PROGRESS IN POTENTIAL DROP TECHNIQUE. APPLICATION TO THREE-DIMENSIONAL CRACK FRONTS

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ABSTRACT

This paper concerns the improvements done on the instrumentation used for determining the existence and the growth of a crack in an electrically conducting material.

An electronic circuit supplies the specimen with current pulses and performs a voltage measurement independent of parasitic voltages such as amplifier drift or thermoelectric voltage, with a good compromise between residual noise and response time. Moreover, the measurement may be synchronized with the cyclic application of the load.

The associated calibration system is of analogic type. It is made of a rheoelectric tank allowing the simulation of arbitrary crack fronts. Voltage readings corresponding to a few important cases are presented.

Lastly, the method is validated by tests of crack growth in prismatic and cylindric light alloy bars.

KEYWORDS : Cracks ; crack propagation ; measuring instruments ; electrical measurement ; calibrating ; rheoelectrical simulation.

INTRODUCTION

Prediction of fatigue crack growth in three-dimensional media is a current theme of research. For this type of problem, the experimental approach plays an important role, whether to help understanding the phenomena involved or for setting initial assumptions or validating prediction methods (Cruse, 1977 ; Labourdette, 1978 ; Son, 1978).
In such experiments, the main difficulty is the crack localization, and more particularly the determination of the crack front propagating through the structure.

Among the methods most often used, let us mention :

- striation counting on the cracked surface ; this method is delicate to interpret (Bathias, 1978) ;
- marking of the crack front by an appropriate loading ; marking by overloads may modify crack growth (Hodulak and co.workers, 1978).

The result provided by these methods is naturally only known after rupture of the specimen ; on the other hand, the methods listed below make it possible to follow the crack growth :

- compliance method, where we go back to the crack shape by measuring the specimen stiffness,
- classical electric method, where this crack shape is estimated from the voltage read between two points usually located on either side of the lips of the open crack, a voltage resulting from the passage of a current circulating within the specimen.

The difficulty common to these two methods is the establishment of a calibration curve defining on a global way the crack shape by a single parameter (stiffness or voltage) : to obtain a calibration curve, it is necessary in practice to use in parallel, at least once, one of the above mentioned first methods. Furthermore, this calibration will only be valid for tests where the crack front evolution is identical to that measured during calibration.

However, the great flexibility of use of the electric measurement led us to propose a method for determining the crack front based on this principle, and characterized by the following points :

— use of an instrumentation giving an acceptable residual noise ; this instrumentation has been developed for crack length measurements in thin sheets ;

— multiplication of measuring points for a given crack front, which gives a more complete information ;

— association with a calibration means of analogical type allowing, in particular, the simulation of an arbitrary crack front.

DESCRIPTION OF THE METHOD

Let us first recall the principle of any electric method : a current is made to pass through a conducting metallic specimen, and we measure the resulting potential difference between two points located on either side of the crack to be observed. The measured voltage is thus a function of geometric parameters such as specimen dimensions, crack length and location of potential sensors. It is also proportional to the applied current, as well as to the resistivity of the material the specimen is made of.

Characteristics of the Apparatus Developed

This apparatus partly reduces the drawbacks pertaining to the electric method such as :

— necessity of an intense current to obtain a useful voltage,

— drift of the c.c. amplifier which amplifies this voltage,

— sensitivity to voltages of thermal origin and to various noises.

It is characterized by the following points (Baudin et Policella, 1978) :

— electric supply by a pulsed current, one of the consequences of which being the reduction of the mean current ;

— the voltage characterizing the measurement is the difference of two readings made with and without current, eliminating the quasi static drifts of various origins, which also attenuates any possible noise due to the mains by a convenient choice of the time interval between two measurements ;

— during a crack growth test, the measurement can be synchronized with the signal of the force applied to the specimen so that the information is taken at the time of complete opening of the crack.

This apparatus is described in detail in reference (Baudin et Policella, 1978).

Application to the Continuous Observation of a Crack in a Thin Plate

This apparatus has been successfully used, in particular in the case of bending tests on light alloy and on IN100 alloy at 1000°C, as well as in tests of crack bifurcation (Baudin et Policella, 1978).

Furthermore, an electric method for measuring deformation and damage has also been developed thanks to this apparatus (Cailletaud, Policella et Baudin, 1980).

APPLICATION TO THREE-DIMENSIONAL CRACK FRONTS

As any experimental method, this presents two aspects : the measurement on a specimen itself, and the implementation, then the utilization of the corresponding calibration, the latter point being the more delicate.

Measurement on Specimen During a Crack Test

The principle of this measurement is represented on figure 1. The reading of multiple measuring points on either side of the crack is realized by a double contact sensor, whose translation can easily be automatized if the shape of the specimen cross section remains simple (e.g. rectangular or circular). The advantage of a mobile sensor is to allow a continuous measurement during its displacement ; however, point measurements by means of soldered contacts and switchings can also be considered for high temperature tests (up to 1000°C). The signal issued from the sensor is later amplified and applied to the electronic instrumentation.

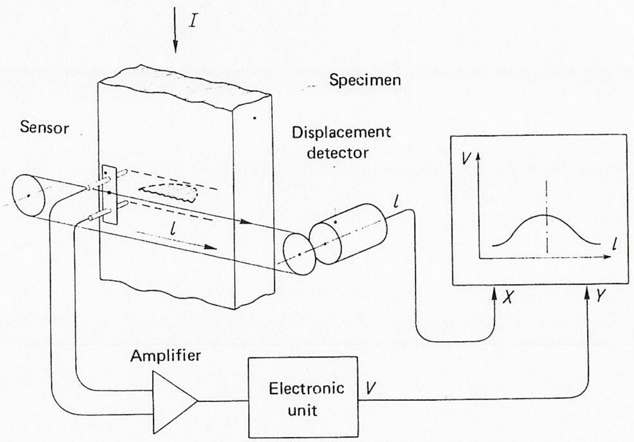

Fig. 1 — Principle of the electric measurement on specimen.

As shown on figure 1, the measured signal is directed to the Y channel of a graphic recorder, while the X channel receives a signal proportional to the sensor displacement. The result is, for instance, one of the curves of the set of figure 7.

Calibration

The problem is to establish the correspondence between a physical parameter (internal contour $\mathcal{C}$ of the cracked surface) and the measured parameter (V (l) curves). It can be solved by a three-dimensional calculation on a computer, but this solution is costly and lacks flexibility. That is why we called upon an analogical method, fast, easy to implement and eventually inexpensive.

Principle of Calibration by Analogy (rheoelectric tank) (Malavard, 1956). We reconstitute within a conducting medium the electric potential existing in the cracked specimen or structure. This conducting medium is water, and the tank used should represent the useful part of the specimen at a given similarity ratio. The crack is simulated by an insulating plate, and the voltage pick-ups are performed by means of a mobile sensor in the same way as in the mechanical test.

Figure 2 shows schematically how the crack front in a specimen is determined with this tank :

— we trace, from the specimen, the curve V(l) resulting from the application of the electric measurement (fig. 2a) ;

— we try to reconstitute, in the rheoelectric tank, a curve V'(l') similar to V(l), by successive modifications of the insulating plate representing the cracked surface (fig. 2b) ; the approximations are made by simply cutting off the plate ;

— the likeness of curves V and V' entails the conclusion that the real crack front and the drawn crack shape are in the specimen-tank similarity ratio.

In practice, it is easier to compare the curves $\frac{V}{V_{REF}}\left(\frac{\ell}{W}\right)$ and $\frac{V'}{V'_{REF}}\left(\frac{\ell'}{W'}\right)$; V_{REF} and V'_{REF} being the reference voltages measured before cracking, which permit one to ignore measuring parameters such as resistivity, amplification coefficient and applied current. In the same manner, all lengths (sensor displacement, distance between voltage pick-ups) are taken relative to the dimensions W and W', respectively widths of specimen and tank.

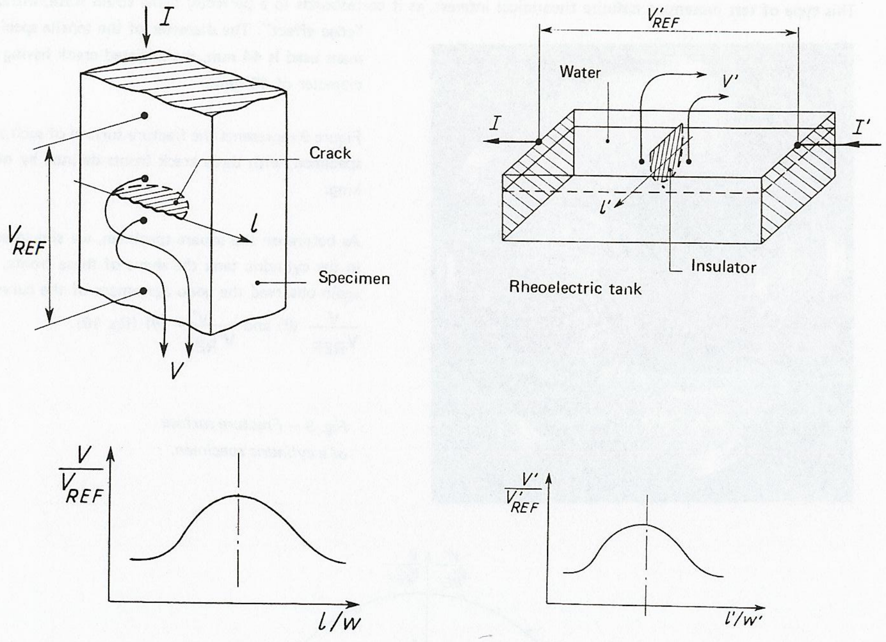

Fig. 2 – Principle of crack front determination by analogy.

Results. This calibration method makes it possible to measure the evolution of voltages V' for arbitrary crack front shapes. We present here a few cases more or less close to actual crack fronts.

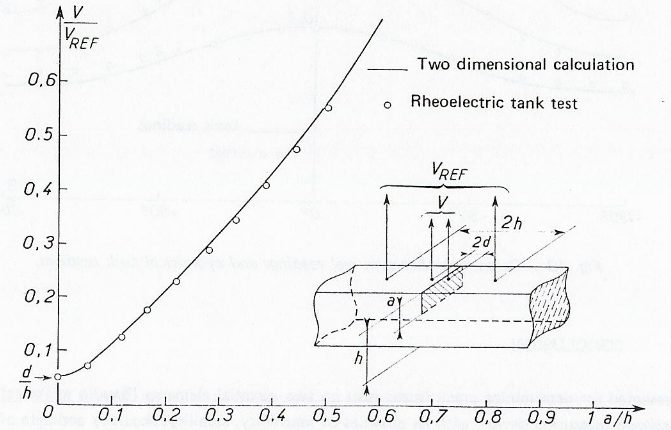

Fig. 3 – Calibration for a straight crack.

Square cross section parallelepipedic specimen

Figure 3 presents the case of a straight crack whose front develops parallel to the starting face. The curve V'/V'_{REF} picked up along the simulated crack lips is a horizontal straight line ($V' = cst$) for each crack depth a'. This example is important, as it is identical to the two-dimensional case for which a calculation method is available (Johnson, 1965). The good agreement of the measurement with the calculation result permits us to make sure that our calibration method is valid.

On figure 4 we present the set of curves obtained for a semi-circular crack of increasing radius.

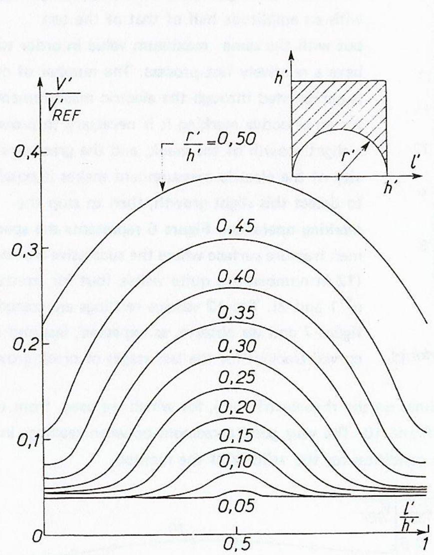

Fig. 4 – Readings for a growing semi-circular crack.

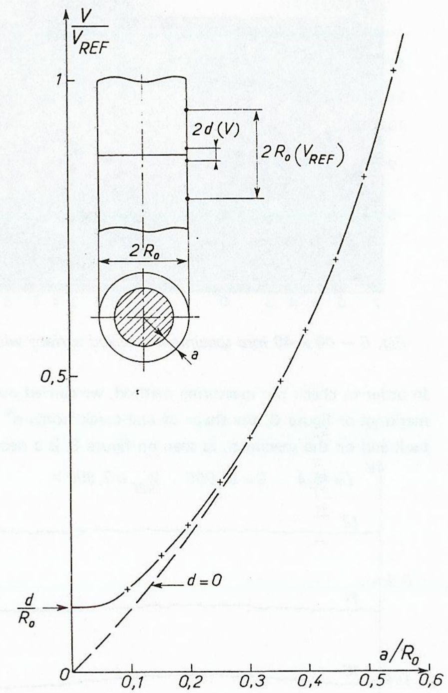

Fig. 5 – Calibration for circular external crack.

Cylindrical specimen

An important case is that of an external crack regularly developing around the specimen, the crack front remaining a centred circumference. Scanning around the specimen gives a constant voltage, and calibration is reduced to a single curve V/R_{REF} function of *a*, the crack depth (fig. 5).

EXAMPLES OF APPLICATION

The proposed measuring method has been developed during actual mechanical crack growth tests. For some of these tests we also tried to define a marking method by lower loads, in order to allow an easy comparison between actual and measured fronts.

All following tests have been performed on tensile specimens made of annealed AU4G alloy.

Specimen of Square Cross-section with Semi-Circular Crack

The crack is supposed to grow in the median section of the specimen from a half circle, of 5 mm radius, machined by electro erosion. The loading force, of sine shape, varies from 1.6 to 118 kN with a frequency of 5 Hz. For the electric measurements, the conditions are : current crossing the specimen $I = 16$ A ; amplification 25 000. The test runs as follows : after a number of loading cycles giving a growth considered sufficient by the operator, the loading is stopped, and readings of voltage V are carried out along the crack lips by means of the above described sensor and electronic unit.

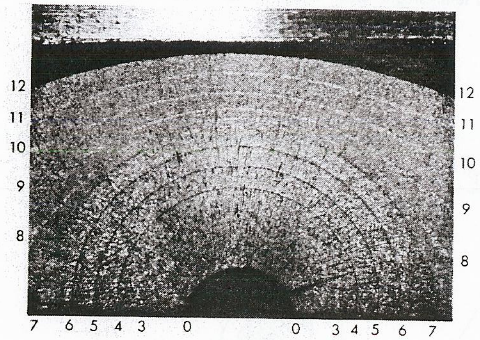

Fig. 6 – 40 x 40 mm specimen. Cracked surface with markings.

Then the marking is obtained by applying a load with an amplitude half of that of the test but with the same maximum value in order to have a relatively fast process. The number of cycles is appreciated through the electric measurement : for an effective marking it is necessary to provoke a slight growth of the crack, and the great sensitivity of the electric measurement makes it possible to detect this slight growth, then to stop the marking operation. Figure 6 represents the specimen fracture surface where the successive fronts (12 in number) are quite visible (but for fronts n° 1 and 2). The 12 voltage readings are traced on figure 7 and we observe, as expected, less and less curved tracings for the last stages of crack growth.

In order to check the measuring method, we carried out readings on the rheoelectric tank for which we used, from the markings of figure 6, the shape of real crack fronts n° 5, 7, 8 and 10. The very good agreement between readings in the tank and on the specimen, as seen on figure 8, is a necessary condition for the validity of the method.

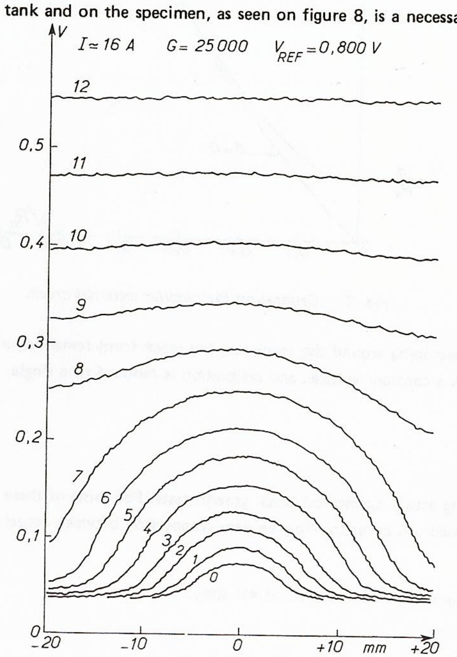

Fig. 7 – Voltage readings (40 x 40 mm square cross-section specimen. 10-mm-dia. semi-circular initial crack).

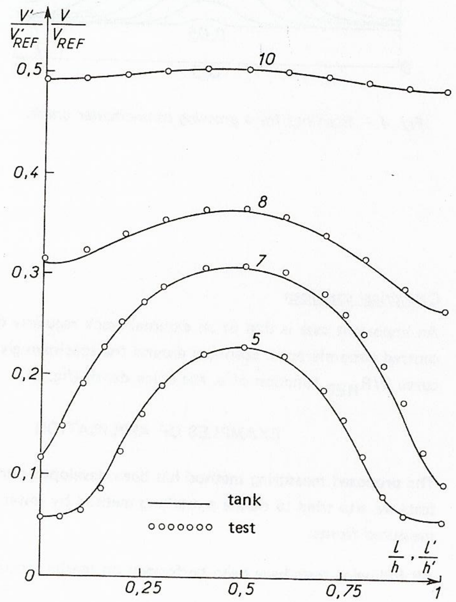

Fig. 8 – Comparison between actual and tank readings.

Specimen of Circular Cross-Section with Circular External Crack

This type of test presents a definite theoretical interest, as it corresponds to a perfectly plane strain state, without "edge effect". The diameter of the tensile specimens used is 44 mm, the initiated crack having a diameter of 40 mm.

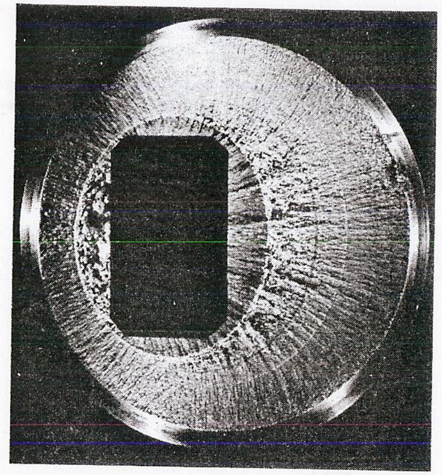

Fig. 9 – Fracture surface of a cylindric specimen.

Figure 9 represents the fracture surface of such a specimen, with three crack fronts defined by marking.

As before on the square specimen, we simulated in the cylindric tank the shape of these fronts, and again observed the good agreement of the curves $\frac{V}{V_{REF}}$ (θ) and $\frac{V'}{V'_{REF}}$ (θ) (fig. 10).

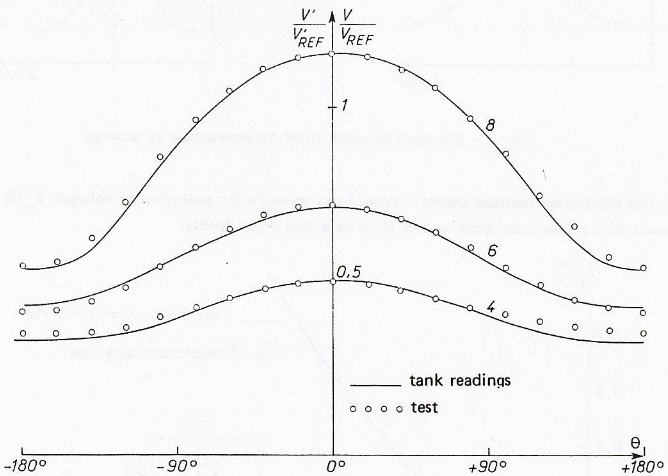

Fig. 10 – Comparison between real readings and cylindrical tank readings.

CONCLUSION

The method presented for determining crack fronts rests on two essential elements (Baudin et Policella, 1979) :
- the specimen measuring device, with its qualities of sensitivity, stability, accuracy and ease of handling,
- the analogical calibration method and its relative simplicity.

Its application during laboratory tests yielded very satisfactory results. Although it is difficult to ascertain an overall degree of accuracy, as this involves such parameters as measuring sensitivity, specimen-tank similarity and crack front configuration, the fact that we repeatedly obtained, in our testing conditions, front localizations with an accuracy better than 0.2 mm bears witness to the efficacy of the method.

Moreover, the instrumentation offers a range of interesting possibilities for the test engineer. First, the survey of rough readings on the cracked specimen is a great help for the correct application of the marking method by underloadings. Also, measurements in the rheoelectric tank offer the possibility of verifying a priori if the electric method is well adapted to the case under study, and consequently to modify the conditions of application.

The development of this electric method is being pursued with a view to its utilization for non-destructive control on real structures.

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