**CALIBRATION OF THE POTENTIAL DROP METHOD BY MEANS OF ELECTRIC FE ANALYSES AND EXPERIMENTAL VALIDATION FOR A RANGE OF CIRCUMFERENTIAL AND ELLIPTICAL SURFACE CRACKS**

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**Abstract**

In experimental fatigue tests it is often necessary to monitor the onset of crack initiation, which is often defined at a given (short) crack length. Different experimental techniques are available to estimate the initiated crack size, one of which is the direct current potential drop (DCPD) technique. In this paper, the calibration curves reporting the potential drop change as a function of the crack depth, have been derived by means of 3D electrical FE analyses. Driven by previous experimental observations, two different crack shapes have been considered: (i) circumferential and (ii) semi-elliptical. Dealing with semi-elliptical cracks, the effects of the aspect ratio of the crack the potential probe locations, the three-dimensional flow of the electric current and the temperature have been investigated. Finally, the obtained calibration curves have been validated against experimental measurements, obtained by fatigue testing notched specimens under a selection of loading conditions.

**Keywords.** Titanium alloy; Potential drop method; Calibration curves; Crack shape.

**NOMENCLATURE**

*a* crack depth

c/a crack aspect ratio

R0 size of the structural volume for averaged SED calculation

r specimen net-section radius

T0 temperature of the reference un-cracked (*a* = 0) specimen

T temperature of the specimen undergoing fatigue testing

V0 potential drop of the un-cracked (*a* = 0) specimen

V potential drop of a cracked specimen

**Symbols**

2α notch opening angle

δI distance between the points for current supply

δV distance between the points for potential drop measurement

θ crack angular position with respect to the V-measuring-points

ρ notch tip radius

ρel electrical resistivity of the material

ρel,0 electrical resistivity of the material referred to room temperature, T0 = 20°C

**Abbreviations**

BN Blunt notch

DCPD Direct current potential drop

FE Finite element

FEM Finite element method

PDM Potential drop method

PL Plain specimen

SED Strain energy density

SN Sharp notch

1. **INTRODUCTION**

In fatigue experiments of specimens or components, crack monitoring is often adopted to investigate damage initiation and spreading. To develop and apply local models for fatigue life prediction it is often necessary to estimate quantitatively the crack size, for example when fatigue life is to be defined at a given physical crack size, occurring well before final fatigue fracture. In a recent contribution of the present authors1, the uniaxial and multiaxial experimental fatigue results obtained from sharp as well as blunt notched and plain bars made of Ti-6Al-4V have been re-analysed by employing the strain energy density2 (SED) averaged over a structural volume having size R0. In this context, a physical definition of “crack initiation” consistent with the SED approach can be singled out when the initiated crack depth leads to the structural volume failure, i.e. *a* equals R0.

Different experimental technique exist to measure the propagating crack size, one of which is the direct current potential drop (DCPD) technique, which has been employed in Ref.1 .

Several methods, which can be classified in experimental, analytical and numerical, have been adopted in the literature to derive the calibration curves of the potential drop method (PDM). Calibration curves can be experimentally4–11 derived by measuring the crack depth with another method and correlating this measurement with the potential drop provided by the PDM device. In the literature, experimental calibration curves have been mainly derived by optically measuring the specimen surface8, by machining slots of increasing depths in a tested specimen9 or by marking the fracture surface taking advantage of an overload or a load ratio change4. Other methods to experimentally derived calibration curves include the electrolytic tank simulations10 or the cutting of graphitized paper11 or thin aluminum foil4 to simulate crack propagation.

The calibration curves can be derived also analytically by solving the Laplace equation ($∇^{2}V=0,$ where V is the steady electrical potential), for given specimen geometry and PDM operating conditions. However, it should be noted that analytical solutions for Laplace equation are only limited to few geometrically simple cases4,12. Among these, the Johnson’s formula has been widely employed in the literature for SEB, CT and DCT specimens13–15. Exact solutions for Laplace equation have been derived also for notches by adopting the conformal mapping approach12,16.

The calibration curves of the potential drop method can be derived also by the finite element method (FEM), as highlighted in the early contributions by Ritchie and Bathe9 and Aronson and Ritchie17. Numerical calibrations allow to treat any kind of specimen geometries and PDM operating conditions, moreover they are less complex than analytical calibrations and less time-consuming than experimental ones. It should be noted that numerical calibrations allow also to investigate the effects of different parameters, mainly geometrical or related to the PDM setup parameters, and, possibly, to optimize them. In the early contributions on the topic, Ritchie and co-workers11,17 studied the effect of the positions of the current input and of the potential measuring probes on the calibration curves of SEN and CTS fracture specimens, while Clark and Knott12 evaluated the effect of the potential probes locations on V-notched components. Later on, the effects of the notch geometry, of the type of electric current input (concentrated or distributed) and of the mesh size adopted in the FE model have been analysed in detail by Wilson18 dealing with CT specimens. In all previous studies, 2D FE models have been adopted to derive the calibration curves of the potential drop method. In more recent contributions19–21, 3D modeling has been employed and the actual crack front shape has been taken into account. A detailed comparison between solutions obtained from 2D and 3D electrical FE analyses has been carried out by Gandossi et al.22.

In the present contribution, the calibration curves of the potential drop method are derived by means of 3D electrical FE analyses by considering the specimens’ geometries and the operating conditions adopted in Ref.1. The effects of the notch geometry, the crack shape, the three-dimensionality of the current flow, and the temperature difference between the tested specimen and the reference un-cracked one are investigated. Finally, the calibration curves are validated against experimental measurements.

1. **SPECIMENS’ GEOMETRIES AND EXPERIMENTAL SET-UP**

The material which has been tested in Ref.1 is a grade 5 titanium alloy, i.e. Ti-6Al-4V, whose chemical composition is reported in Table 1. The considered specimens’ geometriesare reported in Fig. 1 and summarised in Table 2.

The fatigue experimental results have been collected in Ref.1 by performing pure axial tests on a servo-hydraulic MTS testing machine and tests under pure bending, pure torsion and combined in-phase as well as out-of-phase bending-torsion loadings by using a flexible test bench equipped with two independent servo-hydraulic actuators. For more details about the testing equipment and the experimental results, the reader is referred to Ref.1.

The Matelect® DCM-2 direct current potential drop (DCPD) device has been adopted in Ref.1 and the experimental set-up is sketched in Fig. 2. Two specimens are adopted: one is the fatigue loaded specimen, while the other one is the reference unloaded specimen (see Fig. 2). The two specimens are connected in series and a 30-A-constant-current (I in Fig. 2) flowed through both of them, the supply cables being connected to each specimen at a distance δI from each other (see Fig. 2 and Table 2). During each fatigue test, the potential drops ΔV, relevant to the loaded specimen, and ΔV0, relevant to the reference unloaded one (see Fig. 2), have been measured by means of signal cables fixed at two points of each specimen at a distance δV from each other (see Fig. 2 and Table 2).

1. **CALIBRATION CURVES OF THE DCPD METHOD**
2. **Effect of the crack shape: circumferential crack versus semi-elliptical crack**

The calibration curves have been derived by means of 3D electrical FE analyses by considering the specimen geometries reported in Fig. 1. In agreement with the experimental observations performed in Refs.1,23 and summarised in Fig. 3, two different crack shapes have been considered: (i) a circumferential crack (see Fig. 4), typically observed under torsion1 and combined bending-torsion1 or axial-torsion23 fatigue loadings; and (ii) a semi-elliptical crack (see Fig. 5), which has been typically obtained under bending1 and axial1,23 fatigue loadings. It should be noted that the engineering assumptions on the crack shape illustrated in Figs 4 and 5 are idealizations of the actual more complicated material cracking behaviour. Dealing with semi-elliptical cracks, the effects of the aspect ratio *c*/*a*, *c* being the half-surface length, and of the crack angular position *θ* with respect to the potential probes (see Figs. 5a and b) have been investigated, according to the following FE analyses:

* the aspect ratio *c/a* was varied in the range between 3 and 10, such range being typical under pure axial and pure bending fatigue loadings, respectively, according to Ref.1 and next Figs. 13b and c;
* the angle *θ* was varied between 0° and 180° with step of 45°, any crack angular position *θ* being possible under pure axial fatigue loading (see Fig. 3 and an example in next Fig. 13b). Moreover, a couple of cracks at both 0° and 180°, respectively, have been considered, this configuration being typical of pure bending fatigue loading (see Fig. 3 and an example in next Fig. 13c).

All numerical models have been analysed using Ansys® software and by employing 3D, 10-node, tetrahedral, electric solid elements (SOLID 232 of Ansys® element library). According to Wilson18, the potential drop ΔV evaluated far from the notch tip is almost insensitive to the FE size, so that rather coarse mesh patterns, with a global element size d = 1 mm and a local one equal to about 0.5 mm, have been adopted in all FE analyses (see Figs. 4 and 5).

To reduce the computational effort, anti-symmetry boundary conditions have been applied on the specimen net-section, which translates in a 0-V-electrical-potential applied only to the un-cracked portion of the net-section area, in order to simulate the absence of electric contact between crack surfaces. Accordingly, in the case of a circumferential crack (Fig. 4), a a couple of cracks at 0° and 180° (Fig. 5a) and a single semi-elliptical crack at *θ* = 0° or 180°, only one quarter of each specimen has been modelled, taking advantage of the symmetry on the XY plane and of the anti-symmetry on the specimen net-section. On the other hand, in the case of a single semi-elliptical crack with *θ* ≠ 0 and 180°, Fig. 5b shows that half of each specimen had to be modelled, only the anti-symmetry condition on the specimen net-section being active. Furthermore, to simulate the experimental set-up of the Matelect® DCM-2, a 30-A-constant current was input in all FE models (I in Figs. 4 and 5). .

First, the uncracked specimen’s configuration has been analysed by performing 3D electrical FE analyses with a crack depth *a* = 0 and by evaluating the potential drop VA of Figs. 4 and 5. Then, the potential drop V0 has been evaluated as 2·VA, anti-symmetry boundary conditions being active.

After that, several analyses have been carried out by modelling a crack size *a*,in the range between 0.1 and 5 mm and the potential drop VA of Figs. 4 and 5 has been calculated. Finally, the potential drop V has been evaluated as 2·VA.

Table 3 reports a summary of all electrical FE analyses performed .

Figures 6a and b report the results in terms of ratio V/V0 as a function of the normalized crack depth *a*/r (r being the radius of the net-section), for a circumferential crack in notched and plain specimens, respectively. It can be observed from Fig. 6a that the more reduced the notch tip radius is, the more sensitive the potential drop method is, as it was observed also in3 deriving the calibration curves of notched steel specimens characterised by different notch tip radii.

Figure 7 reports the results for semi-elliptical cracks. Fig. 7 shows that the maximum sensitivity holds in the case of a double crack at 0° and 180°, the reduction of the specimen transverse section being maximum as compared to the other geometrical configurations reported in the figure. In the case of a single crack, the lower the crack angular position *θ*is, the more sensitive the potential drop method is for a fixed the crack aspect ratio *c/a*. It is worth noting that the dependence of the calibration curves on the crack angular position *θ* is closely related to the distance δV of the V-measuring-points considered here (see Fig. 2 and Table 2), indeed the greater the distance δV is adopted, the lower the dependence of the calibration curves on the *θ*-angle is expected.

Finally, Fig. 8 shows a comparison between calibration curves of the potential drop method obtained considering a circumferential crack, a double semi-elliptical crack at θ = 0° and 180° and a single semi-elliptical crack at θ = 0° or 180°. For the sake of brevity, only the case of a sharp V-notch with ρ = 0.1 mm and r = 6.5 mm is reported, the results for the other geometries being similar. Obviously, for a given crack depth *a* , the maximum sensitivity of the method is in the case of the circumferential crack, the reduction of the specimen transverse section being maximum.

1. **3D distribution of the electric current density**

The axis-symmetry of the circumferentially cracked geometries suggest to calculate the potential drop by adopting easier and less-time consuming 2D axis-symmetric FE models, even though approximate, and to compare the results with the 3D FE analyses reported in the previous paragraph.

The numerical analyses have been carried out using Ansys® code, by adopting a 2D, 8-node, quadrilateral, electric solid element (PLANE 230 of Ansys® element library) and by activating the axis-symmetric element behaviour (K-option 3 set to 1). Again, rather coarse FE meshes have been adopted and a constant current I = 30 A and a 0-V-electrical-potential have been applied to the FE model, as depicted in Fig.9.

The same set of analyses previously performed with the 3D model has been repeated with the axis-simmetric model and the comparison between the results have been reported in Fig. 10. For given a specimen geometry and a crack depth *a*, Fig. 10 highlights that the deviation of the potential drop V/V0 between 2D and 3D FE analyses is on the order of 1% in the case of short cracks (*a* ≈ 0.5 mm), while it increases to approximately 10% in the case of deep cracks (*a* ≈ 5 mm). This results quantifies the effect of the non-uniform distribution of the current density in the specimen transverse section, which the 3D models are able to take into account, the current input being localized at the specimen lateral surface (see Fig. 2). It is worth noting that these results are closely related to the distance δI of the current supply cables considered here (see Fig. 2 and Table 2), since the greater the distance δI , the more uniform the current is and consequently the weaker the 3D effects of the current flow. As a result, the greater the distance δI, the closer the calibration curves obtained with 3D and 2D axis-symmetric models .

Even at short crack lengths (i.e. on the order of few tenths of a millimetre), Fig. 10 demonstrates that the approximation introduced by the 2D models could be on the order of or even higher than the potential drop increase at the crack initiation during a fatigue test. Therefore, it is recommended to adopt 3D FE models to account for the three-dimensional effects associated to the current flow.

1. **Effect of a temperature difference between tested and reference specimens**

The DCPD experimental setup sketched in Fig. 2 adopts two specimens according to the “normalisation technique”, which allows to compensate any environmental temperature variation, provided that it equally affects both the tested and the reference specimens. However, the temperature of the fatigue tested specimen tends to increase (T in Fig. 2) due to both plastic strain energy dissipation into heat and also heat dissipation from the fatigue test machine. On the other hand, the reference specimen is kept at room temperature (T0 in Fig. 2), so that it hardly compensate any temperature variation of the tested specimen other than room temperature. Therefore, during a fatigue test a temperature difference between the two specimens, T = T - T0, could be generated and its influence on the calibration curves has been investigated in the present section.

The 3D FE models previously described and a temperature difference T varying in the range from 0 to 40 °C have been considered. To do this, the dependence of the electrical resistivity ρel of Ti-6Al-4V on the material temperature (see Fig. 11) has been taken into account in the FE analyses according to Milck24. First, V0 has been evaluated from the un-cracked (*a* = 0) specimen at room temperature T0 = 20°C, by using the relevant electrical resistivity ρel,0; then, V has been evaluated for the different cracked specimens at the temperature T = 20°C + T, by using appropriate electrical resistivity ρel(T) reported in see Fig. 11.

The obtained calibration curves have been reported in Fig. 12 as a function of the temperature difference T. For the sake of brevity, only the results relevant to circumferential cracks have been reported, the results for semi-elliptical cracks being similar. Fig. 12 highlights that the temperature difference T might affect the calibration curves, the deviation of V/V0 for a given specimen geometry and crack depth *a* being equal to 0.3, 0.7, 1 and 1.5% for T equal to 10, 20, 30 and 40 °C, respectively.

These results suggest that the temperature difference T between the tested specimen and the reference one could generate a variation of the potential drop on the order or even higher than the value to be measured at the crack initiation. Therefore, when the “normalisation technique” is adopted, it is recommended to monitor the temperature of both the tested and the reference specimens during fatigue tests.

1. **EXPERIMENTAL VALIDATION OF THE PDM CALIBRATION CURVES**

Some of the calibration curves reported previously have been validated by fatigue testing some Ti-6Al-4V specimens under a selection of loading conditions, according to Ref.1.

More in detail, three sharp V-notched specimens with ρ = 0.1 mm and r = 6.5 mm have been fatigue tested: one under pure torsion with a net-section shear stress range Δτ = 532 MPa, one under pure axial and the third one under pure bending with net-section normal stress ranges Δσ equal to 270 MPa and 490 MPa, respectively. Fatigue tests have been stopped at N = 126850, 160200 and 29800 cycles, respectively, corresponding to an experimentally measured potential drops ΔV/ΔV0 = 1.027, 1.012 and 1.011, respectively. The DCPD Matelect DCM-2 system has been adopted to perform the measurements. Then, all specimens have been brought to failure under static tensile load, to measure the geometrical parameters of the initiated crack by means of a digital microscope: the crack depth *a*, the aspect ratio *c*/*a* and the crack angular position *θ*, where applicable.

The results are shown in Fig. 13, where it can be observed that, as expected, a circumferential crack was initiated under pure torsion, while semi-elliptical cracks have been observed under pure axial and pure bending loadings. Under pure axial load, two semi-elliptical cracks having *c/a* in the range 3÷3.50 and *θ* equal to 143° and 176° have been obtained, while under pure bending loading, the typical double semi-elliptical crack at θ = 0 and 180° and having *c/a* in the range 10÷15 has been observed.

Fig. 14 reports a comparison between the calibration curves obtained numerically and the experimental values of the potential drop ΔV/ΔV0 with the corresponding crack size. It should be noted that in all fatigue tests the temperature difference T between the tested and the reference specimens has been monitored and resulted always lower than 5°C; therefore, the calibration curves derived for T = 0 °C have been adopted in Fig. 14. Moreover, in the case of pure axial loading, dedicated FE analyses have been performed by considering two equally sized semi-elliptical cracks with *c/a* = 3 and *θ* equal to 143° and 176°, respectively, in order to match the *θ* values observed experimentally in Fig. 13b.

A quite good agreement between numerical and experimental results can be observed from Fig. 14, the deviation between the measured crack depth and that estimated from the relevant calibration curvebeing about ±20%, if extreme values of the measured crack depth are considered, while it reduces to ±3% if average values are considered.

1. **DISCUSSION**

When applying the potential drop method to a given material, specimen geometry and loading condition, it should be noted that the crack shape (see examples in Fig. 3 relevant to sharp notched specimens made of Ti-6Al-4V), the aspect ratio *c/a* and the crack angular position θ, where applicable, are not known a priori. Therefore, to select the proper calibration curve to adopt, some preliminary fatigue tests should be executed on all combinations of the specimens’ geometries and loading conditions involved in the experimental campaign.

In all cases considered here, crack paths have been assumed normal to the specimen’s axis, which is the typical situation for sharp V-notched specimens (see Fig. 3). However, in the case of blunt notched and plain specimens made of Ti-6Al-4V and subjected to pure torsion fatigue loading, multiple cracks were seen to initiate along the longitudinal direction of the specimen, i.e. on a plane experiencing the maximum shear stress, as shown in the examples of Fig. 15; after a certain longitudinal crack paths then crack branching occurred causing previously parallel propagating cracks to coalesce. The potential drop method being sensitive to the reduction of section normal to the current flow, a reduced sensitivity would exist during propagation along the longitudinal direction, until crack branching occurs. To conclude this section, the wide variety of crack path orientations, which might be observed during multiaxial fatigue experiments suggests that the location of current input points and potential drop probes should be adjusted with dedicated numerical calibration analyses.

1. **CONCLUSIONS**

In the present contribution, the calibration curves of the potential drop method have been derived by means of 3D electrical FE analyses for sharply as well as bluntly notched and plain bars containing a range of circumferential and elliptical surface cracks, the latter having aspect ratios c/a in the range 3$÷$10 and a angular positions *θ* with respect to the potential probes in the range between 0° and 180°.

The effects of the notch geometry, the crack shape, the three-dimensional distribution of the current flux and the temperature have been analysed. The following conclusions can be drawn:

* Dealing with the effect of the notch geometry on the obtained calibration curves, given an initiated crack depth *a*, the ratio V/V0 increases with decreasing the notch tip radius ρ. Considering the effect of the crack shape for a given crack depth , the maximum sensitivity of the potential drop method is reached in the case of a circumferential crack. In the case of semi-elliptical cracks, the lower the crack angular position *θ*and the higher the crack aspect ratio *c/a*are, the more sensitive the potential drop method is.
* In the case of circumferential cracks, if the current flux distribution is assumed axis-symmetric and analysed by means of 2D axis-symmetric models, the calibration curves deviate of approximately 1% in terms of V/V0 in case of short cracks having size on the order of few tenths of a millimetre. Such deviation might be not small, since could be on the order of the potential drop increase to measure during a fatigue test at the crack initiation. Larger deviations up to 10% exist in the case of deep cracks.
* The temperature difference T between the tested and the reference specimens should be monitored during the fatigue tests to select the proper calibration curve to adopt: when T > 20°C the deviation in terms of V/V0 is greater than 1%.
* Finally, the calibration curves derived by means of FE analyses have been experimentally validated by fatigue testing sharp notched specimens under pure torsion, pure axial and pure bending loadings and by measuring the fatigue crack initiated at a given ratio ΔV/ΔV0. A good agreement has been observed, the deviation between the average measured crack depth and that estimated from the relevant calibration curve being about ±3%.

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