 ))

    return

# Indefinite loop
while True:

    V1, V2, a = sample_data()                  # Normal read of samples

    if ( V2 < 15.0 ):                          # Exception, set zero adjustment
        V1_adj = V2_adj = 0.0
        V1_adj, V2_adj, a = sample_data()
        count = 0
        print_data ( "zero" )
        time.sleep ( 1.5 )                    # Time window to switch current on

    elif ( V2 >= 15.0 ) and ( abs ( V2 - V1 ) < 50.0 ): # Exception, balance gain V1
        V1_gain = V1_gain - min( ( V2 - V1 ), 1.0 ) * 5.0 # Iterate V1_gain to adjust V1
        count = 0
        print_data ( "gain" )
        time.sleep ( 1.5 )                    # Time window to move slide switch V1 = V1

    else:
        print_data ( "test" )                  # Write sample line to Thonny IDE shell
        count = count + 1

```