Measurement of crack length and profile in thick specimens and components using modified DCPD method

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Abstract

Measurements of critical parameters of fracture and fatigue crack growth under mono- and biaxial loading, parameters of leak-before-break, performed usually on laboratory specimens, are often needed to be verified on large scale samples, components or structures. For these measurements, exact information on crack length and profile is an essential condition for performing valid and reproducible tests. As optical methods do not provide any information on internal crack profile, indirect methods have to be used. A modification of direct current potential drop (DCPD) method has been proposed and experimentally verified for: (i) cracks in rectangular specimens of great thickness, (ii) surface fatigue cracks in thick pipes, (iii) through-thickness cracks in pipes with placement of electrodes near crack tip. Precision of the methods and their limits are discussed and results of experimental verification are shown.

1 Introduction

The direct current potential drop (DCPD) method represents one of the possibilities to measure lengths of cracks during either long-time laboratory tests of fatigue crack growth or short-time tests and investigations of problems of fracture mechanics, e.g. measurement of
fracture toughness and J-integral. The DCPD method works on the principle of an occurrence of a potential drop caused by a discontinuity in a specimen, such as crack, when a homogeneous direct current of a sufficient value passes through the whole cross section of a sample.

A big advantage of the DCPD method is the possibility of an analytical expression of the potential drop for various configurations of electrodes, different shape and dimensions of a specimen. Johnson's formula [1] and its modification [2] is one of the most frequently used relations for the analytical description of the dependence and calculation of crack length from the potentials in specimens of a rectangular cross section with a through-thickness crack of straight crack front. Similar expressions also have been derived for other shapes of cracks, e.g. angled cracks [3]. For several shapes of specimens and cracks, possibilities of analogue methods of calibration or combinations of both analogue and analytical methods have been used [4,5]. Eventually, one of possible modifications of the method, suitable for specimens of small length frequently used in laboratories, including CT-specimens, has been described and discussed in [6].

Advantages as well as complications connected with an application of DCPD method were discussed in [6]. It should be remind that the problems, like high-capacity current sources or a necessity to insulate specimens, are mostly negligible in laboratory conditions, in comparison with the characteristic advantages as stability, reproducibility and insensitivity to movement of cables. Therefore, possibilities of an application of the method in unusual cases as measurement of crack length in elastic-plastic fracture mechanics or evaluation of creep crack growth have been recently studied [7]. In any case, the DCPD method represents one of the most reliable and convenient method of automatic monitoring of crack growth process, suitable to be included into monitoring systems controlled by computers.

2 Basic relations of the modification

The modification of DCPD method for short specimens with rectangular cross section described in [6] enables to measure the reference potential used to compensate changes of electric current density due to several reasons in a near-crack region, where the reference potential is affected by the growing crack. The crack length is evaluated using the Johnson's formula:
Figure 1: Placement of electrodes on specimen of rectangular cross section

\[
V(a) \arccosh \left( \frac{\cosh(\pi y/2W)}{\cos(\pi a/2W)} \right) = V(a_o) \arccosh \left( \frac{\cosh(\pi y/W)}{\cos(\pi a/2W)} \right)
\]

(1)

\(a_o\) being the initial crack length, \(V(a_o)\) the corresponding potential and \(y\) represents the distance of electrodes from crack mouth. If reference potential \(V_{\text{ref}}\) is measured, than the quotient \(V(a)/V_{\text{ref}}\) instead of \(V(a)\) is used in the equation.

For reference electrodes placed near the crack mouth according to Fig.1, the reference potential is a function of crack length which can be expressed using correction function \(Q(a)\):

\[V_{\text{ref}}(a) = V_{\text{ref}} Q(a).\]

(2)

The function \(Q(a)\) can be expressed with the help of functions \(k_3(a)\) and \(k_4(a)\) representing the Johnson's formula, where \(y=y_1\) and \(y=y_2\), respectively. In a similar way, \(k_3(0)\) and \(k_4(0)\) is Eqn. (1) for \(y=0\). Then

\[Q(a) = \frac{[y_2/y_1] k_4(a) k_3(0) - k_3(a) k_4(0)}{[y_2/y_1] k_3(0) - k_4(0)}\]

(3)
The measurement and calculation can be simplified using a single electrode instead of the electrodes 2 and 3. Then \( y_1 = y_0 \).

Unlike the case of reference potential \( V_{\text{ref}} \) not being affected by growing crack, when crack length can be calculated directly from Eqn. (1), calculation with the correction function \( Q(a) \) has to be made using numeric methods of gradual approximations.

Advantages of the analytical expression of potentials in Eqn. (1), representing the solution of the Laplace equation, are limited for simple cases as specimens with rectangular cross section. The Laplace equation can also be tackled using numeric methods, e.g. finite element methods. Then practically no limits exist. On the other hand, these methods are very time-consuming and, moreover, the solution is valid mostly for a specific configuration of electrodes which can not be changed. In several cases, there are, however, possibilities to use alternative approaches, partially approximate. Some of these cases are described in this work.

3 Modification of DCPD method

3.1 Thick specimens of rectangular cross section

This type of specimens has been used for investigations of effects of great thickness either on static fracture or on fatigue crack growth. A concrete example of such specimen including dimensions is in Fig.2. The task was to perform fatigue precracking with an exactly determined target crack length and straight crack front. The condition of straight crack front is one of the main problems in such cases because of different growth conditions inside the specimen and in the near-surface areas on the sides. Crack closure is normally one of the most important reasons causing the retardation effect occurring either inside or near the surface.

A configuration of five rows of potential and reference electrodes according to Fig.2 was proposed to monitor differences between the potentials through thickness. The lengths of crack were calculated for each of the five sites separately using the corresponding potentials. As shown in Fig.3, the differences were distinct. There was a strong retardation of crack growth in the central area which could not be found out by optical measurement or standard DCPD measurement using a couple of electrodes (or a single row of electrodes). The information on the curved crack front enabled to change loading conditions, as asymmetry of cycle and load range, to reach the straight front at the final steps.
Figure 2: Triples of electrodes in five rows to monitor crack profile

It should be mentioned, however, that the information on the curvature of crack front only has a qualitative character provided that simultaneous optical measurement of crack length on the sides is not performed. The real crack front at one of the first stages is shown in Fig.4. Potentials at each point result not only from the crack length at the corresponding through-thickness distance, they are, however, also affected by crack length at other points. In comparison with reality, the differences are therefore partially eliminated as shown in Fig.4.

3.2 Surface cracks in tubes

For several investigations of pipes, e.g. leak-before-break problems, fatigue precracking aimed at forming cracks perpendicular to the axis is requested. In such cases, exact crack length determined not only on the outer surfaces, but also inside is needed. It will be shown that this task can be solved with the DCPD method without a need for finite element analysis or another complicated numeric method.

The analytical formulae (Eqns.1-3) can be used with the following approach and modification. The ring cross section of a tube can be assumed to have arised as a result of connection of two curved flat specimens (plates) with the same rectangular cross section together. The thickness of the two specimens is the same as thickness of the tube and their width W ("equivalent" width) conforms to the condition of equivalent cross section area as shown in Fig.5. Since the DCPD method does not measure in fact crack length, but quotient of cracked and uncracked areas in the cross section, Eqn. (1-3) can be used provided that W equals to the
equivalent width. In case of radial crack front of a through-wall crack, internal and external crack length can be simply calculated.

The problem is that the crack is initiated from a shallow surface notch. The cracks begins to grow from the outer surface. To control the process, the combination of optical measurement on the outer surface together with DCPD measurement of cracked area provides sufficient information and crack depth can be estimated. A quite exact evaluation of crack profile can be made with the aid of formula for stress intensity factor (K-factor) for surface penny shaped crack for all the sites of the crack front [8]. A simple numerical integration in several steps using the Paris equation for fatigue crack growth \((da/dN = C \Delta K^{n})\), known for the material being used, demonstrated that the shape of the crack before penetrating the wall corresponded to the ellipse of surface length being more than 3.5-times greater than the depth. The beach-marking on the cracked area after the final cracking in Fig.6 confirmed this computed assessment.

The point of singularity corresponding to the penetration of crack through the wall is very important due to the instantaneous change of K-factor. Fortunately, there is another possibility to monitor this point with the described modification of DCPD method. If the dependence of potential measured near the center of the notch (the central row of electrodes) on surface crack length is monitored, a distinct discontinuity shown in Fig.7 occurs. The potential quickly grows due to the preferential crack growth inside the tube after the penetration. This transient effect is
3.3 Special configuration of electrodes on thick tube

Another configuration of electrodes different from the standard placement described above may be sometimes needed for several reasons. The participation on the evaluation of fracture properties of pipes for nuclear power plants under elastic-plastic conditions having been recently performed can be shown as an example. Crack growth under static loading was measured in the part of the pipe of the thickness 90 mm and external radius 660 mm, with a through-thickness crack perpendicular to the tube axis of the initial length 390 mm in the circumferential direction. The problem was that the experimental arrangement did not allow to attach
electrodes to the central row, but close to both ends of the initial crack.

A partially analogue method was proposed to calibrate DCPD measurement with this configuration. The situation was simulated on the flat specimen shown in Fig. 8. Besides the standard triple of electrodes on the top edge, additional triple was attached onto the side and a growing crack was simulated by cutting. The results are in Fig. 9. Potentials measured on the top row corresponded exactly to the theoretical calibration represented by the solid line. Potentials measured on the side row are represented by the points. There were negligible changes of potentials on the side before the crack tip reached the distance 21 mm from the edge, the distance at which the electrodes were placed. After the short transient region, the calibration curve calculated for the standard placement of electrodes in the top and analogue curve measured on the side were almost exactly parallel. A simple shift of the curve in the vertical direction corresponding to the value dV resulted in an acceptable error (da in Fig. 9) corresponding to 3.5 % of the total crack increment. A more complicated shift perpendicular to the tangent of the curve at each point would give almost exact results. This method is also very suitable for some other cases like CT-specimens.
Figure 8: Placement of electrodes on top edge and side of specimen.

Figure 9: Calibration curves for the different placement of electrodes.

4 Conclusions

The use of direct current potential drop (DCPD) method modified for short specimens in several special cases different from standard specimens of rectangular cross section has been discussed and modifications of the
method without finite element analysis have been proposed and experimentally verified. The results can be summarized as follows:

1. Curved crack profile in thick specimens can be monitored qualitatively. A more exact quantitative evaluation can be made if at least crack lengths on both the sides are available.
2. Profile of a surface crack in tube can be exactly evaluated if surface crack length is known.
3. If potential electrodes have to be placed near the crack tip, not near the mouth or the center of the notch in pipes, the two calibration curves are parallel to each other and the shifted original curve can be used.

References


