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Calibration of the potential drop method for monitoring small crack growth from surface anomalies – Crack front marking technique and finite element simulations

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ABSTRACT

The Direct Current Potential Drop method is one of the possibilities to measure the crack growth during fatigue tests without optical access to the sample. The accuracy of this technique applied to short cracks mainly depends on the calibration curve. In the present work experimental and numerical approaches are proposed to calibrate the potential drop measurement. An optimization of the calibration procedure is supported by finite element calculations. The crack front shape and the location of the potential probes are found to be of great influence. An extensive study is conducted to identify all the mechanisms controlling the potential drop measurement. Plastic deformation remains the last parameter which is not directly considered in this study; therefore a calibration strategy is suggested to take into account this effect and achieve a calibration curve with high accuracy. This strategy shows a very good agreement between the obtained calibration curve and the experimental calibration.

1. Introduction

The Direct Current Potential Drop (DCPD) method has been widely developed and used over the past decades in fatigue researches. This technique allows in particular the detection of crack closure [1,2] and can be derived for the visualization of multiple cracks [3,4] or the monitoring of cracks in mode II [5]. However the main application of the DCPD method is the crack length determination during standard fatigue tests where a crack propagates in mode I [6], especially in cases where optical access to the sample is not possible. Due to its stability, reproducibility and reliability, this technique is selected in many studies to automatically monitor fatigue crack growth.

The principle of the DCPD method is based on a constant electrical current passing through the specimen and the measurement of the potential difference across the crack. As the crack extends, the electrical resistance of the uncracked cross sectional area rises and thus the measured potential drop increases. The main objective is then to determine the most accurate calibration curve to relate the potential drop to the crack length. Many studies have been undertaken with this aim. In most cases, experimental calibration curves have been obtained using optical measurement of the specimen surface [7], by machining slots of increasing lengths in a single test specimen [8] or by marking the fracture surface using a single overload or a change in mean stress [9]. Experimental analog techniques were also investigated using electrolytic tank simulations [10] or simply by cutting graphitized paper [11] or thin aluminum foil [9] to simulate crack propagation. Theoretical calibrations have been developed solving the Laplace equation. Johnson's formula has been widely used and improved over the years [12–14]. Despite the fact they are more complex and not easily applicable, conformal mapping procedures allow to obtain analytical solutions for notched specimens [15,16]. Other calibration curves have been achieved by numerical calculations using finite element analysis [17,18]. This method is especially suitable for the optimization of the accuracy, sensibility, reproducibility and measurability of the potential drop technique. The ease to change the specimen geometry in the calculation is another advantage of the latter method.

In the present paper, the DCPD method is applied to the examination of crack growth from surface anomalies. Indeed, aircraft engine manufacturers have to demonstrate that the presence of small surface anomalies in critical areas do not lead to the structure failure. A study is undertaken in order to characterize the

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harmfulness of surface anomalies and their influence on fatigue life of Direct Aged (DA) Inconel 718 alloy. The DCPD method is used to monitor the initiation, micropropagation and propagation of a crack which initiates from surface anomalies during a fatigue test.

The accuracy of the DCPD method depends mainly on the calibration curve. The objective of the present work is to propose simple methods to calibrate the DCPD method in general case with a high degree of precision. More precisely, numerical and experimental approaches are developed to identify the physical factors controlling the potential drop measurement and thus optimize the identification of a calibration curve.

2. Experimental procedure

The DA Inconel 718 alloy is a Ni-base superalloy which derives his strength from hardening precipitates within the solid solution matrix. This superalloy is widely used in high temperature applications and in particular for high pressure turbine discs due to his high mechanical properties and fatigue performance [25].

Fatigue tests are performed under load control on a MTS hydraulic machine using a sinusoidal waveform signal, a frequency $f = 2$ Hz and at a temperature of 550 °C. The loading conditions were selected in order to cover the stress field encountered during in-service operation of high pressure turbine discs. Fatigue specimens containing two surface anomalies are used for the experiments. Details of the specimen geometrical configuration are indicated on Fig. 1. Finite element simulations proved that a distance of 6 mm between the surface anomalies is sufficient to avoid any interaction between cracks starting from anomalies [26]. Indeed, these calculations show that, at the maximum load range, the stress fields around cracks starting from the two anomalies do not impact each other. However, this statement is only valid in the load conditions under study. The specimens are equipped with a potential drop method to perform crack growth measurements. Two different geometries of anomalies are introduced in the specimens. Scratches are V-type anomalies of 1 mm long and dents are U-type anomalies of 2 mm long. The depth varies from 25 μm to 150 μm for scratches and from 100 μm to 200 μm for dents. The V-profile of scratches presents a notch radius of 30 μm and an angle of 90°.

The potential probes (platinum wires of 0.1 mm diameter) are spot welded symmetrically on both sides of the anomaly. The position of the probes is identified by small Vickers indents. The anomaly width on the surface depends on the depth and the type of anomaly; therefore two different positions for the probes are used. They are positioned to 800 μm on both sides of the crack plane for scratches and 1050 μm for the dents. The control of the power used to weld the probes on the specimen surface is crucial. Indeed, the weld acts as a microstructural notch and initiation under the weld has already been observed [19] and makes the test inoperable.

A continuous current is periodically injected to avoid specimen heating. The electrodes allowing the current injection are screwed on the fatigue machine lines. To avoid any electric noise, the load lines are electrically isolated from the machine frame. A device equipped with two acquisition channels is used to acquire the potential drop measurements corresponding to the cracks initiating from the two surface anomalies. The acquisition is synchronized with the maximum load at each cycle.

The experimental calibration is achieved by means of heat tints as a crack front marking technique. This technique consists in interrupting the fatigue test at different stages of the propagation life and maintaining the specimen at zero force and high temperature for a given time to form an oxide layer which colours the fracture surface. The crack depth corresponding with this marking is then optically measured to determine the calibration curve. In the case of DA Inconel 718 alloy and for the load conditions of the present study, the crack growth rate is not influenced by the heat tint procedure. Indeed, for a given load configuration the same fatigue life is obtained from specimens tested with and without heat tints. Furthermore, the analysis of the crack growth rate data confirms that no delay or acceleration of the crack growth rate is observed after heat tints. Thus no specific specimen is needed to calibrate the DCPD method and data obtained from both heat tinted and un-marked specimens can be used to characterize the harmfulness of surface anomalies. This technique is very simple, low time consuming (two hours were sufficient to realize a heat tint in the present case), easy to implement and furthermore permits to monitor the crack front shape during the propagation after the test. This is a crucial point discussed later because the potential drop highly depends on the crack front shape. Fig. 2 illustrates the procedure of heat tinting (c) and shows an example of fracture surface after heat tints for a scratch (a) and a dent (b). The evolution of the crack front shape initiated from scratches and dents will be discussed later.

3. Numerical approach

A numerical tool has been developed to calculate a calibration curve using finite element analysis. An Abaqus CAE model coupled with a Python script has been used to solve the three dimensional electrical problem. Assuming a steady state electrical potential, it consists to find the solution of Eq. (1):

$$J\rho = -grad(\Phi) \tag{1}$$

Φ being the electrical potential, J the current flow and ρ the electrical resistivity of the material.

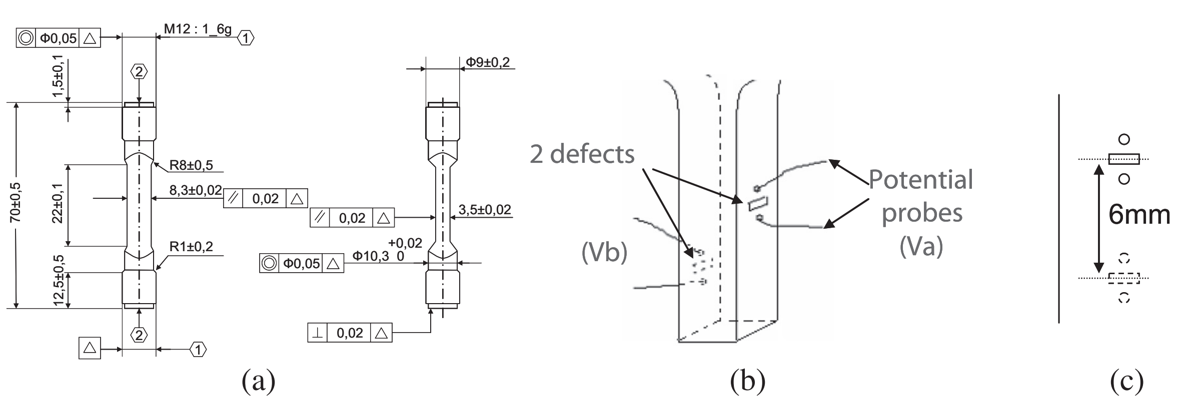

Fig. 1. Geometry of fatigue sample (a). Position of both anomalies and potential probes on the fatigue sample: 3D view (b) and front view (c).