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Fatigue crack observation under biaxial mechanical loading

Cédric Gourdin[1], Grégory Perez[2], Clément Minard[3]

[1] Head of Structural Integrity & Standards Laboratory, CEA Saclay, DES/ISAS/DM2S/SEMT, 91191 Gif-sur-Yvette, France, cedric.gourdin@cea.fr
[2] Research Engineer, CEA Saclay, DES/ISAS/DM2S/SEMT/LISN, 91191 Gif-sur-Yvette, France.
[3] Student Engineer, CEA Saclay, DES/ISAS/DM2S/SEMT/LISN, 91191 Gif-sur-Yvette, France

ABSTRACT

The aim of this bi-axial fatigue test is to provide data that is sufficient for the validation of the predictive fatigue crack model developed on the basis of sub-grain dislocation dynamics in FCC metals proposed by Déprés (2014). However, feasibility tests was carried out with an austenitic stainless steel (316L) available at Laboratory of Structural Integrity and Standardization.

The focus of this work was to fully manage, coordinate, and complete this bi-axial fatigue test as scoped by the fatigue crack model task. After a description of the device capability to obtain surface cracks propagation with different observation means done in the first part.

Equibiaxial fatigue tests were carried out in a second part for different load levels. A thorough and careful analysis of the digital images taken during these tests was set up in order to determine the crack rate propagation on the surface of the FABIME2 specimen. Thus, it is possible to quantify the evolution of the cracks observed during the equibiaxial fatigue tests from a minimum dimension of 0.05 mm up to about ten millimeters.

But the particularity of theses equibiaxial fatigue tests was to show multiple initiations of fatigue cracks, followed by propagation with observations of cracks bifurcations. It is especially this type of fatigue crack initiation and propagation that will be useful for the validation of the advanced fatigue crack propagation model proposed by Déprés (2014).

INTRODUCTION

The aim of this bi-axial fatigue test is to provide data that is sufficient for the validation of the predictive fatigue crack model developed on the basis of sub-grain dislocation dynamics in FCC metals. However, feasibility tests was carried out with an austenitic stainless steel (316L) available at Laboratory of Structural Integrity and Standardization.

Equibiaxial fatigue tests were carried out for different load levels. A thorough and careful analysis of the digital images taken during these tests was set up in order to determine the crack rate propagation on the surface of the FABIME2 specimen. Thus, it is possible to quantify the evolution of the cracks observed during the equibiaxial fatigue tests from a minimum dimension of 0.05 mm up to about ten millimetres.

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DESCRIPTION OF THE WORK

The objective of this work described in this document is to present the equibiaxial fatigue tests realized and their interpretation in term of crack rate propagation.

After a validate phase concerning the modifications made to the biaxial fatigue test method developed for the study of fatigue of stainless austenitic materials used in nuclear power plants. Based on the CEA-Saclay FABIME2 test facility by Bradaï (2014), modifications have been made to improve the crack initiation detection and crack rate monitoring capabilities (on the surface) of a crack network.

Three equibiaxial fatigue tests were carried out for three load levels. A thorough and careful analysis of the digital images taken during these tests is set up in order to determine the crack rate propagation on the surface of the FABIME2 specimen. This interpretation is presented and is applied for the realized fatigue tests. Thus, it is possible to quantify the evolution of the cracks observed during the equibiaxial fatigue tests from a minimum dimension of 0.05 mm up to about ten millimetres.

THE EXPERIMENTAL DEVICE

The aim of this new experimental fatigue test is to obtain a completely alternative mechanical loading on the specimen. The equibiaxial specimen will be loaded with a load ratio equal to -1, like the uniaxial specimen used to obtain the data to determine the reference fatigue curve of the material.

In this study, equibiaxial state loading generated from fatigue will be considered. It will be used to optimize the geometry of a disk specimen refined in its center. It is used as a circumferentially embedded diaphragm with an applied pressure on both sides (P1, P2) in order to obtain an equivalent strain in each loading direction in the plane.

In addition, marking of a grid with a diameter of 10 mm with a pitch of 0.5 mm is carried out with a laser. This grid makes it possible to better estimate the size of the cracks detected and to follow their evolution during the propagation phase. The impact depends on the number of crack initiation cycles, and for lower number of cycles it is negligible –like in our case crack is not initiate on the grid-. But for the next tests (loading are smaller and number of cycles to initiate will be greater), the impact will be checked with previous fatigue tests without grid.

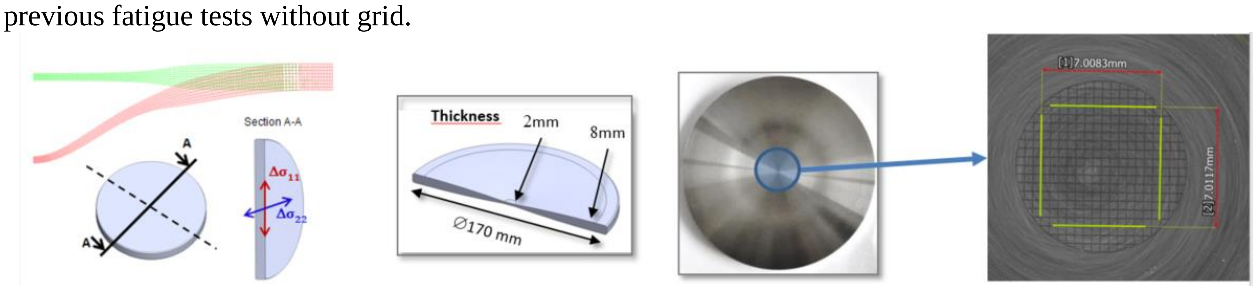

Figure 1 : Modification of the FABIME2 specimen, laser grid marking (diameter of 10 mm with a pitch of 0,5 mm).

The experimental device called « FABIME2 » is divided into four parts:

- Fatigue cell which contains the spherical bending specimen,
- Pressure generating system up to 100 bars,
- Electrical enclosure,
- Inhouse software developed in LABVIEW that provides control and data acquisition during the tests.

Two half-shells allow the positioning of the spherical bending specimen. Seal and embedment are achieved by bolting these two parts.

Maximum experimental conditions are 100 bars for the pressure and 90°C for the temperature. An alternative differential pressure P1-P2 between the two sides of the spherical specimen is applied during the fatigue test.

To ensure well-defined experimental conditions, various measuring means are located symmetrically at the two half-shells:

- Pressure sensor with a measuring range between 0 to 100 bars.
- Type K thermocouple to measure the environment temperature inside the fatigue cell.
- Displacement sensor (LVDT) to measure the deflection at the center of the spherical bending specimen. This sensor has a 5 mm range. Surface observations after the fatigue test show that the contact between LVDT and specimen is negligible (no fretting). No crack initiation is also observed directly under the LVDT.
- Two visualization windows on each half-shell, oriented at 45° with a diameter of 20 mm. The constitutive material is borosilicate glass with a permissible operating pressure of 100 bars.

In order to improve the visual detection of crack initiation, the tests were conducted with only one of the two LVDTs initially present. A modification of the software has been necessary to ensure that the tests can be carried out with only one LVDT. The now non shadowed surface by the LVDT allowed better visibility of crack initiation.

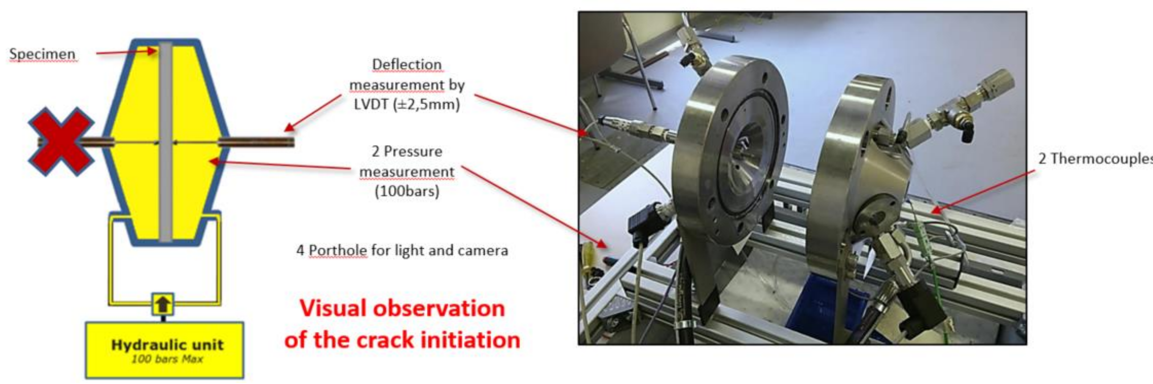

Figure 2: Modification of the FABIME2 device, LVDT removed on the B side of the specimen.

DETERMINATION OF THE CRACK RATE WITH VISUAL OBSERVATION

The determination of the surface cracks rate during fatigue tests requires a significant improvement in the taken pictures. This improvement goes through different stages:

1. Image optimization using photoshop :
   - I. Switch to a higher “color” resolution (from 8 bits to 16 bits),
   - II. Greyscale optimization (levels adjustments - Figure 3) ,
   - III. Cropping and sharpening,
   - IV. Switch back to 8 bit color depth
   - V. Batch creation of a new jpg picture with minimum compression.
2. Image correction with LabView
   - I. Correction of perspective in LabView (Figure 4)
   - II. Batch creation of calibrated pictures
3. Measurements
   - I. Importation of corrected pictures as layers in Photoshop
   - II. Calibration of a corrected image, selection of origin x/y
   - III. Measurement of crack ends position (in pixels)
   - IV. Position conversion: pixels -> mm

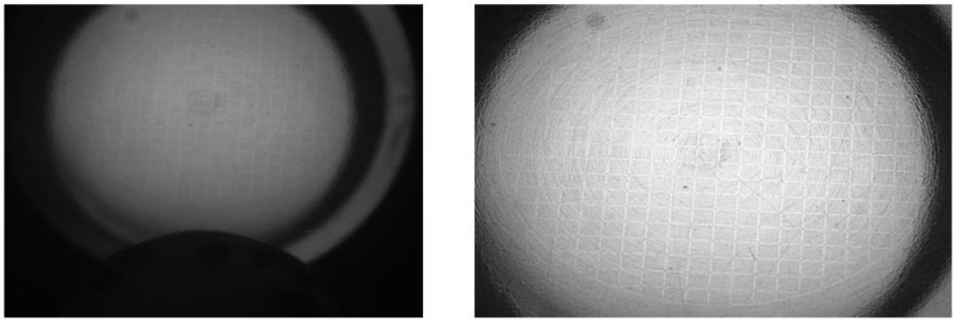

Figure 3: Improvement of the original image by optimization of the gray levels for the picture taken in cycle 8251 on the 743B-V specimen.

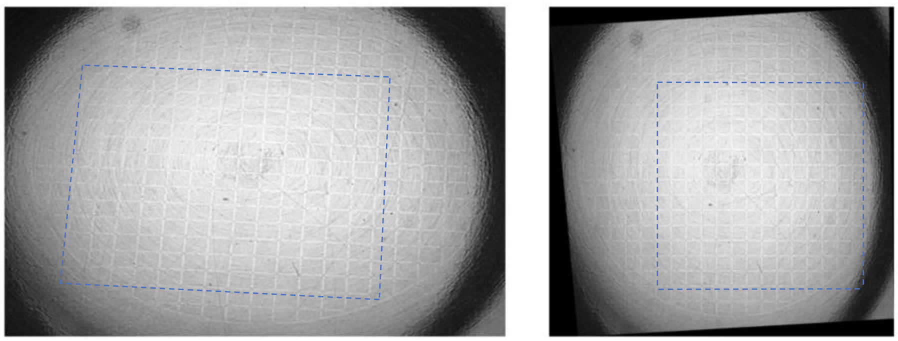

Figure 4: Taking into account the optical perspective.

Once all these steps of optimization and reprocessing of the shots have been carried out, a careful work of observation and quantification of the length of each crack according to the number of cycles is carried out. On top of this important mapping work, the relative determination of the crack size with the number of cycles makes it possible to obtain the rate of each surface crack initiated during the fatigue test (cf. Figure 5 & Figure 6).

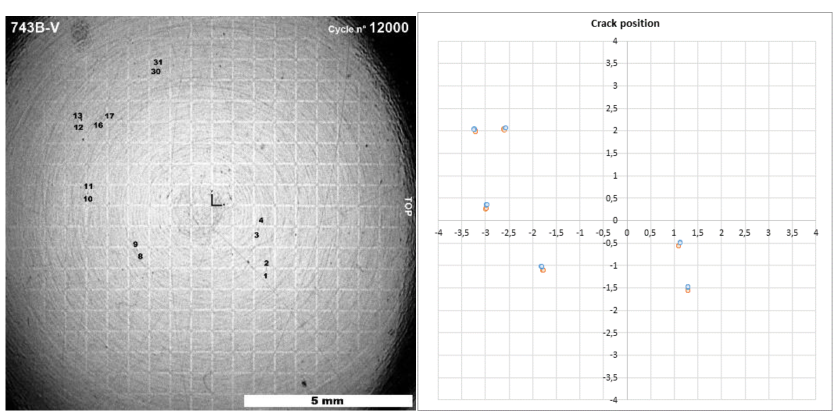

Figure 5: Illustration of the quantification of crack size in the initiation phase during the fatigue test on the 743B-V specimen.

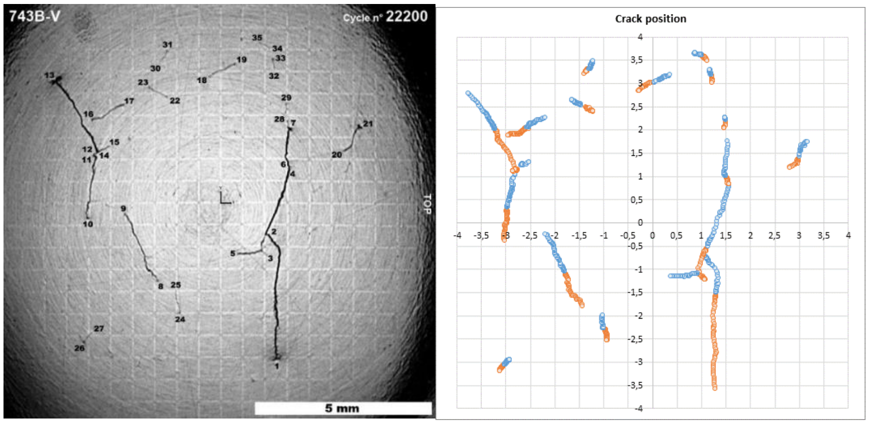

Figure 6: Illustration of the quantification of crack size in the propagation phase during the fatigue test on the 743B-V specimen.

FOCUS ON BIAXIAL FATIGUE TEST

Experimental data obtained during the biaxial fatigue test

In this part, a description of one of the three tests performed is made. This test was carried out with the referenced specimen 743B-AB.

- In consequence of this dissymmetrical displacement, the load ratio R = 0.92
- Frequency of cycling is approx. 1 Hz
- Pictures are taken every 1000 cycles up to 37 000 cycles, then every 250 cycles till the end of the fatigue test (70 000 cycles).

During the fatigue test on specimen named 743B-AB, pressure value inside 1 and 2 and the value of the displacement on the side 2 via the LVDT2 are acquired. For each cycle, the minimum and maximum value of these experimental data are determined. During the entire test, the value of the LVDT 2 maximum and minimum are constant. On the Figure 7, the pressure maximum and minimum time evolution are represented. The softening phase at the beginning of the test until 2500 cycles was well retrieved. Then, until the crack initiation was observed by the modification of the compliance of the specimen, the mechanical behaviour is stabilized.

During the test, the mean displacement for side 2 is 1,098 mm with a range of ±0,01 mm and a standard deviation of 0,0023 mm. And for side 1, the mean value of the displacement is 1,188 mm with a range of ±0,01 mm and a standard deviation of 0,0021 mm.

The mean pressure in the n°2 chamber is 37,45 bar with a range of 0,4 bar and a standard deviation of 0,1 bar. The mean pressure in the n°1 chamber is 37,7 bar with a range of 0,3 bar and a standard deviation of 0,1 bar.

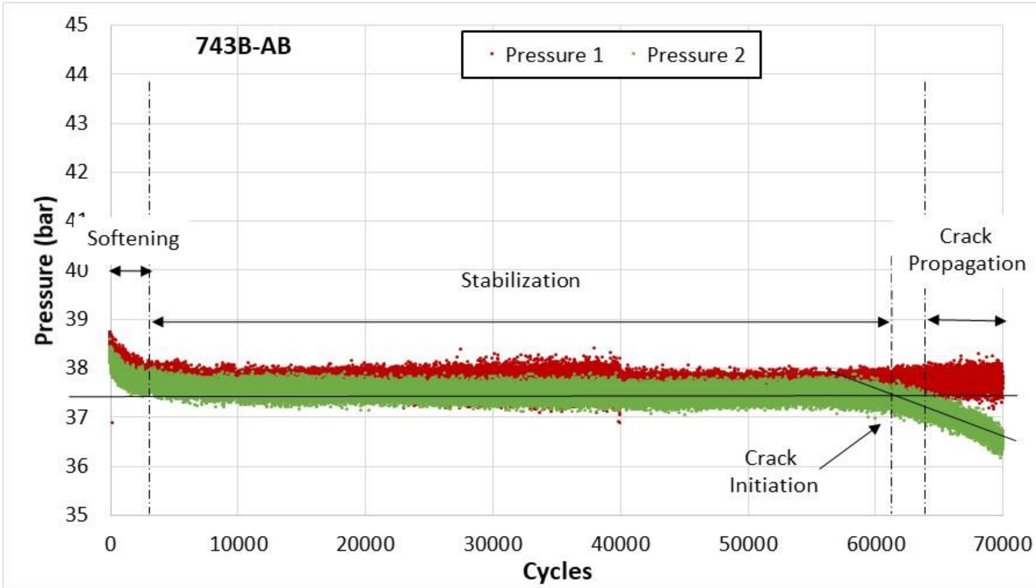

Figure 7: Time evolution of the pressure highlighted the different phase during the fatigue test: Softening, stabilization and crack initiation and propagation on 743B-AB specimen.

Observation of the specimen surface

Pictures are taken every 1000 cycles up to 37 000 cycles, then every 250 cycles till the end of the fatigue test (70 000 cycles). In the next figures, we present different and important moment of the fatigue tests.

- On the Figure 8, Beginning of the test (cycle = 500), no cracks observed.
- On the Figure 9 First picture with crack initiation (cycle = 12500), size of the crack estimated : 0,05 mm (50 µm)
- On the Figure 10, 5 mm Surface crack length corresponding to the fatigue criteria (N5) used to define the fatigue curve and to compare with uniaxial fatigue criteria N25.
- On the Figure 11, Final crack propagation at the end of the test (cycle = 22495)

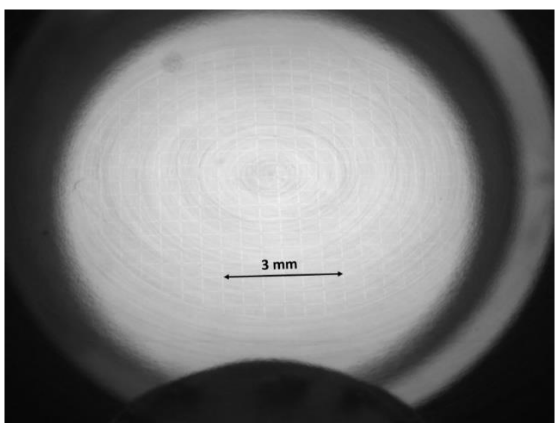

Figure 8: Visual observation of the grid on side 1 at cycle number 500 on 743B-AB specimen.

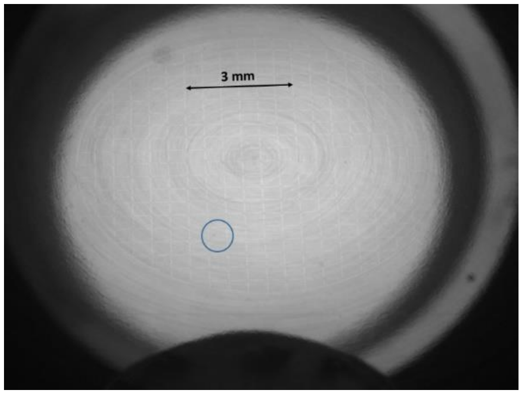

Figure 9: Visual observation of the first crack initiation at cycle number 38 000 with an enhanced zoom on 743B-AB specimen.

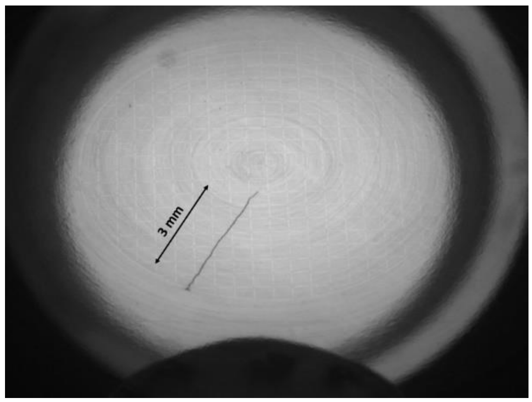

Figure 10: Visual observation of the first crack initiation at cycle number 62 500, corresponding to the N5 fatigue data used for the fatigue curve (surface crack length = 5 mm), on 743B-AB specimen.[1].

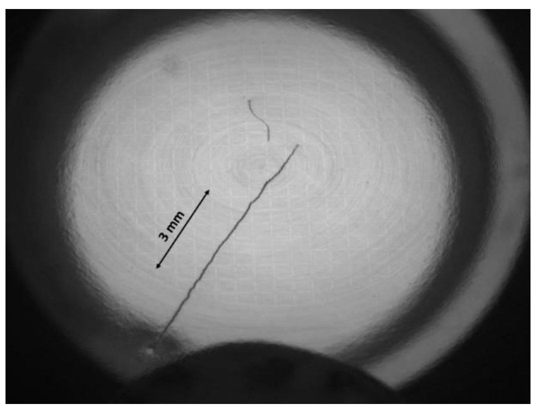

Figure 11: Visual observation of the crack propagation on surface at the end of fatigue test (last cycle number 70 000 cycles) on 743B-AB specimen.

Determination of the fatigue crack propagation

During the biaxial fatigue tests, visual observations were carried out every 250 cycles. The first observation corresponding to the smallest detection of crack at 28000 cycles. The surface crack length is about 50 μm (0.05 mm). Then, two steps of crack propagation are illustrated. At 56000 cycles, the crack length reaches about 2 mm, and at 64000 cycles, the crack length is about 5 mm (this crack length corresponds to the fatigue initiation criterion). With an approximately surface crack length of 2 mm and with a 5 mm surface crack length. The visual observation at the end of the biaxial fatigue test is also illustrated.

From these observations, first crack length measurements allow us to obtain the kinematics of crack propagation under biaxial loading. The first results are showed in the following figures (cf. Figure 12). A zoom on the first propagation results is also presented (cf. Figure 13).

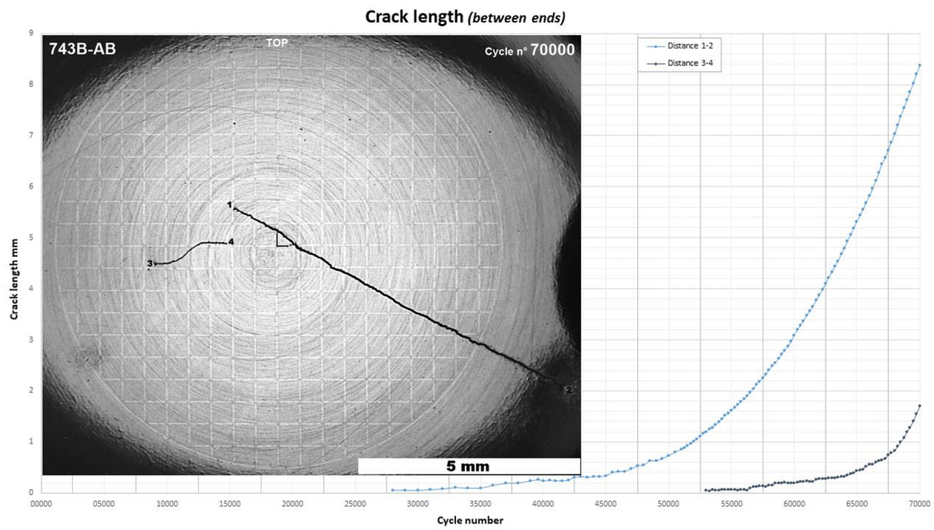

Figure 12: Surface crack length obtained by visual measurement.

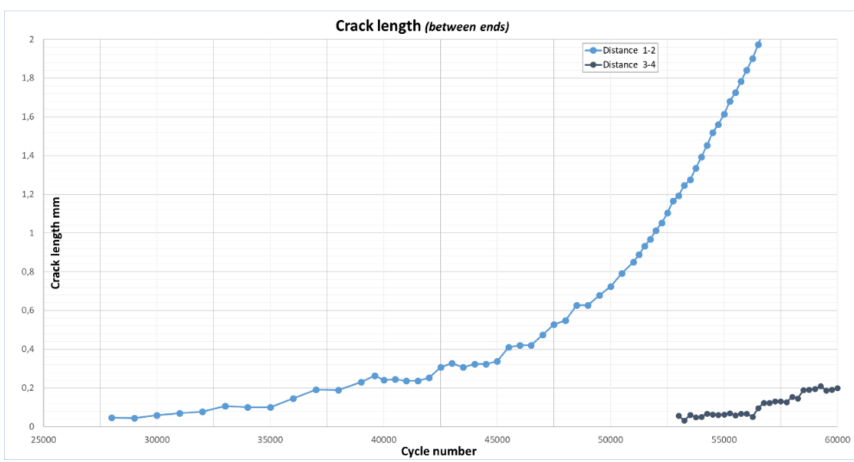

Figure 13: Surface crack length obtained by visual measurement (zoom on the first crack initiation).

CONCLUSIONS AND PERSPECTIVES

The objective of this work described in this paper is to present the equibiaxial fatigue tests realized and their interpretation in term of crack rate propagation.

After a validate phase concerning the modifications made to the biaxial fatigue test method developed for the study of fatigue of stainless austenitic materials used in nuclear power plants. Based on the CEA-Saclay FABIME2 test facility, modifications have been made to improve the crack initiation detection and crack rate monitoring capabilities (on the surface) of a crack network.

Three equibiaxial fatigue tests were carried out for three load levels. One of theses tests conducted is detailed. A thorough and thoughtful analysis of the digital images taken during these tests is set up in order to determine the crack rate propagation on the surface of the FABIME2 specimen. This interpretation is presented and applied for the realized fatigue tests. Thus, it is possible to quantify the evolution of the cracks observed during the equibiaxial fatigue tests from a minimum dimension of 0.05 mm up to about ten millimetres.

The biaxial fatigue tests carried out in the frame of providing data that is sufficient for the validation of the predictive fatigue crack model developed on the basis of sub-grain dislocation dynamics in FCC metals are summarised in the following table.

Table 1 : Summary of the biaxial fatigue tests

N°test	Material	Loading			Number of cycles (crack initiation)	Minimum crack size (mm)	Number of cycle (for 5 mm)	Remarks
		Displacement amplitude (mm)	Mean Displacement	Load Ratio				
743B-U	316L	3,16	0	-1	2771	0,2	6500	Grid with 50% of power
743B-V	316L	2,75	0,11	-0,93	12500	0,05	19680	Mutliple cracks
743A-AB	316L	2,286	0,09	-0,92	62500	0,05	12500	Major crack
743B-Q	316L	2,772	-0,1	-0,92	9500	0,05	16250	Simultanous multiple crack initiation

An important work to improve the monitoring of the crack rate by the implementation of an image processing was make it possible to correct the various optical effects observed (deformation due to the lens, improvement of the contrasts).

A numerical interpretation will be performed to determine the complete mechanical state (strain-stress) in the concerning initiation crack area. These numerical interpretation need to confirm the adequate use of the material behaviour for stainless austenitic steel.

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