# Potential drop technique for bifurcated fatigue crack growth, limitations and comparison with optical methods.

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**Abstract.** This experimental work deals with the application of Direct Current Potential Drop technique (DCPD) on a cross-like specimen for the study of crack growth and crack bifurcation. The specimen has a cruciform geometry and undergoes alternatively equibiaxial and uniaxial loadings. The specimen is instrumented with DCPD method and with two optical monitoring devices: classical optical and 3D Digital Image Correlation (DIC). The DCPD calibration is done by a numerical way based on 3D Finite Element (FE) calculations with 3D numerical crack growth and electrical conduction simulations. A small crack is inserted in the specimen mesh and is grown by a G-θ method with conform remeshing tools in the Z-set software. Good agreement is obtained between optical and DCPD methods for equibiaxial conditions. Nevertheless it is observed that the DCPD method overestimates the crack length during bifurcation and uniaxial loading. The difference seems to be linked with local crack closure effects.

## Introduction

Recent advances in adaptive remeshing techniques now gives the possibility to efficiently simulate complex 3D crack growth using conform meshing of the discontinuity [1]. For instance, Zcrack, is a numerical tool especially developed for 3D crack growth [2]. It's a toolbox linked with the Z-set software jointly developed by Mines Paristech, ONERA and NW Numerics & Modelling. This kind of numerical tool appears to be very interesting to study crack bifurcation problems and especially for the calibration of the DCPD technique [3] knowing that calibration is the step allowing to convert electrical potential evolution into crack length. Indeed classically, three calibration methodologies can be employed:

- Experimental calibration
- Analytical calibration
- Numerical calibration, that is to say a calibration by FE calculation

The use of experimental curves is probably the most common method. For this one may use either an optical method or a special marking during the propagation by varying loading parameters. For this last point a post-mortem observation of lips can reveal a special marking associated to the parameter modification. It may appear like the most natural calibration method since it implicitly includes various influencing factors as material parameters and geometry of the problem. However this method is specimen and time consuming and is not transposable when we operate to a problem change [4]. Another method is to use an analytical solution. For instance Johnson [5] calculated an approximated solution for a single crack in a plate. An undisputed advantage of the analytical calibration is the ease of implementation but it's obviously limited to very simple geometries. The last strategy is to simulate the problem with a FE method by inserting different crack lengths in an electrical conduction problem. This calibration method has been developed since the late 1970s [6] and can be easily applied to a complex problem in the condition that adapted numerical tools are available. In this paper we investigate the DCPD method and its FE calibration procedure on a complex specimen geometry undergoing a planar multiaxial loading. Our goal is to validate the FE calibration method by comparing results with two optical methods for crack length measurement.

**Experimental device & methodology**

In this study, the fatigue test is conducted using a planar biaxial device at a 5Hz frequency at room temperature. The experimental device was specifically designed and manufactured at ONERA. It is based on two hydraulic SCHENK actuators with 160kN capacity each. The specimen has a cruciform geometry with a cylindrical flat area of 10mm diameter and presents a cross-cut at 45° from the loading axis as shown on Figure 1. The material is the Ni-based polycrystalline superalloy N18.

As evoked in a previous paper [7], testing methodology for cruciform specimen requires the assessment of stress components in the gage area. Indeed in this configuration, one can show that the Poisson's ratio produces a structural effect called “ring effect”. It corresponds to a strong coupling between the two perpendicular loading axes. Considering the Linear Elastic Fracture Mechanics (LEFM) approach, the local stresses can be evaluated as follows:

$$\begin{cases} \sigma_{11} = \alpha F_1 + \beta F_2 \\ \sigma_{22} = \beta F_1 + \alpha F_2 \end{cases} \qquad (1)$$

with α and β, two coefficients depending of the Young modulus and also of the specimen geometry.

Identification of the coefficient requires a FE calculation without a notch and applying a purely uniaxial loading ($F_2$=0).

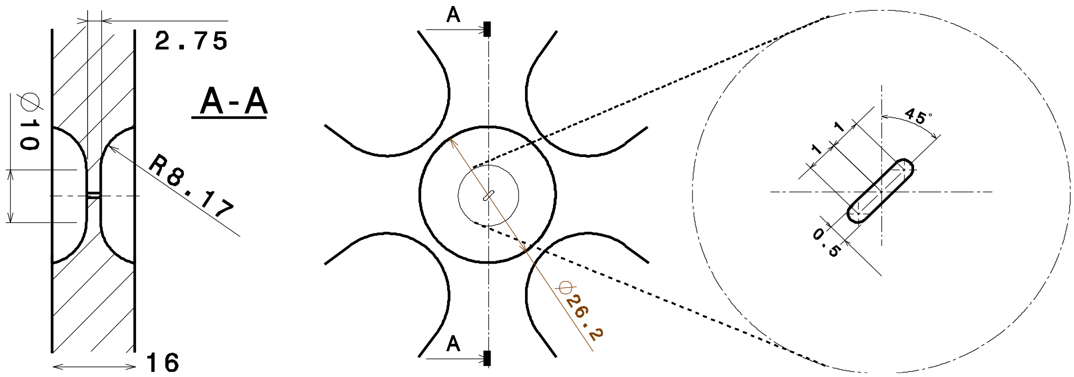
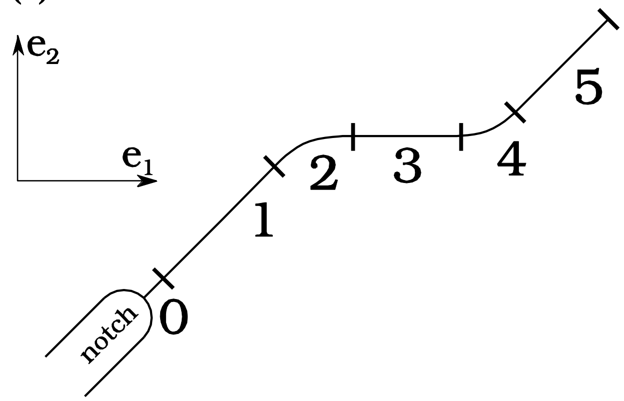



Figure 1 : Geometry of the cross-like specimen

Crack bifurcation is done in several phases as we can see Figure 2a. First, the specimen is submitted to an equibiaxial loading of 65.000 cycles in order to initiate the crack. Then the crack propagates along the notch axis for 31.500 cycles. Next comes a continuous transition of 5.000 cycles to change to an uniaxial state of stress. After that the crack propagates for 4.000 cycles in uniaxial. Another continuous transition of 5.000 cycles is applied to go back to an equibiaxial loading. Finally the crack is propagated for 9.100 cycles with an equibiaxial loading. Both of the transitions consist in a linear change of the maximal applied force on one axis and the right compensation on the other axis. Minimal stress always remains at a value of 0.05 times the maximal stress of the two axes. An example of equibiaxial to uniaxial transition in 5 cycles is shown Figure 3.

(a)




| n | loading | $N_{cycle}$ |
|---|---|---|
| 0 | Equibiaxial initiation | 65.000 |
| 1 | Equibiaxial | 31.500 |
| 2 | Equibiaxial to uniaxial (continuous) | 5.000 |
| 3 | Uniaxial | 4.000 |
| 4 | Uniaxial to equibiaxial (continuous) | 5.000 |
| 5 | Equibiaxial | 9.100 |

(b)

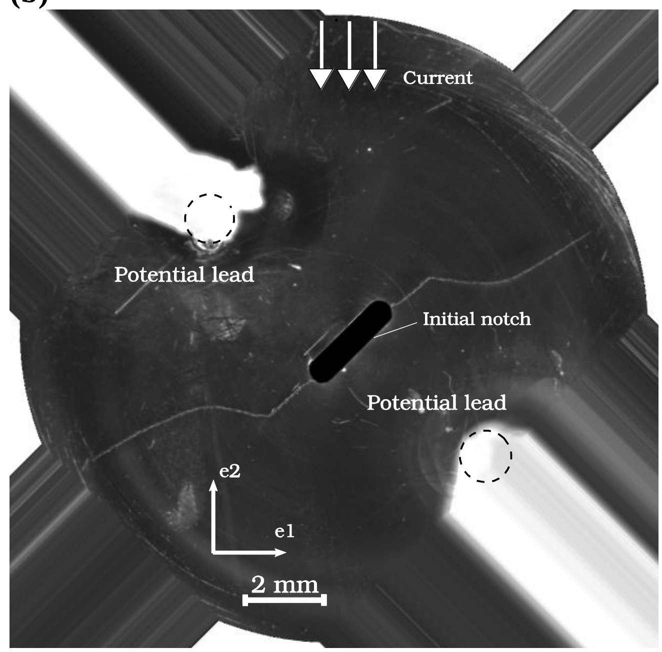



Figure 2 : View of the loading scenario (a): schematic view (b): Obtained bifurcated crack with classical optical method

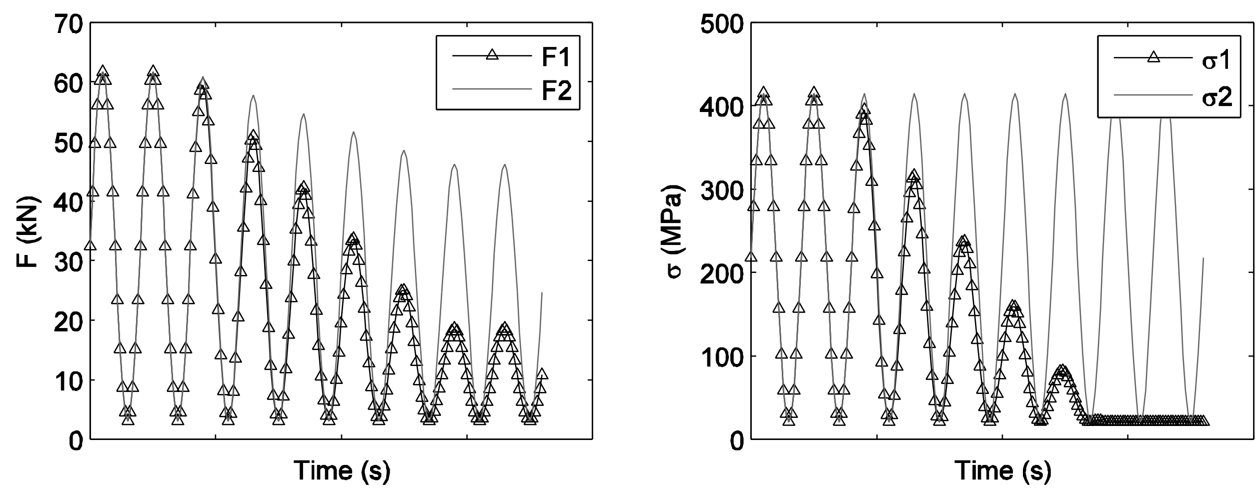



Figure 3 : Example of equibiaxial to uniaxial loading transition in 5 cycles and the associated stress components considering LEFM approach. Real experimental transitions last 5.000 cycles.

**Measurement techniques for fatigue crack growth.**

In order to track the crack front, three methods are used simultaneously as shown Figure 4: DCPD method, a conventional optical observation technique on one face and 3D Digital Image Correlation (DIC) on the other. All the optical measurements are triggered at the maximum of the loading force corresponding to the maximal crack opening. Crack length is considered as a curvilinear length from a front to the other and considering the initial notch, so that initial crack length is 2.5mm.

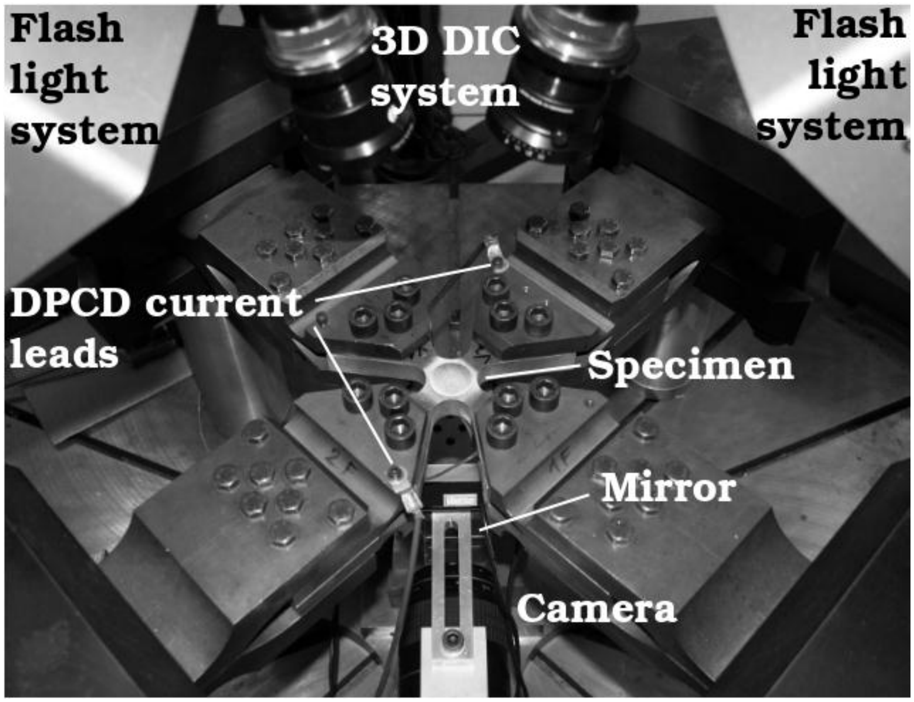



Figure 4 : Sprayed cross-like specimen mounted on a planar biaxial device with optical elements for crack observation.

**Conventional optical observation:** One side of the specimen is polished for classical optical monitoring. The optical observation device is a CCD camera (PCO-pixelfly, 1360x1024 pixels) with a 100mm lens. Lighting is provided by a tilt swivel LED. Because of the lack of space, images are taken through a mirror tilted at 45° from the sample surface.

**3D DIC:** Full-field measurement was performed using 3D Aramis DIC system (GOM GmbH) on the speckled side. Cameras are two ARAMIS 4M 2358x1728 pixels with 100mm lens and the measuring volume is 20x15mm. Speckle is done with white paint and black graphite spray. Stroboscopic illumination is used to acquire DIC images because of the 5Hz loading. Special attention was given to obtain synchronised homogeneous lighting condition. Results of the DIC system are shown Figure 5 in term of displacement and Tresca deformation so the crack appears clearly. Crack length is deduced from the visualization of Tresca deformation after thresholding.

**DCPD:** The DCPD system is based on an ANS system which provides a 5A current in the specimen. Two potential leads are welded at each side of the crack (Figure 2b). The main difficulty of this method is the calibration process that clearly appears to be the crucial point of this technique.

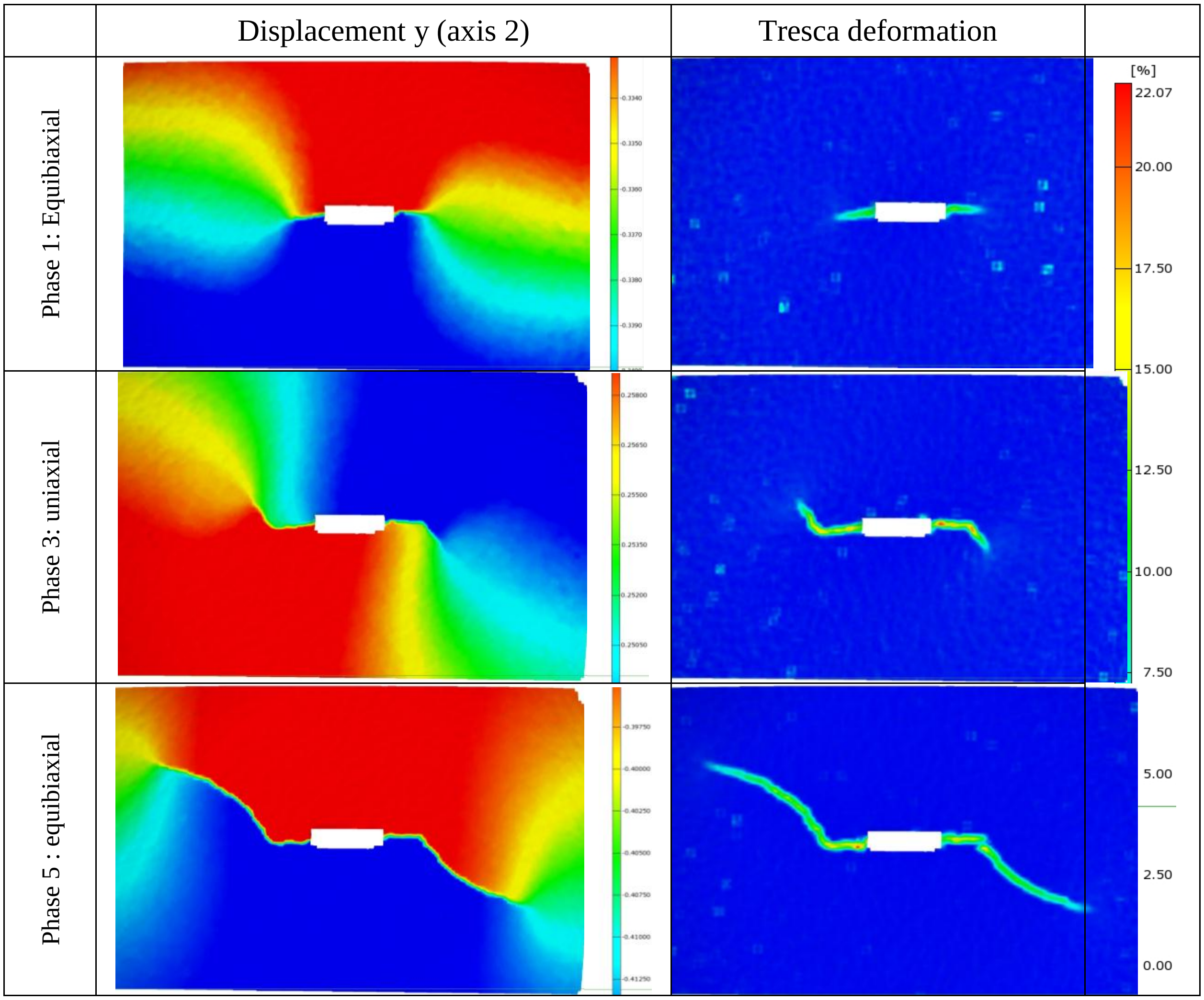



Figure 5 : View of the measured displacement field during crack growth (left) and tresca deformation (right)

**Calibration of the potential drop technique**

As we said in the introduction calibration of the DCPD technique is done in a numerical way using FE calculations. A small elliptic crack of several hundreds of µm is inserted at the notch bottom in the specimen mesh. Then the previously explained loading is applied to the cracked mesh so that the crack can propagate as in the experimental fatigue test.

Crack propagation algorithm is based on a G-θ method coupled with a linear elastic Paris model. Because plasticity effect is not taken into account yet into the crack propagation tool several loading adjustments has to be considered so that the good crack path is obtained numerically. This point is currently subjected to some research at ONERA but it remains a limitation of the FE calibration. Each cracked mesh is used into an electrical conduction FE calculation simulating the current leads and the potential leads as shown Figure 6.

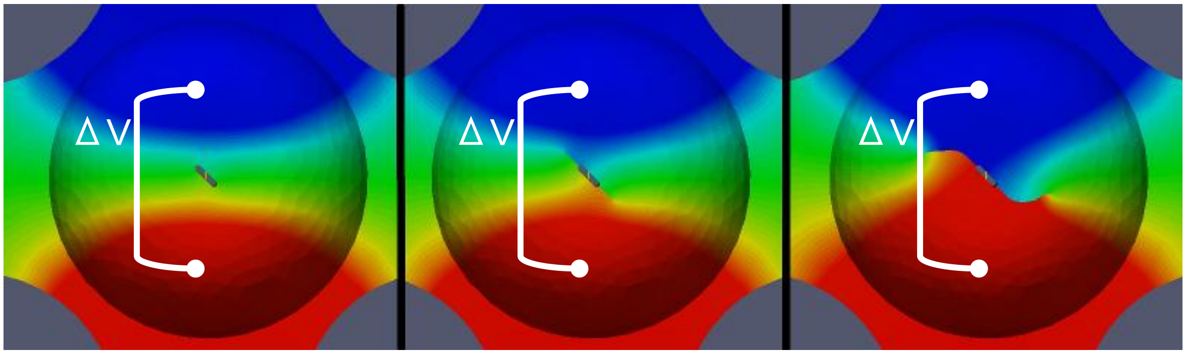


Figure 6 : normalized isovalue of electrical potential in FE electrical conduction simulation for the calibration of the DCPD technique

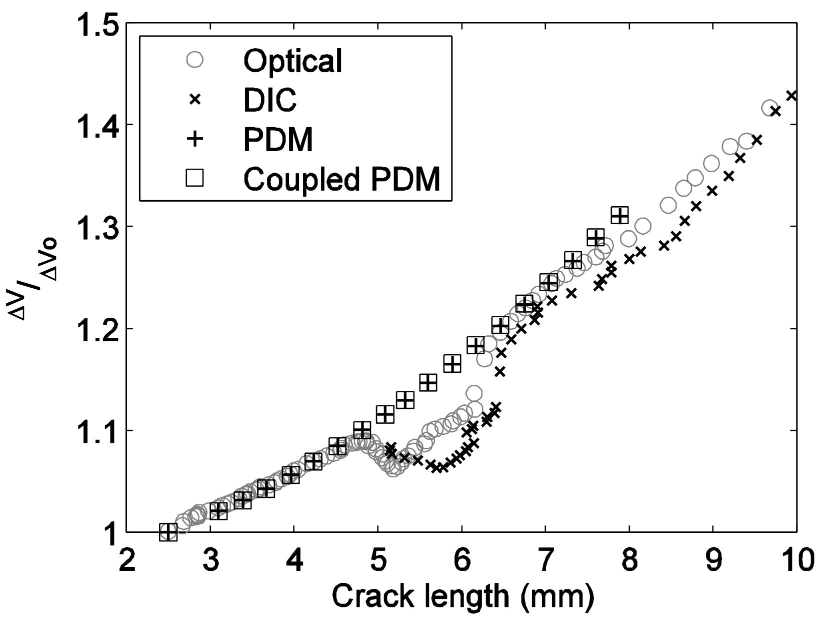


Figure 7 : Comparison of calibration curves from Potential Drop calibration Method and optical calibration method

The effect of the deformation of the specimen was observed by realising a coupled calculation between mechanical and conduction problems. Here the mechanical problem is considered under linear elasticity hypothesis. Thus potential leads distance increase is taken into account in the calibration. In order to eliminate the effect of conductivity and current amplification in the experimental device, the potential difference ΔV is normalized by the potential difference obtained with the initial mesh with the notch. Figure 7 presents the calibration curve obtained by the Potential Drop Method (PDM) calibration by FE technique and also results from classical optical measurements. This figure shows that the geometrical effect of elasticity does not play a role in this problem.

**Discussion on measurement methods for bifurcated crack**

The two optical methods were explored and compared to PDM on our curved crack configuration. Figure 8 presents the evolution of crack length regarding the number of cycles. The first remark is that DIC measurement noise of crack length may be linked with the inaccurate method used to artificially revealing the crack with Tresca strain. Even if displacement discontinuity is successfully detected, the resolution appears too low to show the crack tip accurately. This is especially true for small crack lengths and this is why it is not plotted on the curves. We globally observe a good agreement between the three measurement means for short and long cracks. Nevertheless a mismatch is significant between optical and DCPD methods during the uniaxial phase and the two transition steps. This difference is also visible on Figure 7. It means that crack closure effect acts significantly on the DCPD method but not on optical observations. It can be linked with the internal synchronization of the DCPD device which is not triggered with maximal crack opening.

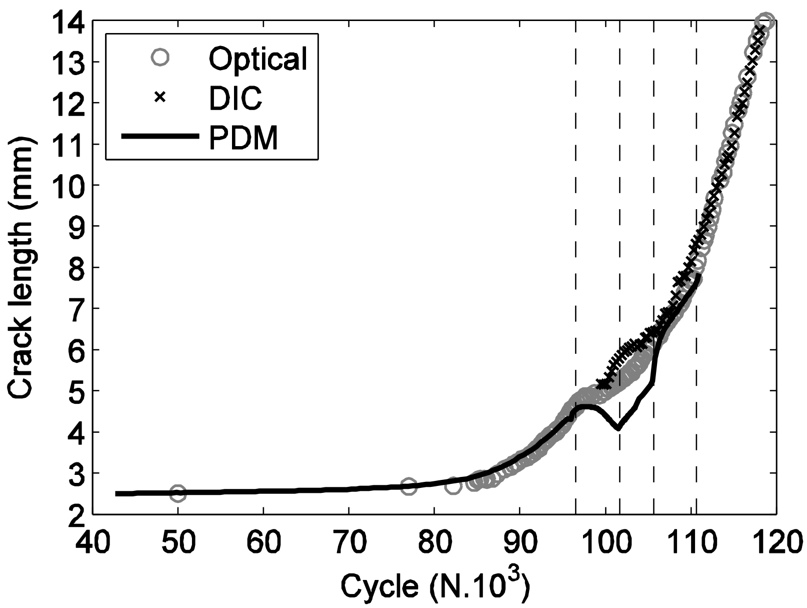



Figure 8 : Comparison of crack length measurement techniques

At a load ratio of zero, crack closure can usually be observed on cracked-center panel. Indeed different authors in literature, like Fleck et al. [7] indicate that a load ratio of 0.3 is classically necessary to avoid crack closure. This statement is reinforced by biaxial investigations of Theilig et al. [9] in which this load ratio gives no crack deviation due to the crack surface roughness induced friction. Moreover, as evoked by Schiijve [10], asperities may cause electrical short-circuiting which also leads to false indications. Finally the effect of the mechanical deformation on the DCPD method seems negligible since both of the coupled and non-coupled simulations give the same calibration curve.

**Conclusion & perspectives**

In this study, three techniques were presented to measure crack path and crack length on cross-like specimen: classic optical, DIC and DCPD methods. The load scenario was a 5Hz fatigue complex loading with different phases including uniaxial and equibiaxial loading with smooth transitions. Optical and DIC methods provided quite similar results in terms of crack length measurements. DIC appeared noisier because of the crack identification procedure with the Tresca deformation which is clearly not optimal. The DCPD method was simulated with FEM in order to realize the numerical calibration. DCPD measured crack lengths where shown to be in good accordance with other methods except during the uniaxial loading and transition phases corresponding to the most significant curvature. It was show that the under-estimation is not due to a coupling effect with the mechanical loading but seems to be linked with a crack closure effect.

Additional investigations have to be done in order to evaluate crack closure effect on DCPD method. A first possibility is to perform the equivalent test at a high load ratio in order to avoid contact between crack lips. Another way could be to add synchronization of the electrical measurement with maximal mechanical loading. Moreover the introduction of plasticity and contact in FE simulations could give information to better calibrate DCPD method in the case of complex crack growth. Because our goal is also to use DCPD at high temperature we could also expect an oxide layer on crack lips that can act as an insulator. This would confirm the crack lip contact hypothesis if the potential decrease is not observed with the same loading scenario.

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