Validation of a calibration procedure for fatigue crack growth measurement in circular section specimens

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Abstract

This paper describes a calibration procedure that is intended to eliminate as much as possible several error sources very common in calibration procedures, which are not frequently discussed and analyzed. Error sources in calibration procedures are as much important as the needed precision increases. In the present situation because is intended to study the fatigue crack initiation, until 1 mm, every detail may become very important. It’s also an aim of this work to identify particular features of the system used in this work (Pulsed DCPD – Pulsed Direct Current Potential Drop) applied to fatigue round specimens.

1 Introduction

Nowadays one may divide fatigue crack length measurement techniques with potential systems in three variants according to the electrical current source used [1]: direct current (DCPD); high frequency alternating current (ACPD) and pulsed direct current (Pulsed DCPD). There are differences between these methods. Wei and Brazill [2] made a comparison between the first two systems. The main features analyzed in this work are as follows:

- The DCPD is sensitive to thermally induced electromotive force (emf) due to the use of high currents in the order of tens of amperes. This
disadvantage may be reduced with the pulsed DCPD technique with the option to choose an interrupted current supply instead of a continuous flow [3].

- The DCPD system is highly sensitive to electrical noise but the introduction of a separate preamplifier greatly reduces the effect of noise [2]. This way impressive crack growth resolutions are possible.
- The electric current used in DCPD systems usually flows through all the section of the specimen while in ACPD systems the current flows mainly through a thin layer in the surface (skin effect) [1].
- The DCPD systems are very sensitive to temperature variations forcing the use of reference specimens in order to reduce errors due to this effect.

The Pulsed DCPD systems are still very common in detection and crack growth measurement [3]. Willowski et al advises the use of DCPD methods particularly in the detection of short cracks [1]. These systems have good resolution and sensitivity on the short crack growth measurement as indicated by Wei, Gangloff, Schwalbe and Shanmugham [2,4,5,6].

In the present study besides the use of a Pulsed DCPD system (DCM-1 - Matelect), the electrical screening signal cables were welded to the specimens since this solution introduces less defects in the specimens that could become crack nucleation sites.

## 2 Main error sources of DCPD systems

In order to obtain high resolutions on the crack growth measurement the system sensitivity must be high and the noise must be low. The sensitivity or equivalent crack growth for specimen geometry depends on the amplifier gain, the placement of the potential screening cables and the applied current to the specimen. In this study will be analyzed the referred features and their influence in the crack growth measurement and calibration.

The specimen used is a 34CrNiMo6 alloy according to ASTM E 606-80 [1] (fig.1) and the pre-crack is shown in figure 2.

![Fig.1: Specimen geometry according to ASTM E 606-80, ⌀=12mm and L=133 mm.](image1)

![Fig.2: Detail of the pre-crack: a=100μm; thickness = 300μm and length = 2200μm.](image2)
2.1. Placement of screening cables

One of the main error sources may result from the use of several specimens to obtain a calibration curve. This is maybe the most used and straightforward procedure. It would be necessary to use several specimens with increasing crack depths obtained through real tests or through machined cuts and measure the respective potential values. With this readings the calibration curve is obtained.

Due to the fact that the potential is a function of the electrical resistance and the electrical resistance changes with the distance between the screening cables, any difference between these wires may produce errors.

When using several specimens and despite the advanced welding techniques it is difficult to reproduce accurately the position of the screening cables in relation to the pre-crack. The influence of deviations in this variable is a source of errors that will be analyzed below.

Next figure illustrates some errors:

Fig.3a: Possible error sources in the placement of the wires.

* - Case 1; • - Case 2; + - Case 3.

Fig.3b: Interaction between the potential measurements and the position of the wires in relation to the crack.

Fig.4: Readings in two situations. Current: 50A; Gain: 6000
Distance between wires (Cases 1 and 3)

In the graphic of figure 4 may be observed that the increase of the distance between screening cables in relation to the pre-crack originates:

- a reduction of sensitivity.
- a non-linear curve in the first millimeters of the crack becoming linear after that. This fact will be analyzed subsequently. As an example we can observe in the graphic of figure 4 that to a increase of 16 times in the distance between wires, in the first millimeter of the crack length, the value of the potential almost duplicates. That means that a variation of 50\(\mu\)m in the position of the wires causes an error larger than 6% in the readings.

Cross-lectures (Case 2)

This situation may cause:

- a reduction of sensitivity;
- a non-linear curve in the first millimeters of the crack becoming linear after that. This fact will be analyzed subsequently. The introduced errors are equivalent to those of the first situation.

It is observed that in order to obtain a crack length with high sensitivity and a linear behavior it is necessary that the distances between the wires and pre-crack borders are smaller than 50\(\mu\)m and cross-lectures should be avoided.

The fact that the calibration curve is non-linear in its beginning and then becomes linear may be related with the specimen geometry and the interaction between the potential measurements and the position of the wires in relation to the crack.

In accordance with figure 3b one may conclude:

Situation 1: As the distance between the screening cables is small the area of the section that the potential wires can detect is thin. Thus, for an equal increase in the depth of the crack, for example 100 \(\mu\)m, there is an equal decrease in the remainder area of the section that can be detected by the potential wires. This is the reason why the calibration curve is linear (this may not be valid for the first 100\(\mu\)m)

Situation 2 and 3: Because the distance between the screening cables is bigger, the area of the section that the potential wires can detect is large. Thus, for an equal increase in the depth of the crack, for example 100 \(\mu\)m, there is a bigger (exponential) decrease in the remainder area of the section that can be detected by the potential wires. This is the reason why the calibration curve is not linear, but is exponential. If the distance between the screening cables is two big, for example 10 mm, the calibration curve will be exponential and never become linear.

2.2 Gain

The sensitivity is directly proportional to the gain but presents the disadvantage of increasing the electrical noise. Thus it is necessary to achieve a good balance
between the obtained sensitivity and the originated noise in order to effectively increase the readings resolution.

2.3 **Current intensity**

The increase of electrical current improves the sensitivity presenting also a linear relation. The current intensity does not introduce noise, which is an advantage.

2.4 **Electrical noise**

The noise is introduced by several ways. The most important may be the gain, the absence of electrical isolation of the specimen relating to the machine and the electrical contacts.

2.5 **Temperature**

The variation of ambient temperature may have some influence in the resolution of the readings, mainly for higher sensitivities. The following graphic (fig.5) shows the variation of the electrical potential for an oscillation in the temperature of only 1.5°C. The maximum potential occurred for a temperature of 23°C and a minimum potential occurred for a temperature of 21.5°C. For this test conditions (Current=2A; Gain=50000) this oscillation is equivalent in terms of sensitivity to a crack length of 4µm. To current intensities of 50A and gains of 6000 (conditions used in short crack growth measurements) oscillations of 6°C are equivalent to 48µm of crack length which is a very high error for the study of short cracks.

The specimen temperature may also be affected by the high current densities and consequently affect the readings resolution.

![Variation of Potential with ambient temperature](image)

**Fig.5:** Variation of electrical potential as a function of temperature in a 24-hour test, beginning at 12h00.
2.6 Other error sources

Other error sources may result from the use of different dimensions in the calibration specimens and test specimens or from different characteristics in the material or even assembly conditions of the specimens and systems.

3 Proposed solution

In order to avoid the referred problems in point 2, during the attempts of obtaining a calibration as accurate as possible and with high resolution we proceeded to a study of different possibilities of calibration having arrived to a satisfactory solution for the proposed aims, that is the study of short cracks. The solution is presented below.

![Calibration system](image)

Fig. 6: Calibration system of fatigue crack growth measurement

This system is composed of:

- Cutting equipment for the specimen with diamond disc wrapped up with resin and with thickness of 300μm. The cutting equipment is simple and allows the assembly of the specimen with electrical isolation. The disc is wrapped up with resin in order to not affect the readings of potential. The diamond and the resin are not electrical conductors so they don’t interfere with the current flow.
- Micrometric position indicator. This is assembled in order to measure the crack depth. It has a resolution of 1 micrometer.
- Pulsed DCPD system to obtain the readings of the potential.
- Computer system for acquisition and saving of the readings. A simple software was developed to save the data.
The crack is gradually machined through the cut with the diamond disc and the depth of the crack is measured and manually registered simultaneously with the potential values. This could be done continuously but due to the friction of the disc in the specimen electrical changes could appear. The test may be stopped at each 10, 20, 50, or 100 micrometers of crack depth and the potential values were then registered. This system allows the resolution of some of the problems referred in point 2, namely:

- It eliminates the errors associated with the use of different specimens and the consequent difference in the position of the welding points of the screening cables. The calibration is made with one specimen only.
- It eliminates the effects that could result from changes in ambient temperature since the process takes only a few minutes.
- This procedure also eliminates error sources that may result from different dimensions of specimens; material characteristics or variations in assembly conditions of specimens and systems.

The other source errors may be dealt with the most common ways, namely:

- Gain - it's recommended a good balance between the increase in sensitivity which is achieved with an increasing of the gain and the noise that also increases, in order to increase effectively the resolution;
- Current intensity - it's recommended the highest current intensity in order to increase the sensitivity;
- Temperature - problems with temperature in the specimen due to current intensity may be overcome with bigger intervals between readings. Problems with ambient temperature may be overcome with the use of a reference specimen.

4 Results

In the present case it is intended to register only the first two millimeters of the crack length. In order to obtain the highest sensitivity and resolution, a combination of current intensity=50A and a gain of 6000 was the best solution achieved. This means that we cover the amplitude of the equipment, aprox. 2.5 V, with the two millimeters of crack length.

With a single specimen was achieved the calibration curve below in figure 7. The obtained results are very satisfactory. As can be observed, a very accurate calibration curve is obtained, mainly after 200 μm. Since the resolution of the equipment is 1 mV, we obtain a sensitivity of 0.8 μm, as we can observe in figure 7 (for a variation of the crack length of 100 μm the reading suffer a variation of 129 mV)

The noise affects the resolution. With a current of 2 A and a gain of 50000 (maximum gain allowed by the equipment), the resolution is affected by noise as can be observed in figure 8 and figure 9.
Fig. 7 - Calibration curve. Current = 50 A; Gain = 6000.

Fig. 8. Reading with a reference channel. I=2 A; Gain= 50000.

Fig. 9. Noise of the readings. I=2 A; Gain= 50000.
We clearly observe the existence of a noise with an amplitude of 2 mV. Even better results can be obtained with lower gains. Thus, for a sensitivity of 0.8 \( \mu \text{m} \), the resolution of crack length readings in the referred test conditions (current=50 A; gain=6000) is 1.6 \( \mu \text{m} \).

5 Validation of the Calibration Procedure

In order to validate this calibration procedure some specimens were tested until they reached different crack lengths, according to the calibration curve. Then, the tests were stopped, the specimens were broken and the crack lengths measured with an optical microscope. The results are displayed in table 1.

Table 1: Values of the crack lengths read with DCPD system and from optical microscope.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Crack lengths optical microscope (mm)</th>
<th>Crack lengths DCPD (mm)</th>
<th>Corrected values (mm)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.66</td>
<td>0.60</td>
<td>0.65</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>1.04</td>
<td>0.96</td>
<td>1.01</td>
<td>2.9</td>
</tr>
<tr>
<td>3</td>
<td>1.20</td>
<td>0.98</td>
<td>1.03</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The corrected values result from the fact that the first 100 \( \mu \text{m} \) are not linear as can be observed in figure 7. The correction of this value that corresponds to an error of about 50 \( \mu \text{m} \) in relation to the calibration straight line gives origin to the corrected values presented in the table. After that correction, the maximum error is 6%.

Fig. 10 shows a morphology of specimen 2 in order to see the geometry of the crack.

Fig.10. Morphology of specimen 2. Crack with a depth of 1.04 mm.
6 Conclusions

The main conclusions of this work are:

- A quick and reliable calibration procedure was obtained;
- It is possible to balance high sensitivities with low noises achieving very good resolutions;
- For the study of small cracks and for round specimens, a resolution of 1.6 \( \mu \text{m} \) was achieved;
- Low reading errors are obtained (less than 6%);
- Particular attention is necessary to the first 100-200 \( \mu \text{m} \) where the calibration curve may not be linear.

References


