



Characterization of fatigue cracks in metallic materials by X-ray tomography

Ce Xiao

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**Characterization of fatigue cracks in
metallic materials by X-ray tomography**

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Abstract

X-ray tomography is the most commonly used and most advantageous method for 3D crack characterization in metals, especially in the in-situ fatigue test. The shape and size of cracks can be observed and characterised with a resolution varying from 10 to 1 μm depending on the kind of X-ray source used, either laboratory sources or synchrotron sources.

In some cases, there are some challenges to analyse the crack tomography images. For laboratory tomography image, the limited X-ray energy and signal-to-noise ratio give low contrast and relatively noisy gray scale images which makes difficult to extract completely the 3D crack shape from matrix. Thus, a image segmentation method based on an Hessian matrix has been proposed for noisy laboratory CT image of crack. Digital Volume Correlation as another effective method for quantitative analysis method has been used to study internal fatigue crack closure in cast iron from limited resolution laboratory tomography images.

In synchrotron tomography images, phase contrast helps for detecting the cracks with sub-voxel opening, but it also complicates the analyses of the cracks in the image as it brings some specific artifacts (streak artifact and wrinkled artifact) affecting the image quality. A development of segmentation method based on neural network have been proposed to automatically extract the 3D crack from a series of in-situ synchrotron tomography images.

To better understand crack contrast in the reconstructed images, we investigate the source of streak artifacts and wrinkled artifact and find some ways to reduce these artifacts, simulations of phase contrast tomography have been performed in this thesis and the results correspond well to the experimental images.

Résumé en français

La tomographie à rayons X est la méthode expérimentale la plus couramment utilisée et la plus efficace pour la caractérisation en 3D des fissures dans les métaux, notamment dans le cadre des essais de fatigue in-situ. La forme et la taille des fissures peuvent être observées et caractérisées avec une résolution variant entre 10 et 1 μm selon le type de source de rayons X utilisé, qu'il s'agisse de sources de laboratoire ou de sources synchrotron.

Dans certains cas, l'analyse des images de tomographie de fissures présente un certain nombre de problèmes. Pour les images de tomographie de laboratoire, l'énergie limitée des rayons X et le rapport signal/bruit donnent des images en niveaux de gris à faible contraste et bruitées, ce qui rend difficile l'extraction automatique et précise de la forme des fissures. Ainsi, une méthode de segmentation d'images basée sur les matrices Hessienne a été utilisée pour une image de tomographie de laboratoire contenant une fissure faiblement contrastée. La corrélation d'images volumiques, une autre méthode efficace d'analyse quantitative, a été également utilisée pour caractériser des fissures avec le même type d'images. La fermeture de fissures de fatigue internes dans une fonte à graphite sphéroïdal a ainsi pu être mesurée pour la première fois à partir d'images de tomographie de laboratoire.

Dans les images de tomographie synchrotron, le contraste de phase aide à détecter des fissures dont l'ouverture est inférieure à la taille du voxel, mais il complique également le contraste des fissures dans l'image et génère certains artefacts spécifiques (streak artefact et wrinkled artefact notamment) lorsque l'algorithme de reconstruction classique par rétro-projection filtrée est utilisé. Une méthode de segmentation basée sur un réseau neuronal a été développée pour extraire automatiquement des fissures de fatigue 3D d'une série d'images de tomographie synchrotron in-situ.

Afin de mieux comprendre le contraste des fissures dans les images 3Dreconstruites, d'étudier la source des artefacts mentionnées précédemment et de trouver des moyens de réduire ces artefacts, des simulations de la tomographie par contraste de phase ont été réalisées et les résultats en bon accord avec les images expérimentales ont permis une meilleure analyse de ces dernières.

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INTRODUCTION

In industry, many components work under cyclic load, such as shafts, springs, gears, etc. In spite of the fact that they usually work under load lower than the yield strength of the material, after a long period of work they can suddenly fracture: a process called fatigue fracture. Fatigue fracture often does not produce significant plastic deformation, and the fracture occurs unexpectedly with very high risk of causing serious accidents, like the German high-speed train which derailed in 1998 due to fatigue fracture inside the wheels or the PUMA helicopter which crashed in the sea off Norway in 2016 due to the propagation of cracks inside the gears.

In the 19th century, the research on fatigue by August Wöhler [BLA 18] who introduced the S-N curves, also known as Wöhler curves, is the first systematic work in that field. Microscopic investigations (in the beginning of the 20th century) have been used for the observation and characterization of crack initiation and crack growth [SCH 09]. In the middle of the 20th century, Paris proposed to correlate the crack growth rate da/dN (in meters per cycle) to the variation of the Stress Intensity Factor (SIF), noted ΔK [PAR 63] which provided a “universal” formula for studying crack growth rate in many experimental materials and experimental conditions.

For materials with defects, early studies have shown that the formation of a fatigue crack from a subsurface or internal defect is a three dimensional process which is difficult to image from 2D observations [CLE 84] [NAD 04]. Therefore a 3D characterization of cracks is important for a thorough understanding of fatigue mechanisms [BUF 17]. Several 3D non-destructive methods for cracks detection are currently being applied: pulsed thermography (PT) is a non-contact, quick inspection method that detects defects (cracks), but it is not suitable for surface fatigue cracks with large opening in metals [LI 11]; ultrasonic guided waves have been used to monitor fatigue crack growth in plate structures [CHO 12], but this method is limited to plate structures; nowadays for 3D crack characterization in metal, X-ray tomography is increasingly used. The ability of X-ray tomography to provide directly and non destructively three dimensional (3D) images of the interior of optically opaque materials was realised a while ago by researchers. Voids, defects or cracks have been imaged with a resolution varying from tens to 1 μm depending on the kind of X-ray source used, either laboratory sources or synchrotron sources [BUF 10].

The fatigue properties of various materials (cast iron, steel, aluminium alloys, titanium alloys, etc.) have been studied in the MATEIS laboratory over the last two decades, X-ray tomography is employed to observe and characterise the shape and size of cracks, especially during in-situ fatigue test [BUF 08]. Crack segmentation from a gray scale image plays

a key role in the quantitative analysis [LUD 03]. However, in some cases segmenting fatigue cracks can be very difficult: for laboratory CT images, the limited X-ray energy and signal-to-noise ratio give low contrast and relatively noisy gray scale images. In synchrotron images, phase contrast helps for detecting the cracks, but it also complicates the contrast of the cracks in the image and brings in some specific artefacts to affect the quality of the segmentation. Therefore, **the first goal** of this thesis is to develop a semi-automatic method for the accurate and complete segmentation of cracks in laboratory CT and synchrotron CT images. Two under-studied artefacts in images of phase-contrast tomography pose difficulties for the quantitative analysis of cracks: the first one is streak artifacts that appear at ends of flat cracks, which usually show bright contrast (white) and have a similar shape to crack (flat), which makes the crack tip difficult to identify; the second is the “wrinkled” artifact, which usually appears around cracks parallel to the incident beam, resulting in a blurring of crack edges. **The second goal** of this thesis is to understand the nature of the contrast in phase-contrast CT images, to investigate the sources of the two mentioned artifacts and look for some ways to reduce them.

In addition to crack image segmentation, Digital Volume Correlation (DVC) is also an effective method for the quantitative analysis of cracks. It has the advantage that it is possible to compare the CT images before and after loading, and directly calculate the displacement field at a sub-pixel level. This method requires markers in the CT image. Limodin et al. have studied crack closure and measured the Stress Intensity Factor along the front of surface crack in nodular graphite cast-iron by using DVC methods [LIM 09]. More recently, Junet et al. have proposed a method for studying the cracks starting from an internal defects in a Ti alloy [JUN 19]. **In the last part of this thesis**, the closure level of internal cracks in cast iron and the measurement of stress intensity factors have been studied using the DVC method.

The current PhD manuscript is composed of five chapters organised in the following manner:

Chapter 1 gives a general background on X-ray tomography. First, the principles of X-ray tomography are presented. Then, two different types of X-ray tomography (laboratory tomography and synchrotron tomography) have been introduced. A comparison of the two types of tomography showing their respective advantages and disadvantages and the different characteristics of the reconstructed crack images is presented.

Chapter 2 describes the development of segmentation methods based on neural network and hessian matrix for fatigue crack images obtained with X-ray tomography. First a segmentation method based on the application of Hessian Matrix is described. This method which is very efficient for extracting planar features within noisy images (like

those produced by lab tomography) is presented. Then a method based on a deep learning algorithm has been used to threshold cracks in synchrotron CT images. The trained model is used to segment successive images of the same specimen obtained during an in-situ fatigue test at different number of fatigue cycles showing the efficiency of the method. The content of this chapter has appeared in 'Scientific Report', C.Xiao, J.Letang, J.Buffiere, "Characterization of internal fatigue cracks in aluminum alloys by simulation of phase contrast tomography".

Chapter 3 focuses on the characterization of streak artifacts and the interpretation of gray scale 3D images of cracks in phase contrast tomography. To better identify and characterize the cracks, simulations of the phase contrast synchrotron tomography with various crack sizes and structures have been obtained by using GATE software. Analyzing the simulation results, firstly, we confirmed that the bright parts with strong contrast in SRCT image are streak artifacts; secondly, we found that the gray scale values of cracks in SRCT images are related to the crack size; eventually, a reanalysis of the cracks in the experimental SRCT images was achieved with the help of simulation results. The content of this chapter has appeared in 'Engineering Fracture Mechanics', C.Xiao, J.Buffiere, "Neural network segmentation methods for fatigue crack images obtained with X-ray tomography".

Chapter 4 deals with wrinkled artifact in phase contrast synchrotron tomography image of fatigue cracks via simulations and experiments. To investigate the origin of wrinkled artifact and to find ways to avoid or reduce it, phase contrast tomography simulations (using GATE software) as well as experiments (carried out at ESRF) were performed. The source of the artifacts is considered as the two-dimensional interference of x-rays (2D Fresnel diffraction) on the detector; and it can be reduced by reducing the phase contrast intensity (smaller objet-detector distance/higher x-ray energy), or, more simply by inclining the crack to avoid the 2D interference.

Chapter 5 describes the characterization of closure of internal crack and stress intensity factor measurements in nodular graphite cast iron using 3D correlation of laboratory X-ray tomography images. Using Femto Laser machining and Spark Plasma Sintering (SPS), internal defects can be fabricated in fatigue samples of a nodular cast iron without changing the microstructure and mechanical properties of the material. Specimens with internal cracks and surface cracks were scanned in laboratory tomography at different loads after different number of fatigue cycles. Their displacement fields were calculated by the DVC method, and the stress intensity factors were calculated along the crack front by Williams series, and the closure phenomenon of internal cracks and surface cracks was discussed.

Chapter 1

General background on tomography

1.1 Principle of X-ray tomography

A new kind of electromagnetic rays called 'X-ray' because of their unknown nature has been discovered by Wilhelm Conrad Roentgen in 1895 [THO 96]. Since X-ray has different absorption efficiencies for different materials, it has been widely used in the medical field since the 1970s. The technique of acquiring x-ray projections from different angles and reconstructing a 3D image of the scanned object is called x-ray tomography. With the development of optical detectors, the resolution of X-ray tomography has improved from the initial 300 μm to a few μm . It is now widely employed in materials science. Since its invention in the 1970s, X-ray tomography has been the topic of numerous books and articles. In what follows we recall the essential features of the technique which are related to this thesis. The interested reader can find a very detailed description of the technique for example in [STO 19].

The principle of X-ray tomography is presented schematically in Figure 1.1. An X-ray beam passing through a rotating sample gives a series of two-dimensional projection which are recorded by a CCD detector after being transformed into visible light by scintillator (for example monocrystal of cadmium). In laboratory tomography, the contrast in the 2D projections is due to the attenuation of the beam by the scanned object. In synchrotron tomography, due to the coherent X-ray source, phase changes of the x-ray beam induced by the sample are also recorded by the detector (detailed explanations are given in the following sections). In both case, the recorded projections are used for reconstructing a numerical volume of the sample by using a reconstruction algorithm. The final result is a 3D gray-scale image whose elementary element is called a voxel (3D equivalent to the 2D

pixel).

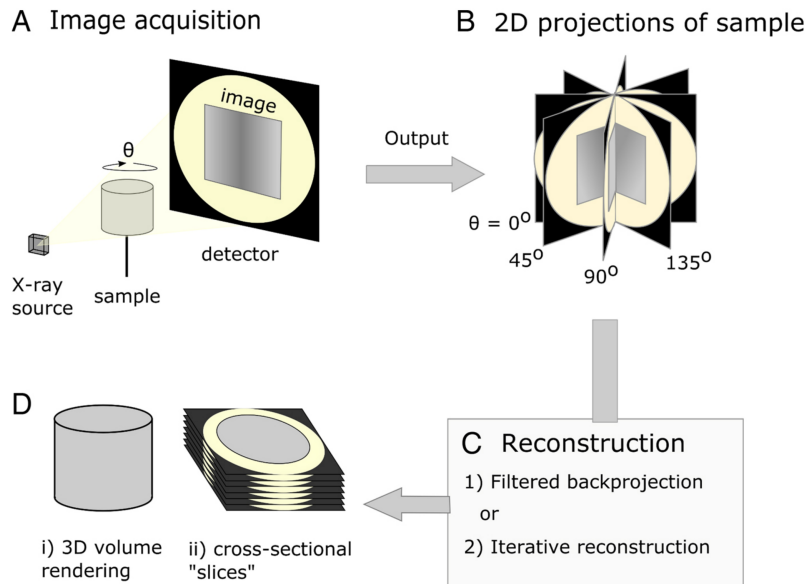


Figure 1.1: Schematic operation principle of X-ray tomography (A) Basic illustration of tomographic apparatus, including the X-ray source, detector and sample. (B) The raw output of the tomography is a series of projections of the sample taken at different angles. (C) Projections are digitally ‘reconstructed’; reconstruction algorithms output a data-set which is suitable for analysis. (D) The final output of tomography: a 3D gray-scale image.

Depending on the sources of X-ray, two types of tomography are commonly used in materials science (especially for 3D characterization of cracks within metals): laboratory tomography (Lab CT) and synchrotron tomography (SRCT). Usually, SRCT images can achieve higher resolution, and with the help of phase contrast, SRCT is more capable of detecting small opening cracks. In the next section, their imaging principles as well as their respective advantages and disadvantages will be presented and discussed.

1.2 Laboratory tomography

Since the 2000s, Lab CT with cone X-ray beam has become a standard characterisation technique in materials science laboratory. As shown in Figure 1.2a, basically, a Lab CT consists of an X-ray point source, a rotation stage and a CCD detector. MATEIS laboratory has for example a Lab CT machine since June 2006 (Phoenix-xray) which has an internal useful volume of $1m \times 1m \times 1m$ (Figure 1.2b) [BUF 10]. The accelerating voltage the X-ray tube can be turned between 40 kV and 160 kV. The detector is made of amorphous silicon with 1920×1536 pixels.

The voxel size in the reconstructed image is one of the most important parameter for

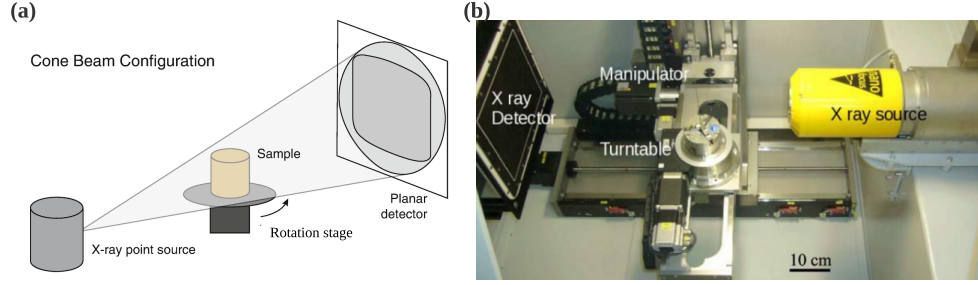


Figure 1.2: (a) Schematic of laboratory tomography with conical X-ray beam. (b) Close view of the interior of the laboratory tomography used in MATEIS showing the detector, the rotating stage and the X-ray source.

crack detection. In conebeam CT, the voxel size depends on the distance between the scanned object and the x-ray source: the theoretical best resolution is of the order of $1\text{ }\mu\text{m}$. In practice, the size of the scanned object sets some limitations on the voxel size:

- The minimum distance between the object and the X-ray source should be sufficiently larger than the radius of the object to ensure that the object does not touch the X-ray source tube during the rotation.
- Classically, the voxel size is chosen so that the sample projection fits on the detector.

Therefore, if a better resolution is required, the size of the sample must be as small as possible, e.g. for $1\text{ }\mu\text{m}$ voxel size, the largest dimension of the sample is at most 2 mm for a $2k \times 2K$ detector.

Laboratory tomography is based on x-ray attenuation by the material of scanned sample. The Beer-Lambert law describes the attenuation of the photons in a medium. We consider an incident beam composed of N_0 photons of energy E , going through an inhomogeneous material, of spatial attenuation coefficient $\mu(z, E)$ (in cm^{-1}), along the z -direction. The recorded intensity I is shown in Eq 1.1, where N_t is the number of transmitted photons [BAL 15].

$$I = \ln \left(\frac{N_0(E)}{N_t(E)} \right) = \int_{\text{path}} \mu(z, E) dz \quad (1.1)$$

2D projections are acquired at different rotation positions (usually 900 or 1200 projections). A reconstruction algorithm is used to construct 3D gray-scale images from the projection set. The filtered back projection (FBP) is the standard and most popular algorithm for Lab CT image [KAK 01]. Theoretically, the gray value in the reconstructed images represents the spatial distribution of attenuation coefficient within the sample.

1.3 Synchrotron tomography

Synchrotron radiation (SR) was discovered in 1946 by F. R. Elder et al. in a General Electric cyclotron accelerator. In the early 1960s, synchrotron radiation turned out to have a great potential in medical and material imaging because of its high intensity, strong coherence and collimation. As shown in Figure 1.3a, electrons are injected and accelerated in a linear accelerator (“Linac”). Then, they are transmitted to the booster synchrotron, before being transferred in to the accelerator where they produce intense SR. The ESRF produces hard X-rays with energy from 10 to 120keV (wavelength from 0.1 to 0.01nm).

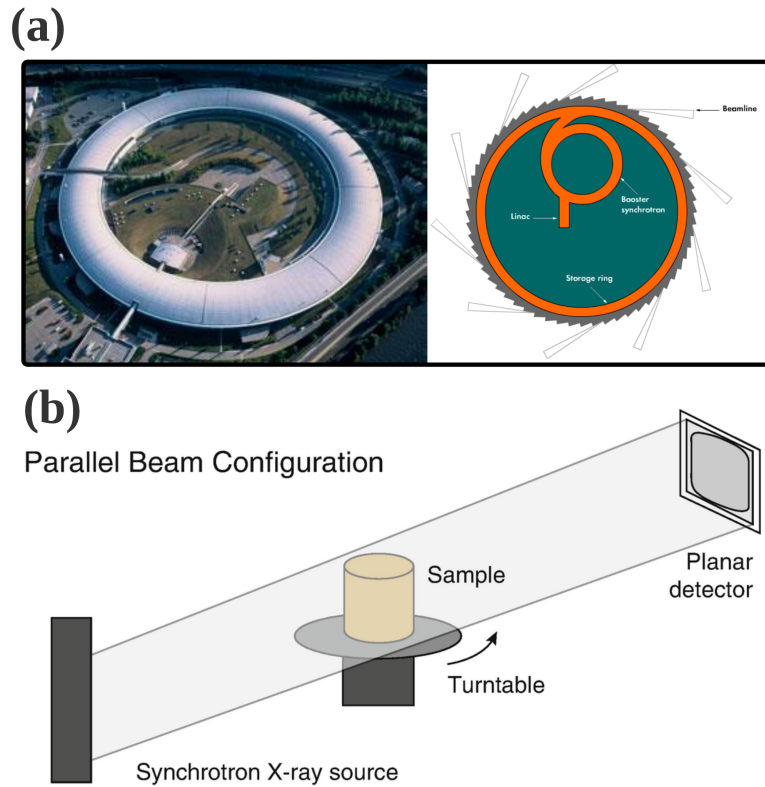


Figure 1.3: (a) Aerial photo and scheme of ESRF (source: www.esrf.eu). Electrons are injected and accelerated in the Linac, re-accelerated in the booster synchrotron, to circulate at a constant speed in the storage ring. (b) Geometric schematic of synchrotron tomography with parallel X-ray beam.

Contrary to laboratory tomography, synchrotron tomography uses a parallel beam, as shown in Figure 1.3b, therefore, the voxel size of SRCT images is no longer limited by the size of the scanned object but only by the pixel size of the CCD camera and the optics recording the visible light after the scintillator; resolution of the order of $0.5\ \mu\text{m}$ can be routinely achieved. Meanwhile, with synchrotron radiation facilities, the x-ray beam

is much more coherent than with a Lab source, which allows the detector to record the phase change information of x-rays and phase-contrast is by default observable [CLO 97]. Most common types of phase contrast CT are propagation-, analyser- or grating-based. Propagation-based topographies (single-distance tomography and holotomography) are convenient techniques since they do not require any optical elements such as analyser crystals [MAI 14]. Single-distance propagation-based phase contrast tomography is widely preferred to save time in in-situ experiments [BUF 10]. For the study of fatigue crack propagation in metals, phase-contrast tomography is exploited to enhance the visibility of edges and boundaries within an object [CLO 99].

In single-distance propagation-based phase contrast tomography, the contrast is due to free space propagation in the near-field regime of a highly spatially coherent beam, after passing through the object [BRO 02]. It creates interference patterns (Fresnel fringes), recorded by the detector. In this case, $I_D(x, y)$ the recorded intensity can be written as:

$$-\ln(I_D(x, y)) = \frac{4\pi}{\lambda} \int \beta(x, y, z) dz - D \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \int \delta_n(x, y, z) dz \quad (1.2)$$

Where λ is the X-ray wavelength, β is the absorption index, D is the distance between objet and detector and δ_n is the refractive index decrement.

As in the case of Lab CT, after completing the scanning process (sample rotation), the set of projections can be reconstructed using the FBP method. The gray value in the reconstructed images can be written as [CLO 97]:

$$g(x, y, z) \simeq \mu(x, y, z) - D \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \delta_n(x, y, z) \quad (1.3)$$

Phase retrieval methods can be used to obtain gray-scale images containing only phase information; for single-distance phase contrast tomography, the Paganin method [PAG 02] is the most common method; it allows to only retrieve phase-change information from radios recorded at a single sample-detector distance by assuming that the ratio of δ to β is constant (Eq 1.4). Ideally, the gray value in the reconstructed image here represents only the reactive index decrement δ .

$$\varphi(\mathbf{x}) = \frac{\delta_n}{2\beta} \ln \left(\mathcal{F}^{-1} \left\{ \frac{\mathcal{F} \left(\frac{I_D(\mathbf{x})}{I_0(\mathbf{x})} \right)}{1 + \lambda D \pi \frac{\delta_n}{\beta} \|\mathbf{f}\|^2} \right\} \right) \quad (1.4)$$

1.4 Laboratory tomography versus Synchrotron tomography

The two types of tomography typically applied for 3D characterization of cracks: laboratory tomography and phase contrast synchrotron tomography were introduced in the previous section. In order to compare more clearly/visually the advantages and disadvantages of both tomography in metal crack detection, the same specimens were scanned separately using the above two types of tomography and the results are shown in this section.

As shown in Figure 1.4a, a disc-shaped specimen (diameter 80mm, thickness 10mm) was machined out from a bar in M50Ni steel and submitted to a rolling contact fatigue test at the Rolling Contact Test laboratory (RCLab) of the University of Brescia. Two artificial defects (cylindrical holes, depth 0.2mm, diameter 0.4mm) were obtained by Electrical Discharge Machining (EDM) on the disc-shape specimen. The contact pressure during the fatigue test was 2603MPa and the total number of cycles was 11 million.

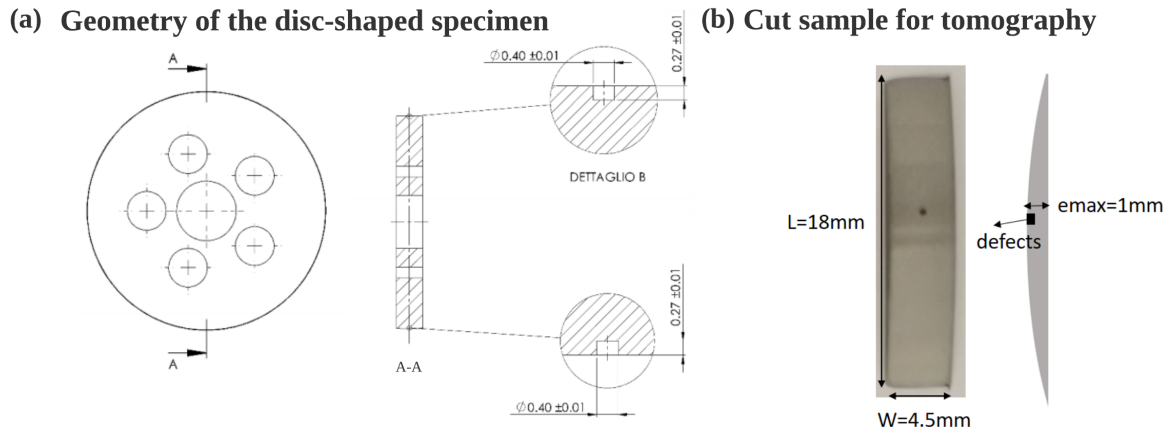


Figure 1.4: (a) Geometry of the disc-shape specimen used for rolling contact fatigue test. (b) Photo and geometry of the scanned sample extracted from the disk by EDM machining.

To observe the propagation of cracks inside the specimen, laboratory tomography and synchrotron tomography were used. Steel is a material with high x-ray absorption, so it is impossible for Lab CT and quite difficult for SRCT to penetrate an 80mm Steel specimen; moreover, as mentioned above, a smaller specimen size is necessary to achieve a high spatial resolution in the case of Lab CT. Thus, the scanned specimen has been machined out of the disc-shaped specimen. The geometry is shown in Figure 1.4 (width 4.5 mm, maximum thickness 1 mm, length 18 mm).

First, the specimen was characterized by laboratory tomography (Phoenix-xray machine at MATEIS laboratory) with the following conditions: accel voltage 160kV, voxel size $3\mu\text{m}$ (smallest as possible), exposure time 667ms, and projection number 1200. 3D gray-scale images are reconstructed using the classical FBP algorithm. Sub-surface cracks that propagated from the surface defect were observed in the lab CT images, but due to the poor signal-to-noise ratio, a part of crack with small openings appeared with very low contrast in the images. Therefore, it was difficult to accurately identify the position of the crack tip. The largest crack length was measured to be $674\mu\text{m}$ it is visible in the slices shown in Figure 1.5a. It is very challenging to obtain a 3D image of the complete cracks from such CT images of this quality. Due to the low contrast of cracks, the commonly used image segmentation methods yield discontinuous 3D shapes which cannot be quantitatively analyzed. Thus, in this thesis, a hessian matrix based method has been developed to threshold low contrast/noisy crack Lab CT images (see Chapter 2). Meanwhile, the DVC method presented in Chapter 5 is another method for quantitative analysis of CT images in which the displacement field at the sub-pixel scale can be directly obtained without thresholding image.

Subsequently, the cracked specimens were scanned using synchrotron tomography at ESRF BM05 with the following conditions: energy 109 keV (monochromatic beam), voxel size $1.4\mu\text{m}$, object-detector distance 144 mm, exposure time 5 ms, and projection number 2500. 3D gray-scale images are reconstructed using the Paganin method [PAG 02]. As shown in Figure 1.5b, a longer crack length was measured in the SRCT image than in the Lab CT image. The length of the crack was measured to be $1489\mu\text{m}$. However, compared with Lab CT (for which the gray-scale value of the reconstructed image is proportional to the linear attenuation coefficient of the material), phase contrast in synchrotron tomography also increases image complexity. It typically generates fringes at the edges of cracks/defects in the reconstructed images. For cracks with small openings (several pixels), these fringes make the cracks present different contrasts, e.g. in Figure 1.5b, some parts of the cracks appear as high-contrast dark (black), or as high-contrast bright (white), and sometimes “blurred”. In addition to this, some streak artifacts (marked by red arrow in Figure 1.5b) which gray-scale values and shapes are close to that of the cracks further enhance the difficulty of crack detection. Segmentation of SRCT images based on gray-scale values is not feasible; therefore to overcome this problem, a deep learning based segmentation method (U-net) was developed in Chapter 2 for automatic segmentation of a large number of SRCT images acquired during an in-situ experiment. Understanding the relationship between gray-scale values of the crack and the crack size in SRCT images and investigating the causes of streak artifacts by simulation of phase contrast tomography is the topic of Chapter 3. Another type of artifacts that causes crack edges blurring in SRCT

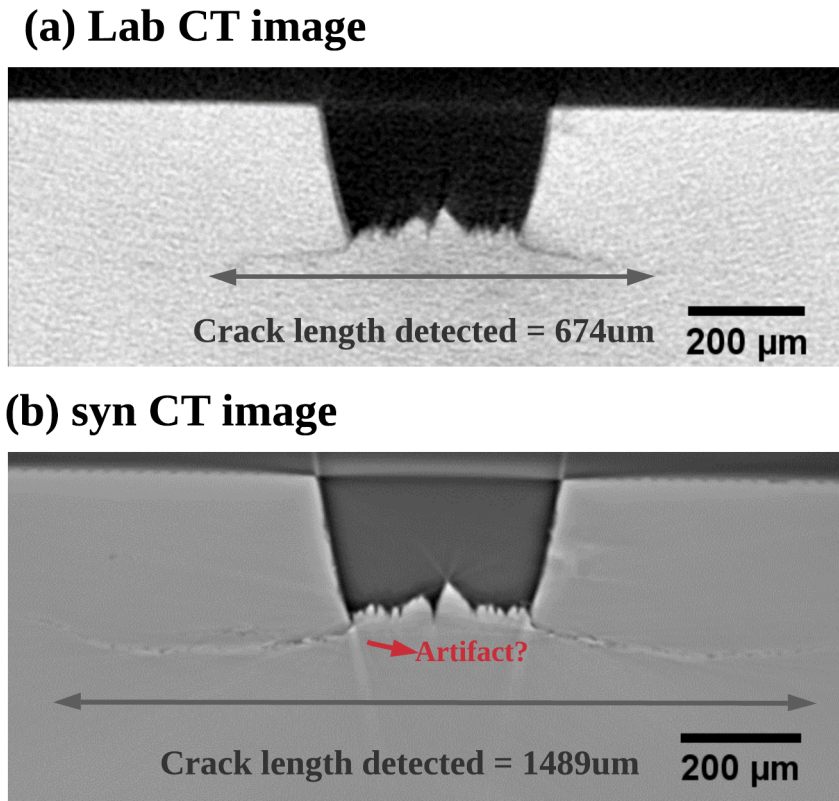


Figure 1.5: Comparison of crack visualisation using laboratory and synchrotron tomography: the latter clearly provides a better detectability for small opening cracks. The rotation axis of the sample is perpendicular to the figure on both images.

images (called wrinkled artifact) is discussed in Chapter 4, and several possible methods to reduce the wrinkled artifact are provided.

Table 1.1: Parametric comparison of employed Lab CT and SRCT.

CT type	Voxel size	Scan time	FOV	Crack length detected
Lab CT	3um	48min	6mm $\times$ 4.8mm	1495um
Syn CT	1.4um	3min	3.9mm $\times$ 3.8mm	2470um

As a summary, synchrotron tomography has the following advantages over laboratory tomography for 3D crack characterization (a parametric comparison of employed Lab CT

and Syn CT can be found in Table 1.1):

- Thanks to phase contrast, synchrotron tomography provides better visibility of cracks (sub-pixel cracks are potentially detectable);
- More flexible voxel size selection, not limited by the size of the scanned object;
- Higher energy to get through thicker samples;
- Faster scan times.

The disadvantages are:

- An increase in image complexity due to phase contrast;
- Artifacts caused by interference (streak artifacts, wrinkled artifacts and etc.);
- Limited availability.

Chapter 2

Developments of segmentation methods for fatigue crack images obtained with X-ray tomography

This chapter is dedicated to develop method to segment complete 3D shapes of internal fatigue cracks in metals from laboratory CT images and synchrotron CT images. First a segmentation method based on the application of Hessian Matrix is described. This method which is very efficient for extracting planar features within noisy images (like lab tomography images) is presented. Then an image segmentation method based on a convolutional neural network is developed to replace the user interpretation of synchrotron CT images. Combined with a ‘Hessian matrix’ filter, this method can successfully extract 3D shapes of internal fatigue cracks in metals. This chapter has been published on the journal of Engineering Fracture Mechanics as an article entitled "Neural network segmentation methods for fatigue crack images obtained with X-ray tomography" written by C. Xiao, J.Buffiere.

2.1 Introduction

X-ray Computed Tomography(CT) has become a well established characterization technique in materials science. It allows to observe defects (cracks, voids, inclusions) or phases in the interior of optically opaque samples with a spatial resolution close to that of optical microscopy (*i.e.* in the micrometer range). Because of its non destructive character, tomography is often used to monitor the evolution of materials microstructure submitted to various experimental conditions during *in situ* tests [BUF 10]. For example 3D images of damage development in metallic samples during monotonic cyclic tests [SAL 03] [MAI 01],

in Al alloys [TOD 03], steels [MAI 08], Ti alloys [BIR 11], Mg alloys [KIN 11] have been published. A detailed review can be found in [WU 17]. With the development of faster detectors and more brilliant sources, during one single test at a synchrotron facility, several tens of 3D images can be recorded. The quantitative analysis of such large data sets must be carried out by automatic or semi automatic image analysis of binary images obtained by segmentation. This step is crucial in the data processing chain; it must extract the phenomenon of study (cracks or pores formation under mechanical loading, cell swelling or collapsing in a foam, phase coarsening during heat treatment, particle tracking ...) from a gray scale image and turn it into binary data.

A range of thresholding methods can be found in the literature: classic gray level threshold methods [YAN 89] combined with morphological operations [BHO 14] [TAN 09], feature extraction methods [LAR 11] [WOL 16], machine learning methods [OLI 14][SHI 16], neural network methods [CIC 16] [RON 15].

Thresholding the gray level histogram is the simplest and most widely used method for image segmentation, but it is highly sensitive to noise and artifacts and thus not very efficient in the vicinity of the crack tip where the crack opening is low, even if the sample is under load. Feature extraction methods, including Hough transform [SHA 09], finite plane integral transform [LI 11] or filtering based on Hessian matrix [VOO 13], assume that the crack has a prescribed shape in the image such as a line (in 2D) or a plane or a portion of plane (in 3D). Such methods have been used for example in the case of bones [LAR 11] or concrete [CHA 18] for which crack opening can be very small (lower than $1\ \mu m$). More recently, with the development of machine learning algorithms, the random forest method [SHI 16] or the convolutional neural network method [RON 15] have been developed for image segmentation. The basic ideas of those methods is to 'train' the segmentation algorithm on a set of manually segmented images (the ground truth). Recent results on high resolution synchrotron images of Al alloys show that by using such methods the total time required for segmentation is much lower than that required by manual segmentation [STR 19]. To the best of our knowledge, such methods have not yet been applied for fatigue crack segmentation.

Fatigue cracks in the interior of metals can be observed by laboratory tomography or by synchrotron tomography. The challenges for segmenting the cracks are different for the those two types of CT images. For the former, the limited x-ray energy and signal-to-noise ratio give low contrast and relatively noisy gray scale images (Figure 2.1.a and b). In synchrotron images, phase contrast helps for detecting the cracks, but the interpretation of the gray-level is more complicated: because of diffraction effects the same crack can appear black or dark in the reconstructed image depending on its opening. This type of contrast, which will be described in more details in section 2.3 of the chapter, poses a number

of challenges for automatic segmentation methods which have to be carried out at least partially manually. In this chapter we propose to use deep learning methods to reproduce the user intervention for obtaining continuous, complete, and physically meaningful 3D cracks.

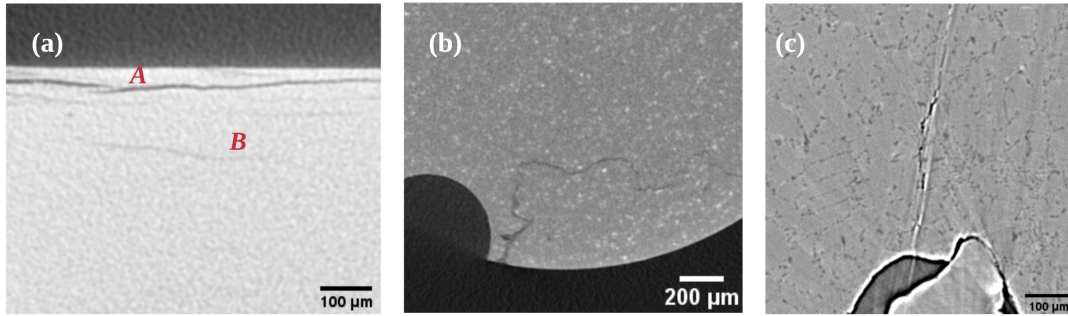


Figure 2.1: Reconstructed images of fatigue cracks obtained by laboratory (a)-(b) and synchrotron x ray Tomography(c). Lab tomography: (a) Bearing steel after Rolling Contact Fatigue Test, voxel=2.1 μm , Accel voltage 160 kV. Cracks connected to the sample surface (detail A) appear with a better contrast than internal crack (detail B) because of lower opening; (b) Al alloy sample, voxel size=2.5 μm , Accel voltage 160 kV; Synchrotron tomography: (c) Al alloy sample, voxel size =1.3 μm , Beam energy 29keV, the distance between the detector and the object: 15cm.

The chapter is organised as follows: first a segmentation method based on the application of Hessian Matrix is described. This method which is very efficient for extracting planar features within noisy images (like lab tomography images) is presented. Then a method based on a deep learning algorithm has been used to threshold cracks in synchrotron CT images. The trained model is used to segment successive images of the same specimen obtained during an *in situ* fatigue test at different number of fatigue cycles showing the efficiency of the method. The effect of the input Ground Truth on the segmentation results is then discussed using an image with a larger voxel size and different reconstruction parameters.

2.2 Methodology

2.2.1 Hessian matrix-based method

As shown in Figure 2.2g, the method consists of three steps:

Step 1 subtraction filter

A smoothed image (3D median filter) of the crack is subtracted from the original image

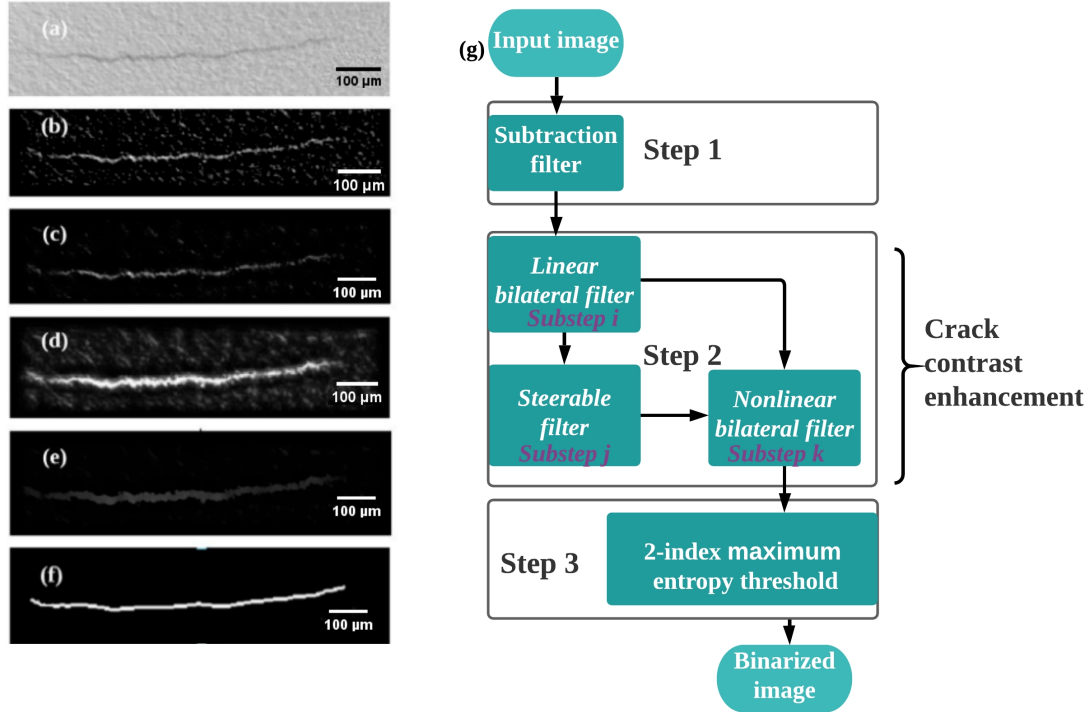


Figure 2.2: Algorithm flow chart of the Hessian matrix-based method: (a) 2D slice of a laboratory tomography image from a bearing steel sample containing a crack (b) Output of optimized subtraction filter (c) Output of linear bilateral filter (d) Output of steerable filter (e) Output of nonlinear bilateral filter (f) Binarized image (g) algorithm flow chart of the method.

bringing the crack in the foreground and reducing the noise level. (Figure 2.2b). The value used for the window size for the median filter (11 voxels) is a compromise between a value small enough to reduce the processing time and large enough to remove the crack from the matrix [FUJ 11].

Step 2 Crack contrast enhancement

Inspired from a method developed for segmenting micro-cracks in bones [LAR 11], a combination of linear bilateral, steerable and nonlinear bilateral filters (sub step i to k) is used for increasing the contrast and denoising the crack image.

- Substep i: Linear bilateral filter

Before calculating the Hessian matrix, it is necessary to smooth the image to perform second order derivation operations. To do so, a bilateral 3D Gaussian filter [TOM 98] is used; it allows to remove noise in the image while preserving the edges of the cracks. The equation of this filter is written:

$$F(X) = \frac{1}{\mu} \int f(X) e^{-\frac{1}{2} \left(\frac{\|Y-X\|}{\sigma_{d1}} \right)^2} e^{-\frac{1}{2} \left(\frac{\|f(Y)-f(X)\|}{\sigma_{d2}} \right)^2} dx$$

$$\text{with } \mu = \int e^{-\frac{1}{2} \left(\frac{\|Y-X\|}{\sigma_{d1}} \right)^2} e^{-\frac{1}{2} \left(\frac{\|f(Y)-f(X)\|}{\sigma_{d2}} \right)^2} dx \quad (2.1)$$

Where $X(x,y,z)$ and $Y(x,y,z)$ are the coordinates of a given pixel and its neighbors, respectively, $f(X)$ is the gray value of the input image (output of subtraction filter). σ_{d1} and σ_{d2} are the scale constants of the Gaussian distribution (values corresponding to the different volumes investigated are given in 2.1).

- Substep j: Steerable filter

To optimally enhance the contrast of cracks in the reconstructed volumes, the 3D steerable filter based on the Hessian matrix proposed by F.Aguet [AGU 05] is used. Some examples of Hessian matrix based methods for crack segmentation can be found in the literature. For example, low contrast micro-cracks in human bones have been detected with this approach by A.Larrue *et al.*. Although in this case the cracks were investigated by synchrotron tomography they present some similarities with those shown in Figure 2.a like a low contrast due to low opening [LAR 11][WOL 16]. Using the same idea, C.Chateau has used the eigenvalues of the Hessian matrix to construct a contrast-enhancing filter to segment cracks in lightweight concrete; in that specific case the segmented cracks correspond to the residuals of a Digital Volume Correlation calculation [CHA 18]. The basis of the Hessian matrix based method is briefly summarised hereafter, more details can be found for example in [VOO 13].

The eigenvalues of a Hessian matrix calculated for each pixel of an image represent the anisotropy of the variation of the gray value along the direction of the corresponding vector. According to this, steerable filters can be designed for different features detection, and here we use the planar detector [AGU 05]. For a voxel belonging to a locally planar feature, the eigenvalues of the Hessian matrix should be larger in one direction (the normal of the plane) and smaller in the remaining two directions. It is assumed that the shape of fatigue cracks correspond to a series of adjacent planar portions of various sizes. The eigenvalues of the 3D Hessian matrix are calculated at each voxel and its the maximum value is assigned to the voxel.

- Substep k Nonlinear bilateral filter

The output image of the steerable filter contains a lot of noise (see Figure 2.2d) as the crack is not the only planar structure detected (Figure 2.2d). To keep only those voxels belonging to the crack, a nonlinear bilateral filter [PAC 13] is used; it combines the output of the steerable filter (substep i) and that of the linear bilateral filter (substep j); it is written:

$$F(X) = \frac{1}{\mu} \int f(X) e^{-\frac{1}{2} \left(\frac{\|Y-X\|}{\sigma_{d1}} \right)^2} e^{-\frac{1}{2} \left(\frac{\|S(Y)-S(X)\|}{\sigma_{d2}} \right)^2} dx$$

$$\text{with } \mu = \int e^{-\frac{1}{2} \left(\frac{\|Y-X\|}{\sigma_{d1}} \right)^2} e^{-\frac{1}{2} \left(\frac{\|S(Y)-S(X)\|}{\sigma_{d2}} \right)^2} dx \quad (2.2)$$

Where $X(x, y, z)$ and $Y(x, y, z)$ are the coordinates of a given pixel and its neighbors, respectively, $f(X)$ is the gray value of the input image (result of the linear bilateral filter), $S(X)$ is the value of the output image of the steerable filter. σ_{d1} and σ_{d2} are scale constants of the Gaussian distribution. The term non-linear means that in this bilateral noise filtering process, the output of the linear bilateral filter $f(X)$, is different from the image ($S(X)$, the output of the steerable filter) which is used to calculate the parameters of the filtered convolution kernel. The results of this last filtering step shown in Figure 2.2.e.

Step 3 Double index maximum entropy threshold

To eventually obtain the binary image of the crack after those filtering steps the ‘two-index entropy threshold’ introduced by Bhowmik *et al.* [BHO 14] is used (equation 2.3). The first index is the gray value of a single-pixel and the second one is the average gray value in the neighborhood. In our case the first index is the average gray value in the in-layer neighborhood (3×3). The second indicator $g(x, y, z)$ correspond to the continuity between two adjacent layers (equation 2.3). For a given voxel, $g(x, y, z)$ counts how many voxels (ignoring those at the edge of the image) have close gray value and eigenvectors (computed in the Steerable filter) within a radius w of the two adjacent layers (e.g. $w=1$, represents a 3×3 windows centered on the considered voxel in the two adjacent layers). The two threshold values for each slice are chosen to maximize the information entropy of each slice.

$$g(x, y, z) = \sum_{i,j=-w}^w \delta(x+i, y+j, z \pm 1)$$

$$\delta(x+i, y+j, z \pm 1) = \begin{cases} 1, & \text{if } \frac{|f(x, y, z) - f(x+i, y+j, z \pm 1)|}{f(x, y, z)} < \alpha \\ & \text{and } |d(x, y, z) - d(x+i, y+j, z \pm 1)| < \beta \\ 0, & \text{else} \end{cases} \quad (2.3)$$

$f(x, y, z)$ is the output of the non linear filter, $d(x, y, z)$ is the eigenvector of the Hessian matrix calculated in the steerable filter. α and β are two parameters which are tuned to achieve crack continuity (see appendix A).

2.2.2 Deep learning thresholding method for synchrotron CT images

The global approach is divided into three steps: first, a 2D deep learning method (U-net) provides a probability maps; second, the method described in section 2.2.1 extracts the

crack from the probability maps; third, the crack tip is smoothed method (Alphashape method). The flowchart of the algorithm is shown in Figure 2.3.

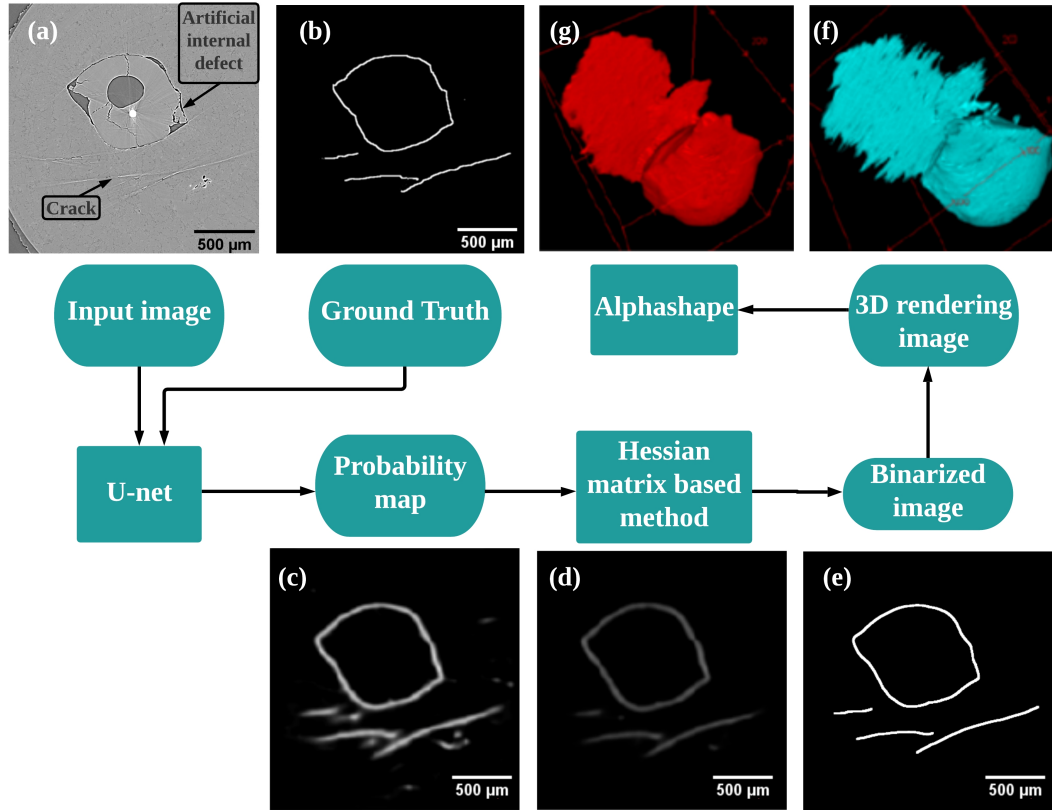


Figure 2.3: Flowchart of the segmentation algorithm for synchrotron images. (a) 2D slice of a synchrotron tomography image of a cast Al sample showing a crack (bottom arrow) and an internal artificial defect (upper arrow), the crack also appears in Figure 2.6 with an improved visibility; (b) Manually segmented image of (a) used as Ground Truth for training the U-net network; (c) Probability map of (a); (d) Enhanced and denoised image obtained with the Hessian matrix method; (e) Binarized image of (d); (f) 3D rendering image of (e); (g) 3D rendering image with smoothed crack tip by Alphashape.

2.2.2.1 U-net

In the last years, several deep learning methods have been proposed for image classification and recognition (e.g. ImageNet, AlexNet ...) see [RON 15] for a review. In this work we use a convolutional neural networks (CNN) called U-net, following the approach of Strohmman *et al.* [STR 19] who also used this type of algorithm for segmentation of the microstructural components of an Al-Si alloy within a high resolution synchrotron tomography image.

The network (U-net) structure used here is shown in Figure 2.4. The encoder procedure Step 1-4 aims at identifying features at different scales by a series of convolution (Conv2D) and downsampling operations (Maxpooling2D). After each step, the image size is halved and the feature maps number is doubled. The purpose of the decoder Step 6-9 is to restore the feature image to its original resolution by Convolution (Conv2D) and upsampling operation (bilinear interpolation). After each step in decoder, the image size is doubled and the feature maps number is halved. Each output of the decoder is concatenated with the output of the encoder with the same dimension. A more detailed presentation of the Unet method can be found for example in [RON 15]. The details of each step to reconstruct the Neural work can be found in Table 2.2 and the basic explanation of the operations used here can be found in Table 2.3.

As shown in the top part of Figure 2.4, the training process of the network consists first in generating a binary image with randomly initialized kernel values. From this image and the ground truth, a loss is calculated (loss function: binary cross entropy), from which updated kernel values are generated. With those values a second iteration can start. The process is repeated for a given number of iterations.

The ground truth was obtained by manually segmenting some slices using the pixel brush tool in Matlab ¹. The time to manually segment a 512×512 pixel image containing a crack is about 2 minutes (total time for 80 slices: approximately 3 hours). In order to avoid over-fitting, ‘data augmentation’ is performed on the training data by using gray scale and manually segmented images rotated at a random angle.

The training and testing of Unet was implemented in Python 3.0 (Tensorflow Keras), using Adam optimizer (learning rate=0.0005) and ‘binary-cross-entropy’ as a loss function. Training was carried out for 100 epochs each with 50 images batch. The total training time of the Unet (input image size= 512×512) for each epochs is about 10 minutes on a standard PC with 16 GB DDR3 memory and Intel(R) i5 Core 1.9 GHz² (total time for 100 epochs 16h).

2.2.2.2 Hessian matrix based filter and Two-index entropy threshold

The output of the above described method is a 3D probability map (values between 0 and 1). Such maps can be transformed into binary data by using a threshold [STR 19]. Instead, in order to reinforce the crack 3D continuity we have used the method described in section 2.2.1: the ‘Hessian matrix based filter’ is used first to detect planar structures belonging to the crack, the output is thresholded using the ‘2-index entropy threshold’.

¹Image Labeler plugin in Matlab 2018

²This machine has been used for all calculations reported in this work

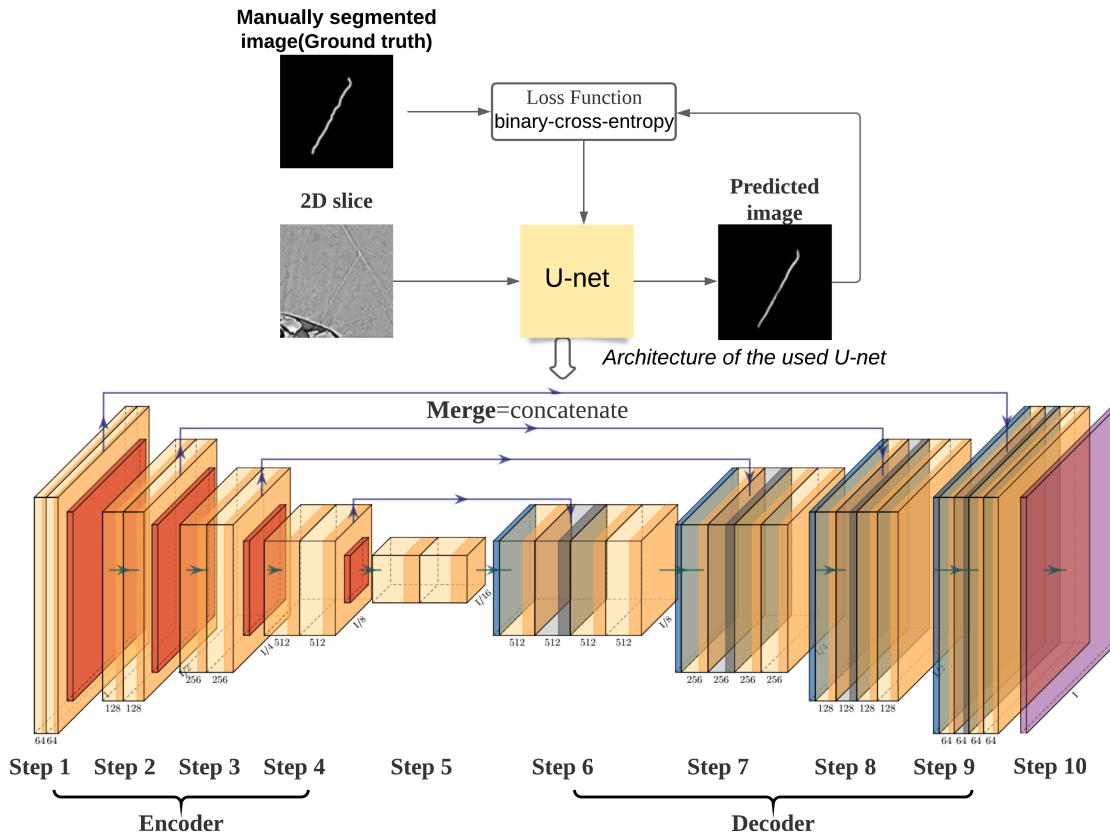


Figure 2.4: Schematic explanation of the U-net training process and visualization of the network structure. The details of each step to reconstruct the Neural work can be found in Table 2.2

2.2.2.3 AlphaShape

The relatively jagged crack tip obtained after thresholding (Figure 2.3.e) is finally smoothed as suggested by Lou *et al.* [LOU 13] who used the ‘3D AlphaShape’ algorithm initially proposed by H.Edelsbrunner and E.P.Mucke [EDE 94].

2.3 Results and discussion

2.3.1 Segmentation of crack images obtained by laboratory CT

In principle Laboratory CT machines can reach voxel sizes which are comparable to those of synchrotron tomography. In practice, however, lab sources suffer from i) a lower signal/noise ratio and ii) a non coherent x-ray beam (much less coherent than that at a synchrotron source). The coherence produces phase contrast which helps to detect sub voxel features [CLO 97]. Internal fatigue cracks visible on Figure 2.1a have a lower opening

than surface ones. As shown in Figure 2.1a, the most visible cracks are those connected to the surface; cracks in the bulk appear with a much lower contrast and are hardly visible on the raw image. Such internal cracks represent a big challenge for thresholding. In Figure 2.1.a, the voxel size is $2.1\mu\text{m}$. A lower voxel size could deliver a better image as shown in [DAN 19] with a $0.7\mu\text{m}$ voxel size also on rolling contact fatigue cracks in steels³. However such small voxel sizes have at least two drawbacks. First, the sample dimensions are reduced [BUF 06] and, second, large exposure times are required. In the above mentioned paper Danielsen *et al.* [DAN 19] mention an exposure time between 10 and 20s resulting in scanning times larger than 10h [Fæ 19]. Such long scans cannot be used for *in situ* experiments. For those reasons one has very often to bear with larger voxel sizes and/or shorter scans.

The result of the classical crack segmentation method on the internal crack of Figure 2.1 is shown on Figure 2.5.b; the thresholding process is as follows: i) contrast enhancement by brightness adjustment, ii) 3D Gaussian filtering denoising iii) segmentation by using a threshold value on the grayscale histogram. As can be seen on the figure, the crack with low contrast has not been properly detected. In the 3D rendering some parts of the crack are missing making quantitative analysis very difficult. Figure 2.5 shows the results obtained on the same crack by the Hessian matrix method described in section 2.2.1. A much more continuous crack is obtained even in crack sections with very low opening. Another example is given in 2.5.3 on an Al sample. In both cases, the proposed algorithm performs well compared to single value gray level histogram threshold providing a much more continuous crack surface. It is likely, however, that the real crack tip will remain undetected given the voxel size used⁴ but one can assume that the error remains constant along the crack front allowing to capture the *shape* of the cracks with a reasonable accuracy. As explained in section 2.1, being able to extract automatically crack fronts is a key issue for *in situ* experiments where many successive crack fronts are recorded on a single sample. The proposed algorithm can also help for thresholding cracks imaged by synchrotron tomography as explained in the next section.

2.3.2 Segmentation of cracks in synchrotron tomography images

2.3.2.1 Limits of the Hessian matrix based method

3D images of fatigue cracks have been recorded by synchrotron tomography in a cast Al sample during a series of *in situ* ultrasonic fatigue experiments [MES 20b]. The tests were

³in that specific case the authors have also used different threshold values depending on the crack thickness. Those values were defined manually.

⁴As a rule of thumb the spatial resolution is of the order of twice the voxel size

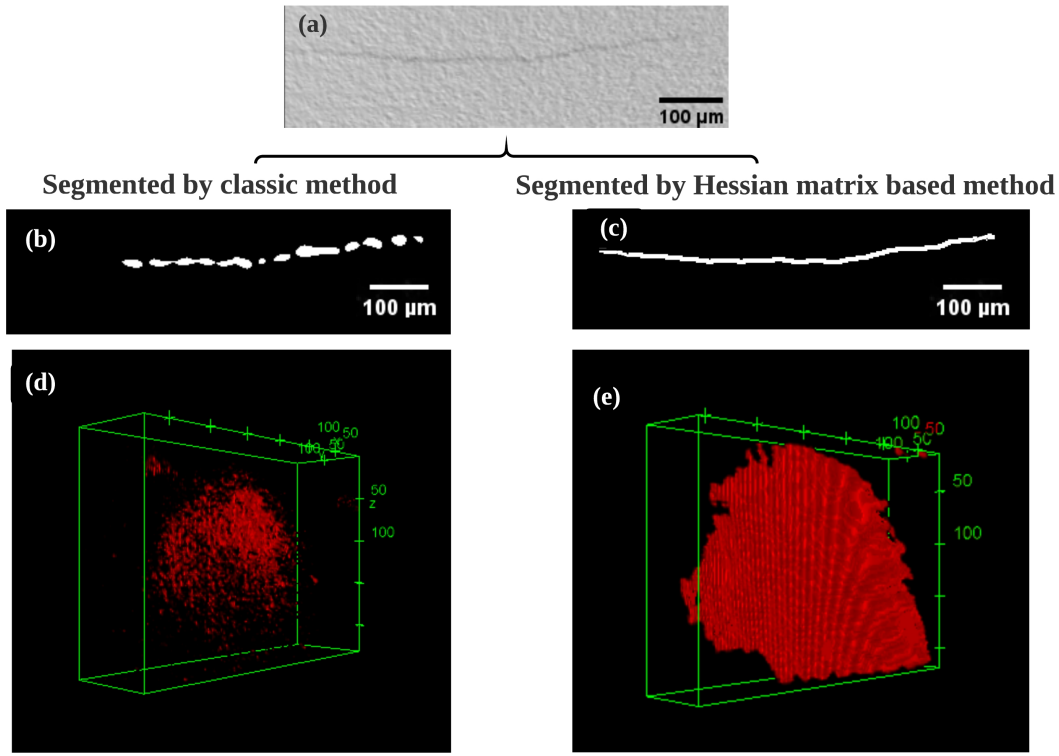


Figure 2.5: Segmentation of a rolling contact fatigue crack obtained by laboratory CT. (a) Reconstructed slice in the raw image (voxel size = 2.1 μm) (b) and (d) Segmented slice and 3D rendering obtained by classical gray level histogram threshold (c) and (e) Segmented slice and 3D rendering obtained by the Hessian matrix-based method. The Hessian matrix improves the continuity of the binary crack in spite of its low contrast and opening.

carried out at PISCHE beamline of Synchrotron SOLEIL, the energy of the beam (filtered white beam) is 29keV the voxel size 1.3 μm. Figure 2.6 shows an image of one specimen after 1.91×10^7 cycles. The fatigue specimen contains an internal artificial defect (partly visible on the bottom left of the figure) in order to foster internal crack initiation.

The Hessian matrix method described in section 2.1 was used to segment the crack observed in this sample. The result, shown in Figure 2.6.c is that this method fails at producing a continuous crack. This is because the contrast created by the crack in the reconstructed image is different from that obtained in laboratory CT. Because of the spatial coherence of the beam, some phase contrast appears at the crack surface.

More precisely, as shown in Figure 2.6.a, three different type of contrast (or gray levels) can be observed:

- black (type 1 on Figure 3.a) for voxels belonging to a crack part with opening larger than 1 voxel (attenuation contrast);

- white (type 2 on Figure 3.a) for voxels belonging to a crack part with sub voxel opening (phase contrast);
- white (type 3 on Figure 3.a) for voxels belonging to a streak artifact;

Cracks which propagate in metals from internal defects grow in an environment which is not the ambient air. As a result the crack surfaces are extremely flat because they correspond to crystallographic planes [SER 16]. The alloy studied here being a foundry alloy, the grain size is of the order of $600\text{ }\mu\text{m}$ so that those flat surfaces can extend over several hundreds of micrometers. This creates some streak artifacts, mostly at the end of the cracks, where they seem to extend the crack plane (Type 3 defect in Figure 2.6.a). Those artifacts are known in synchrotron tomography although their exact origin remains unclear. F.P.Vidal *et al.* have discussed the origin of similar streak artifact in 3D images of Ti/SiC fibre composites. For the authors, the existence of artifacts may be due to the detector impulse response [VID 05]. The same conclusions are given by L.Croton *et al.* from simulation of phase contrast synchrotron tomography of the human brain [CRO 18]. C. Madonna *et al.* found similar streak artifact in synchrotron tomography images of rock. According to these authors, they are due to exponential edge-gradient effects [MAD 13]. Without a better understanding of the origin of such artifact it is not possible, yet, to suppress them from reconstructed images and one has to adapt the segmentation methods to their presence.

In practice, the only way to distinguish real cracks from artifacts relies on the user judgement during thresholding, based on what can be expected from the crack in terms of propagation direction. That is, cracks should start from the internal defect, and grow towards the sample surface. Also, the crack opening should decrease from the crack mouth (at the internal defect) to the tip.

When some black segments are present in the image (Figure 2.6b) one can reasonably assume that a crack is present; often those segments are joined by white ones (Figure 2.6b) and the crack position corresponds to the union of those segments. When the crack opening is too small, it appears as a white line ('Type 2'). Instead, the part marked 'Type 3', is judged as a strike 'artifact'.

Because both strike artifacts and partially opened cracks appear in white it is not possible to extract them simply based on their gray levels. It is the user who decides which is which based on his/her experience and also by looking at the crack shape/position in neighbouring slices or on slices with a different orientation (e.g. orthogonal views like those labeled 'sectional view' on Figure 2.6). Needless to say that such a process is long (approximately 2 minutes per slice), tedious, prone to errors and almost impossible to carry on more than a few volumes. Typically however the quantitative analysis of an

in situ fatigue test might require thresholding tens of such 3D images. To try to solve this problem which is a true bottleneck in data analysis, we have used the deep learning algorithm presented in section 2.2.2. The results obtained are presented in the following section.

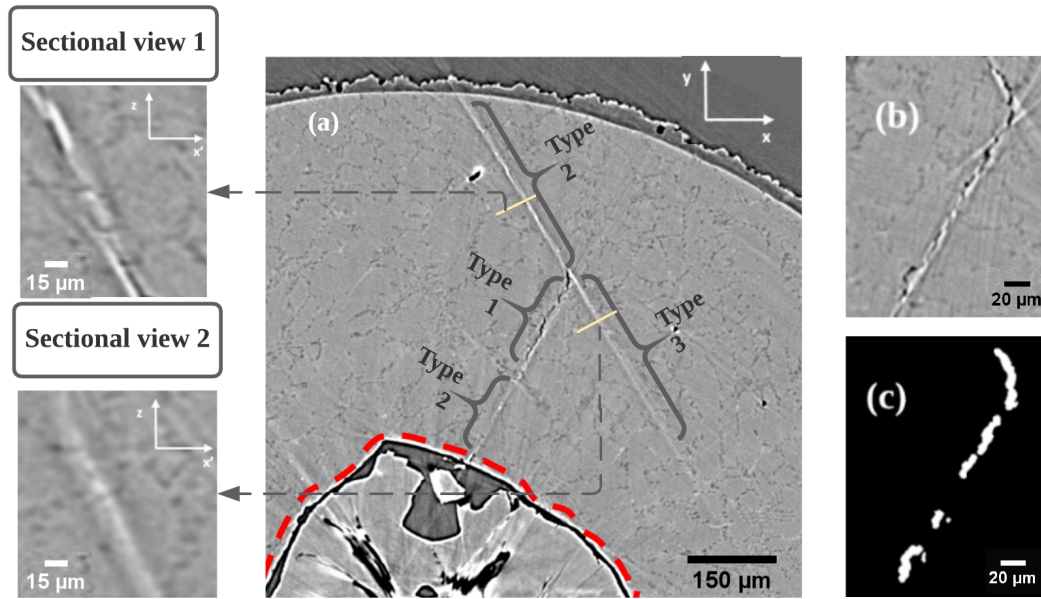


Figure 2.6: (a) 2D slice of a synchrotron tomography image of a cast Al sample showing an internal fatigue crack initiated from an artificial defects (underlined by a dashed red line) after 1.91×10^7 cycles (voxel size $1.3 \mu\text{m}$). Three types of contrast are observed: 1. crack with opening of the order or larger than 1 voxel (black); 2. crack with subvoxel opening (white); 3. streak artifact (white). (b) and (c) thresholding of the crack using the Hessian matrix method described in section 2.2.1.

2.3.2.2 Application of deep learning based method to fatigue crack in synchrotron tomography volume

The deep learning algorithm is used to segment the volume shown in Figure 2.6. As explained in section 2.2.2.1, 80 slices (out of 1200 for the whole image) were manually segmented (70 for training and 10 for validation). To reduce the computation time, the original image (1200×1200) is resized to 512×512 pixels before training the network.

The 3D probability map obtained from the whole block by the U-net algorithm has been first binarized using a threshold of 0.5. The result is shown in Figure 2.7e and f and compared with the results obtained with the Hessian matrix approach (Figure 2.7b and c). If the Unet network is more successful at thresholding the crack, some discontinuities

remain. In particular, the part of the crack close to the internal defect surface is missing. Changing the threshold to a lower value enables to detect that part but a lot of noise appears in the map. Improving the accuracy of the probability map would require more labor cost (see next section). In addition, this method is a slice by slice 2D approach that does not take advantage of the 3D information of the crack image. As a result, as explained in section 2.2.2 we have used the Hessian based algorithm developed for lab CT images to obtain a binary image from the probability map. The result is shown in Figure 2.7g and h; the crack appears much more continuous and the missing part connecting the internal defect is now visible. This is obtained thanks to i) the Hessian matrix method which reinforces the contrast of planar features and ii) the 2-index max entropy threshold which takes advantage of the 3D information in the probability map.

2.3.2.3 Application: segmentation of a series of synchrotron tomography volumes obtained during an *in situ* test

For illustrating the ability of the trained algorithm to process series of dataset automatically, we have used two volumes of the same sample reconstructed after 1.84×10^7 and 1.98×10^7 fatigue cycles [MES 20b]. Those volumes were segmented by the U-net model trained on a third volume as explained above. The segmentation of the two new volumes using the trained network is relatively fast: 20 minutes on the computer mentioned above. The results are shown in Figure 2.8. In spite of the complex contrast visible on the 2D graylevel slices, the proposed method allows to obtain complete images of the two successive crack positions (shown in blue and yellow). After registration of the reconstructed volumes using the defect, the two reconstructed cracks superimpose satisfactorily and, interestingly, one can see that the propagation of the crack detected at 1.84×10^7 cycles is not uniform but a part of its front is arrested. Such crack arrests have been rarely reported in 3D; they can only be observed if the number of tomographic scans is large enough which results, as explained, in large series of dataset which must be systematically analysed. As mentioned before, it is unlikely that the thresholding process can detect the "real" crack front, nevertheless assuming that the error is roughly constant along the crack front (same opening level) a systematic thresholding/processing, even imperfect, can help to detect interesting regions of the crack or cycling steps which can be analysed with more details if necessary (for example using gray level 2D slices). The proposed segmentation method delivers *continuous* crack surfaces, which can be transformed into meshes for finite element calculations without further treatment.

As a final remark, in the proposed approach, each segmented 3D image of a crack is independent of the previous or the next 3D image in the series, although a clear continuity exist between them. Some deep learning algorithms (Recurrent Neural Network - RNN

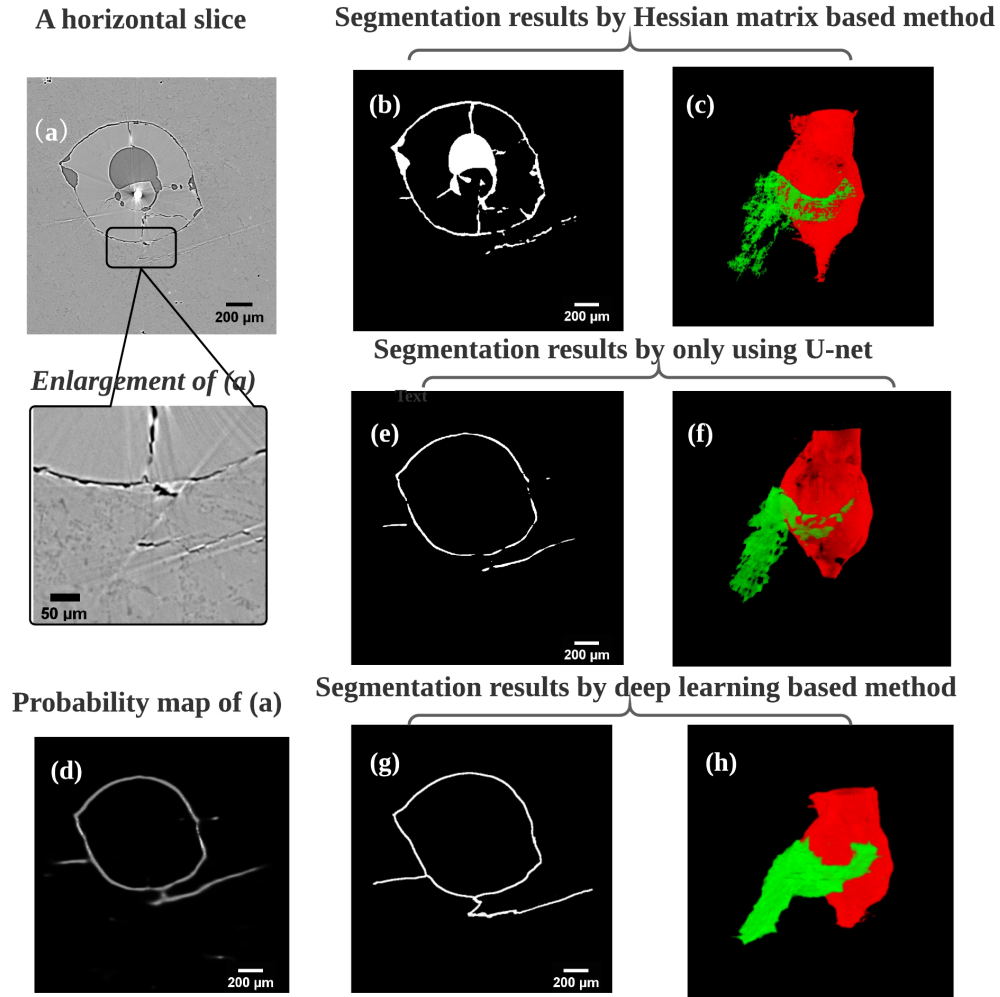


Figure 2.7: Results of different segmentation methods: volume obtained at PISCHE beamline of synchrotron SOLEIL: energy=29keV, distance between specimen and detector=15cm, voxel size=1.3 μm , crack observed after 1.91×10^7 cycles. (a) 2D horizontal slice; (b)~(c) 2D segmented slice and 3D rendering by 'the Hessian matrix based method'; (d) Probability map of (a); (e)~(f) the 2D segmented slice and 3D rendering by only using U-net; (g)~(h) 2D segmented slice and 3D rendering by deep learning based method.

or Long Short Term Memory-LSTM) have been suggested for taking into account the continuity between different data-sets in the field of 3D biomedical imaging [CHE 16] or in the prediction of gradual ocular disease [JIA 18]. This type of algorithms could be used to ensure a better compatibility between the different 3D images in the temporal sequence and produce more reliable results on crack growth.

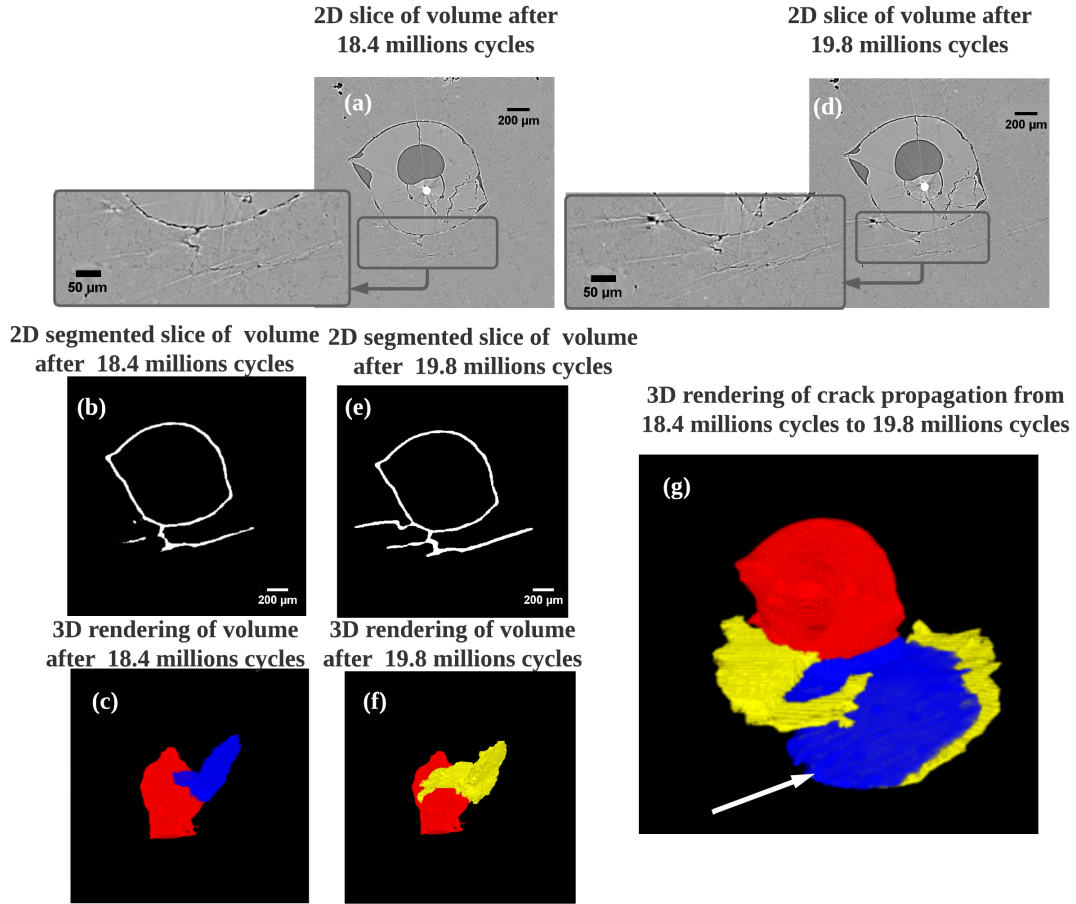


Figure 2.8: Segmentation results obtained with the trained U-net model for two successive volumes of an Al samples after 1.84×10^7 cycles (a,b,c) and 1.98×10^7 cycles (d,e,f). The U-net is trained on a third volume at a different number of cycles. The systematic analysis enabled by the algorithm of the successive volumes reveals a crack arrest on a region of the crack front (see arrow on g).

2.3.2.4 Influence of reconstruction parameters

If the reconstruction of 3D images always use the Filtered Back Projection algorithm, the contrast obtained in the raw images that are to be segmented varies from one synchrotron source to the other because the beam coherence, the type and quality of optics, detector and scintillators vary. We have therefore tested the applicability of our segmentation method on a dataset different from the one described above. The material used is the same (cast Al alloy) and the experiments are also similar (same in situ rig and cycling conditions). The images have been recorded at the SYRMEP beamline of Elettra synchrotron in Trieste. The Energy of the beam (29keV) and the specimen to detector

distance (15cm) are the same as in SOLEIL but the voxel size is different ($2.2\text{ }\mu\text{m}$) and the Paganin method [PAG 02] for phase retrieval was used during reconstruction. As shown in Figure 2.9.a, the contrast of the cracks is different from that observed in Figure 2.6 or 2.7 (cracks with low openings tend to appear with white contrast only) in part due to the Paganin filter which reduces the spatial resolution because it acts as a low-pass filter [IRV 14]. Distinguishing the cracks from the strike artifacts becomes more difficult even with the eye.

First, the U-net network was trained with 70 manually segmented slices (learning rate, type of loss function and other parameters are the same as in section 2.3.2.1). After 100 epochs (50 images batch), the probability maps obtained are shown in Figure 2.9.b. Compared with the probability map observed in Figure 2.7, overall, the cracks show a lower contrast and some parts are not detected (e.g. the part labeled Part A in Ground Truth Figure 2.9.d). The 3D rendering shown in Figure 2.9.c, shows that some parts of the cracks close to the internal defect are completely missed during segmentation (see arrow on the figure). To improve crack detection, the number of manually segmented images was doubled (140 images). By doing so, Part A was detected in the probability maps (Figure 2.9.e), but with a low contrast and, as a result, this part of the crack is still not completely imaged in the 3D rendering. By looking closely at the shape of Part A it was noticed that it is a crack which grows from the defect perpendicular to the stress direction (Mode I) which is also the rotation axis during the tomography experiment. Thus Part A only appears on a few (approximately ten) of the horizontal slices (perpendicular to the rotation axis) used for training the model. In practice, for manually thresholding that part of the crack, the user would use the 3D information by looking at slices with different orientation to confirm (or infirm) his/her interpretation.

In slices containing the rotation axis mode I cracks such as part A are indeed more clearly observed (Figure 2.9.g). Therefore, 70 vertical slices of the same volume were used to train the network (Figure 2.9.j). By comparing Figure 2.9j and h one can clearly see that the probability map is much closer to Ground Truth than when horizontal slices were used (compare with Figure 2.9d and e). The new 3D rendering produced with the vertical slices (Figure 2.9.i), now shows a more complete crack, with a fully detected Part A.

From the above results, we can conclude that the network should be trained in the most favourable configuration, i.e. using slices where the cracks are the most evident to visualise by eye. From that point of view, however, the cracks investigated here form a special case as they are very planar (crystallographic) and strongly inclined with respect to the stress direction. Such cracks are therefore well detected/visible on slices perpendicular to the rotation axis. However, in a more general case, cracks initiated from a surface during uni-axial tension-compression tests would generally grow in mode I and therefore it is

advised to train the model on slices containing the rotation axis. It also seems that the use of a slightly larger voxel (allowing larger samples to be imaged) and a limited loss of spatial resolution can be compensated by an increase in the number of slices used to train the network but more data would be required to confirm that point. Similarly, the parameters of the neural network training (learning rate/ type of loss function /network structure, etc.) will also affect the segmentation results. For example, changing the type of loss function has been shown to improve the segmentation quality of different phases in synchrotron CT images of an Al alloy [STR 19]. These parameters can be seen more as a talent of the neural network learning. In this work, we focused more on the effect of different user mind inputs on the same neural network. Some results obtained with different loss function type and learning rate are shown in 2.5.4.

2.4 Conclusion

With the development of fast tomography at synchrotrons facilities, scans typically last less than 5 minutes. As a result, *in situ* experiments monitored by tomography can generate a considerable amount of data. In the processing of such data, thresholding is a bottleneck on which relies the efficiency and quality of quantitative analysis. In this chapter we have described several methods for the thresholding of fatigue cracks in tomographic volumes. In a reconstructed 3D image, such cracks can be quite difficult to threshold when their opening is low, particularly in the case of laboratory tomography.

The first method described in this chapter for thresholding fatigue cracks in lab CT relies on and merges several approaches developed for bones or concrete. A Hessian matrix approach coupled with a series of bilinear filters are used to detect flat features which connectivity in 3D is reinforced by the 2 index entropy method. Examples of application for cracks obtained with relatively large voxel sizes (allowing scan times of the order of 30 minutes) have been shown for two different alloys.

In the case of synchrotron tomography, the thresholding process is made more complex by the coherence of the X-ray beam which produces diffraction effects and artifact at the crack edges. A reliable segmentation of such images normally involves a lot of human intervention and can hardly be automatic. We have proposed a deep learning method which uses a U-net network to replace human intervention during thresholding. By manually segmenting a limited amount of images (less than 2%) the software can be efficiently trained to detect internal cracks in a cast Al alloy. The probability map obtained from the neural network is thresholded using the algorithm developed for laboratory CT images. Finally, without supplementary training, 3D images of the propagation of a crack acquired during an *in situ* fatigue test have been successfully thresholded, showing the possibility

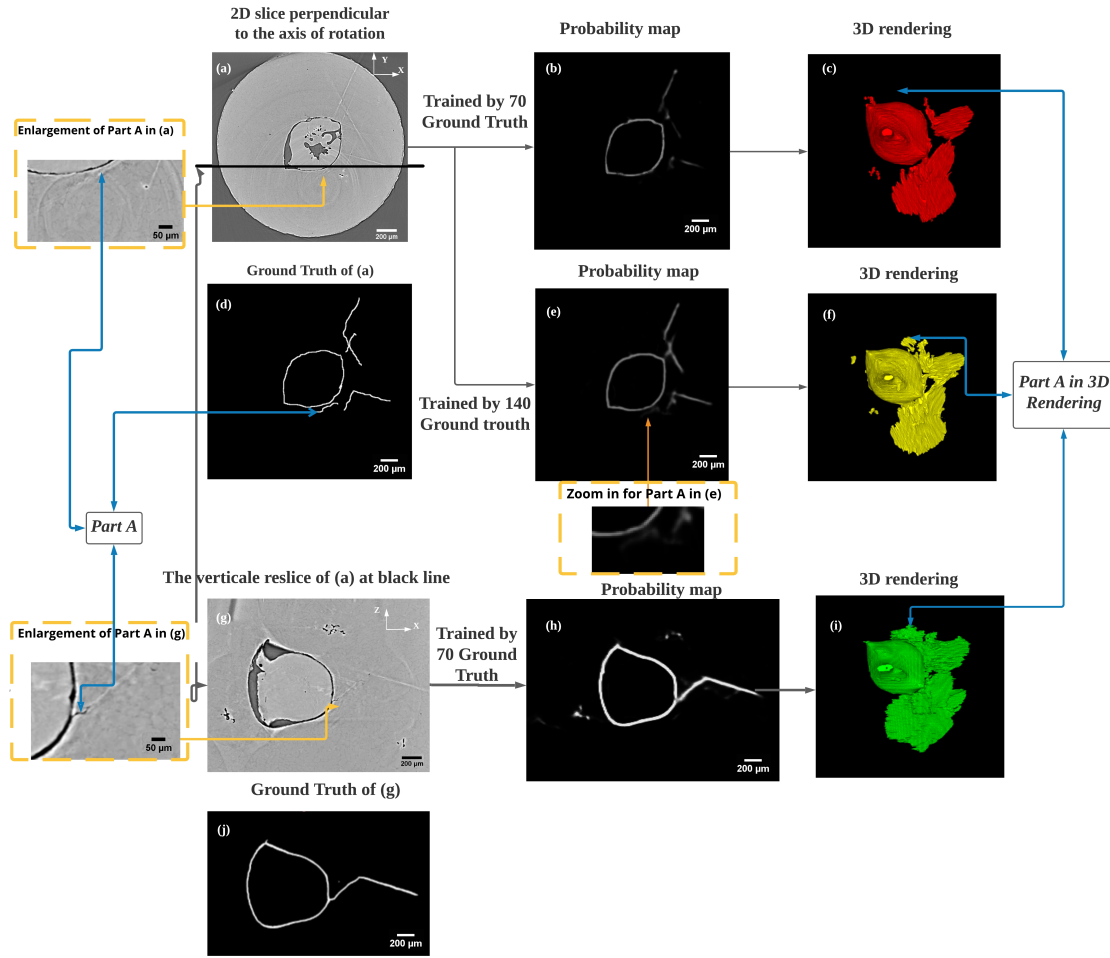


Figure 2.9: Effect of different inputs on deep learning based method segmentation results (volume obtained at Elettra Synchrotron: energy=29keV ,distance between specimen and detector=15cm, voxel size =2.2 μ m reconstruction with FBP and Paganin). (a) 2D slice perpendicular to the rotation axis (*horizontal* slice); (b)'Probability map' obtained with 70 horizontal Ground Truth slices; (c) 3D rendering obtained with network trained using 70 horizontal Ground Truth slices; (d) Ground Truth of (a); (e) 'Probability map' obtained with 140 horizontal Ground Truth slices; (f) 3D rendering obtained with network trained using 140 horizontal Ground Truth slices; (g) 2D slice parallel to the rotation axis (*vertical* slice) corresponding to the black line shown in (a); (h) 'Probability map' obtained with 70 vertical Ground Truth slices; (i) 3D rendering obtained with network trained using 140 vertical Ground Truth slices (j) Ground Truth of (g). In (i) a more complete crack is obtained.

to automatize the process. The same network was used successfully on a data-set obtained at a different synchrotron with different imaging and reconstruction conditions.

2.5 Appendices

2.5.1 Appendix A: Segmentation Parameters

Table 2.1: Parameters used for crack segmentation. In the first row of the table: 'Tomo lab'=volume obtained by laboratory CT, 'Tomo syn'=volume obtained by Synchrotron CT.

Step	Variable	ER7(Tomo lab)	Al(Tomo lab)	Al(Tomo syn Soleil)	Al(Tomo syn Elttra)
Subtract filter	window size(voxel)	11×11×11	11×11×11	None	None
Linear bilateral filter	window size(voxel)	5×5×5	5×5×5	5×5×5	5×5×5
Linear bilateral filter	σ_{d1}	3	3	2	2
Linear bilateral filter	σ_{d2}	0.3	0.3	0.2	0.2
Steerable filter	window size(voxel)	3×3×3	5×5×5	3×3×3	3×3×3
Nonlinear bilateral filter	window size(voxel)	5×5×5	5×5×5	5×5×5	5×5×5
Nonlinear bilateral filter	σ_{d1}	3	3	3	3
Nonlinear bilateral filter	σ_{d2}	0.3	0.3	0.3	0.3
2index maxentropy threshold	α	0.3	0.3	0.2	0.2
2index maxentropy threshold	β	0.3	0.4	0.2	0.2
Unet	Learning rate	None	None	0.00001	0.00005
Unet	Type of loss function	None	None	Cross entropy	Cross entropy

2.5.2 Appendix B: Details about U-net

Table 2.2: Detailed operations and parameters in the construction of the used U-net network

Step number	Operation number	Operation name	Parameters
Step 1	Operation 1	Conv2D	Kernel size=(3,3), filters number=64, activation function=Relu, Padding=1
Step 1	Operation 2	Conv2D	Kernel size=(3,3), filters number=64, activation function=Relu, Padding=1
Step 1	Operation 3	MaxPooling2D	Pool size=(2,2)
Step 2	Operation 1	Conv2D	Kernel size=(3,3), filters number=128, activation function=Relu, Padding=1
Step 2	Operation 2	Conv2D	Kernel size=(3,3), filters number=128, activation function=Relu, Padding=1
Step 2	Operation 3	MaxPooling2D	Pool size=(2,2)
Step 3	Operation 1	Conv2D	Kernel size=(3,3), filters number=256, activation function=Relu, Padding=1
Step 3	Operation 2	Conv2D	Kernel size=(3,3), filters number=256, activation function=Relu, Padding=1
Step 3	Operation 3	MaxPooling2D	Pool size=(2,2)
Step 4	Operation 1	Conv2D	Kernel size=(3,3), filters number=512, activation function=Relu, Padding=1
Step 4	Operation 2	Conv2D	Kernel size=(3,3), filters number=512, activation function=Relu, Padding=1
Step 4	Operation 3	MaxPooling2D	Pool size=(2,2)
Step 5	Operation 1	Conv2D	Kernel size=(3,3), filters number=1024, activation function=Relu, Padding=1
Step 5	Operation 2	Conv2D	Kernel size=(3,3), filters number=1024, activation function=Relu, Padding=1
Step 5	Operation 3	Dropout	Rate=0.33
Step 6	Operation 1	UpSampling2D	Magnification=(2,2), Method=Bilinear interpolation
Step 6	Operation 2	Concatenate	input=(output of Step 6.1, output of Step 4.2)
Step 6	Operation 3	Conv2D	Kernel size=(3,3), filters number=512, activation function=Relu, Padding=1
Step 6	Operation 4	Conv2D	Kernel size=(3,3), filters number=512, activation function=Relu, Padding=1
Step 7	Operation 1	UpSampling2D	Magnification=(2,2), Method=Bilinear interpolation
Step 7	Operation 2	Concatenate	input=(output of Step 7.1, output of Step 3.2)
Step 7	Operation 3	Conv2D	Kernel size=(3,3), filters number=256, activation function=Relu, Padding=1
Step 7	Operation 4	Conv2D	Kernel size=(3,3), filters number=256, activation function=Relu, Padding=1
Step 8	Operation 1	UpSampling2D	Magnification=(2,2), Method=Bilinear interpolation
Step 8	Operation 2	Concatenate	input=(output of Step 8.1, output of Step 2.2)
Step 8	Operation 3	Conv2D	Kernel size=(3,3), filters number=128, activation function=Relu, Padding=1
Step 8	Operation 4	Conv2D	Kernel size=(3,3), filters number=128, activation function=Relu, Padding=1
Step 9	Operation 1	UpSampling2D	Magnification=(2,2), Method=Bilinear interpolation
Step 9	Operation 2	Concatenate	input=(output of Step 9.1, output of Step 1.2)
Step 9	Operation 3	Conv2D	Kernel size=(3,3), filters number=64, activation function=Relu, Padding=1
Step 9	Operation 4	Conv2D	Kernel size=(3,3), filters number=64, activation function=Relu, Padding=1
Step 10	Operation 1	Conv2D	Kernel size=(3,3), filters number=2, activation function=Relu, Padding=1
Step 10	Operation 2	Conv2D	Kernel size=(1,1), filters number=1, activation function=Sigmoid, Padding=0

Table 2.3: Explanation list of technical terms using in Deep Learning, more details can be found in [STR 19] [RON 15]

Conv2D	A 2D Convolution operation, which uses K convolution kernels (size: $N \times N$) which are applied to the input image to produce K new images (called feature maps). The feature maps size is the same as input image (while preserving the edges, a process called padding).
Relu	(rectified linear activation function) is a linear function that will output the input directly if it is positive, otherwise, it will output zero. It has become the default activation function for many types of neural networks because a model that uses it is easier to train and often achieves better performance.
MaxPooling2D	A 2D down-sample operation, which takes the maximum value within a $M \times M$ window and outputs a smaller image (generally half size).
Upsampling2D	A 2D upsample operation, which uses bilinear interpolation to increase the input image size.
Dropout	The Dropout layer randomly sets input units to 0 with a frequency of rate, which helps prevent overfitting. Inputs not set to 0 are scaled up by $1/(1 - \text{rate})$ such that the sum over all inputs is unchanged (0.33 and 0.5 are the commonly used empirical values of rate).
Concatenate	Two batches of feature maps of the same size (one obtained during Encoding and one obtained during Decoding) are stacked together and the channel of output is equal to their sum.
Softmax	(normalized exponential function) produces a probability distribution of values between 0 and 1 from the last step of the network.

2.5.3 Appendix C: Segmentation of a fatigue crack in Al alloy

A fatigue crack initiated from an artificial surface defect during ultrasonic fatigue has been observed in a cast Al sample by laboratory tomography. Because of the sample size (3mm) a relatively large voxel size had to be used ($2.5\text{ }\mu\text{m}$) resulting in a very low contrast for the crack (Figure 2.10). In spite of those difficult conditions the crack could be successfully segmented by the segmentation method described in this work (section 2.2.1). The total segmentation time is 2 hours.

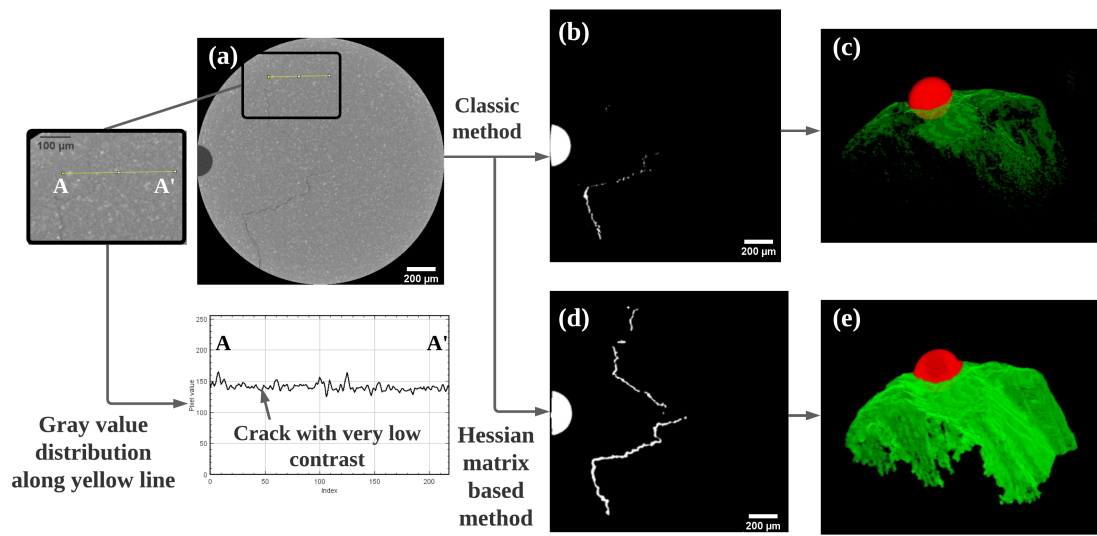


Figure 2.10: Segmentation of a fatigue crack observed by laboratory CT in a cast Al sample. (a) 2D reconstructed slice (voxel size $=2.5\text{ }\mu\text{m}$) because of the small opening (unloaded sample) the crack contrast within the Al matrix is very weak. (b) and (c) Segmented slice and 3D rendering obtained by classical gray level histogram threshold (d) and (e) Segmented slice and 3D rendering obtained by the Hessian matrix-based method. The Hessian matrix improves the continuity of the binary crack in spite of its low contrast and opening. In the 3D rendering, the artificial hemispheric surface defect located on the surface is shown in red. Sample diameter 3mm, voxel size $2.5\text{ }\mu\text{m}$, Accel. voltage 160 kV, scanning time 30 minutes.

2.5.4 Appendix D: Effect of loss function and learning rates

A range of parameters and functions can be used to tune the Unet network. In this work, as a first approach, we have investigated the number of images composing the ground truth, two loss functions and two learning rates. The results obtained by varying the number of images have been shown in section 2.3.2.4, in this part we summarize the comparison of results obtained with two loss functions and learning rates. The two tested loss functions are the *dice loss* and the *binary cross-entropy*. As shown in Figure 2.11, at the same learning rate (1×10^{-5}), with ‘dice loss’ the Unet model converges faster than with ‘cross-entropy’, but the former ends up with a higher loss: 0.2 against 0.1 for cross-entropy. The same trend is observed on the validation images. Moreover, the predicted image obtained using cross-entropy appears closer to Ground truth than when dice-loss is used.

Two different learning rates have been tested. As shown in Figure 2.12.h and .g, the predicted image obtained with ‘learning rate= 1×10^{-5} ’ has less noise than the one trained with ‘learning rate= 1×10^{-4} ’ and was selected.

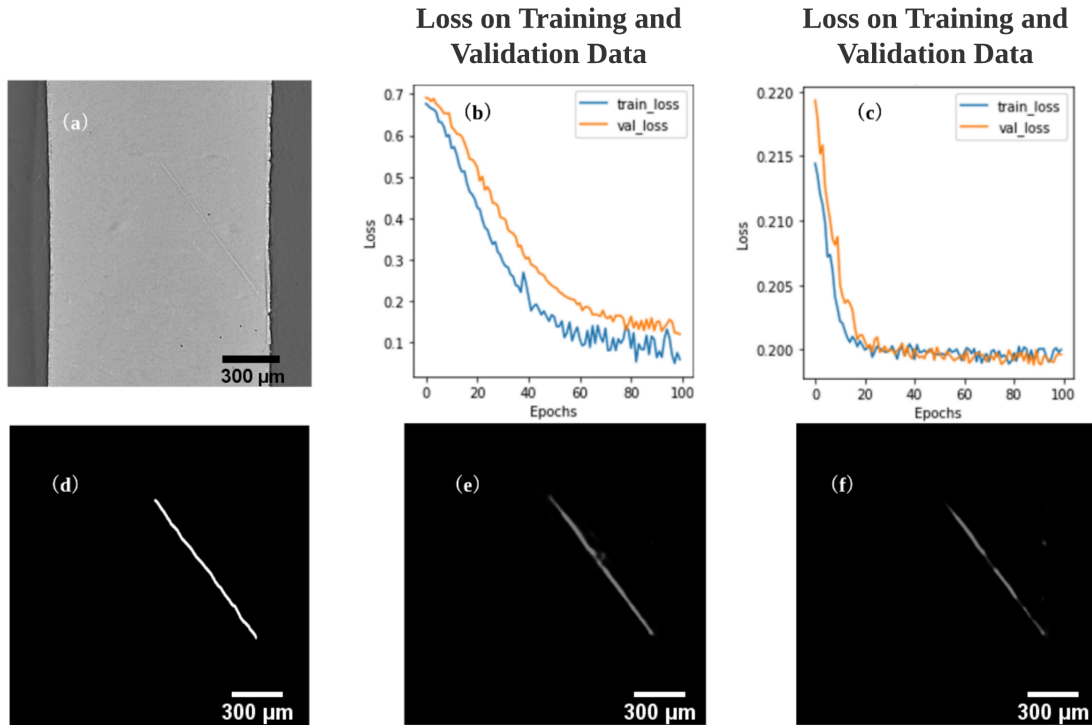


Figure 2.11: Effect of loss function on predicted image. (a) test image. Loss evolution during training for ‘cross-entropy’ (b) and ‘Dice loss’ (c) (d) Ground Truth of test image. (e) Probability map of test image obtained with ‘cross-entropy’; (f) Probability map of test image obtained with ‘dice-loss’

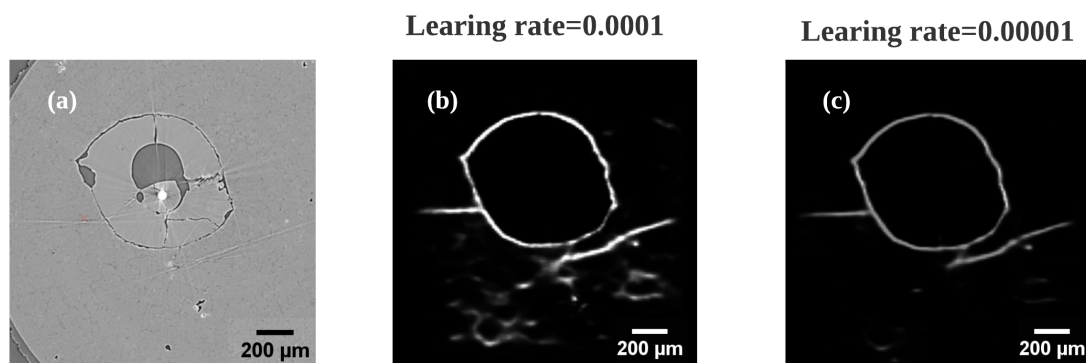


Figure 2.12: Effect of learning rates on predicted image. (a) 2D test image. (b) Probability map obtained with 'learning rate= 1×10^{-4} ' (c) 'learning rate= 1×10^{-5} '.

Chapter 3

Characterization of internal fatigue cracks and streak artifacts by simulation of phase contrast tomography

This chapter is dedicated to better identify and characterize the cracks from phase contrast SRCT images. By simulations of the phase contrast synchrotron tomography with various crack sizes and structures, firstly, we confirmed the bright parts with strong contrast in the reconstructed images are streak artifacts; secondly, we found that the gray scale values of cracks in SRCT images are related to cracks size; eventually reanalysis the cracks in the experimental SRCT images were made legible with the help of simulation results. This chapter has been written to the journal of Scientific Report as an article entitled "Characterization of internal fatigue cracks in aluminum alloys by simulation of phase contrast tomography" written by C. Xiao, J.Letang, J.Buffiere, a new subsection is inserted in the discussion section about using deep learning network (U-net) to achieve automatic segmentation via newly understood crack features and a more detailed description of the Fresnel propagator has been added in the appendix of this chapter.

3.1 Introduction

Computed Tomography is an efficient non-destructive testing technology for observing internal features (cracks, defects, inclusions, etc.) in opaque materials. For the characterization of damage inside metals, two main tomography modes are widely used: attenuation CT and phase contrast CT. With standard industrial sources, the size of the focus spot

is usually too large and the x-ray energy spectrum too broad to make it possible to see x-ray interference effects, only attenuation CT is therefore possible. On the other hand, with nanofocus laboratory sources or synchrotron radiation facilities, the x-ray beam is much more coherent, which allows the detector to record more effectively the phase change information of x-rays and phase-contrast is by default observable. For the study of fatigue crack propagation in metals, Fresnel diffraction of x-rays is exploited to enhance the visibility of edges and boundaries within an object [MAI 14]. Most common types of phase contrast CT are propagation-, analyser- or grating-based [STO 19]. The opening of fatigue cracks in metals at the crack tip is in the micrometer range, which results in a very low contrast, and Synchrotron Radiation Computed Tomography (SRCT) is therefore crucial to observe sub-voxel features thanks to phase contrast [CLO 99].

However, compared with standard attenuation tomography, for which the gray-scale value of the reconstructed image is proportional to the linear attenuation coefficient of the material, phase contrast tomography brings an increase in image complexity: phase contrast typically generates fringes at the edges of objects in the reconstructed images [CLO 99; VID 05]; in addition, streak artifacts are generated [CRO 18]. This complexity makes it difficult to precisely identify the cracks in the reconstructed image and quantitatively analyze it [BUF 06]. Some reconstruction methods enable phase retrieval in single distance phase contrast tomography: the Paganin method [PAG 02] or the Moosmann method [MOO 13]¹. Single-distance propagation-based phase contrast tomography is widely preferred to save time during in-situ experiments [BUF 10]. However, for SRCT reconstruction of fatigue cracks in metal, the Paganin method causes blurring of the crack edges; meanwhile, the Moosmann method requires long object-to-detector distances (typically several meters for metals) which are not easily obtained in all beam-lines. Therefore in studies reporting 3D crack images published so far, the classical Filtered Back Projection (FBP) reconstruction method is used as for example in Al alloys [MES 20b; WIL 13]; in Ti alloys [BIR 09; TUB 21]; in cast iron [MAR 04]; in Mg alloy [KIN 11]. The simulated images in this work are obtained using the FBP method.

Figure 3.1 shows a typical reconstructed image of an internal fatigue crack inside a cast aluminum alloy sample. This image has been obtained at SOLEIL (PSICHE beam-line) with an energy of 29 keV, a sample-detector distance of 15 cm and a voxel size of 1.3 μm . Because internal fatigue cracks grow without being into contact with ambient air, the crack surfaces correspond to crystallographic slip plane ($\{111\}$ in that specific case) often inclined with respect to the tensile/sample axis [SER 16; SER 17]. The dark features in this image correspond to voxels with near zero attenuation i.e. belonging to the crack. However, many bright features with strong contrast also appear as white lines in the slices.

¹named after the 1st author of the corresponding paper

In vertical slices (Figure 3.1a), those white lines are parallel to dark lines corresponding to voxels belonging to the cracks; in horizontal slices the white lines tend to appear at the end of the dark lines (Figure 3.1b). It is difficult to interpret those white features unambiguously. They might be flat internal cracks with small opening, but they may also be streak artifacts. If they correspond to cracks, one clearly needs a criterion to decide when a crack appears dark and when it appears bright. If they are artifacts, one needs to know how they are related to the cracks. For addressing those issues, a simulation approach is needed first.

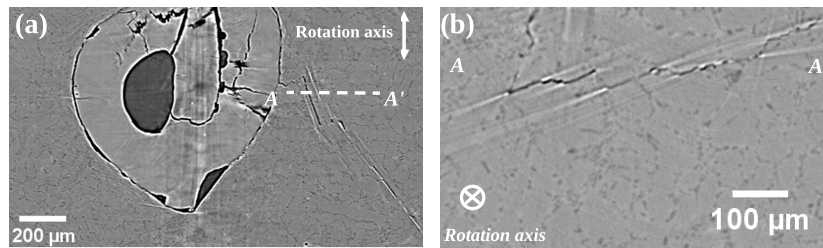


Figure 3.1: (a) Reconstructed image (vertical slice) of a fatigue crack within a cracked aluminum alloy sample obtained at SOLEIL (PSICHE beam-line) with an energy of 29 keV, a distance sample-detector of 15 cm and a voxel size of $1.3\text{ }\mu\text{m}$, the stress direction is parallel to the rotation axis; (b) Horizontal slice along the AA' dashed white line. In both slices dark lines correspond to voxels belonging to the crack, the brighter parts may be streak artifacts or flat cracks with small voxel opening.

The simulation of the whole X-ray imaging chain, from the source to the detector can be obtained with different methods which can be divided into probabilistic methods and analytic methods [VID 05]. In this work, a method proposed by Langer *et al.* [LAN 20a] using a ray casting procedure to obtain integral of the refractive index, as well as an analytical wave optics approach for generating Fresnel diffraction patterns is used to simulate phase contrast tomography. The implementation is in the GATE software (version 8.2 and later).

The purpose of this article is to better analyze the flat crack signatures in SRCT images reconstructed by the FBP method by phase contrast tomography simulations. In a first step, the simulation results allow us to compare a known crack structure (phantom) to the simulated reconstructed image, thereby distinguishing cracks from artifacts. By changing the geometry and size of the crack in the phantom, the relationship between the crack gray value and the crack size was obtained. Finally, cracks observed in experimental SRCT images were reanalysed and a better understanding of the crack path was obtained. To the best of the authors' knowledge there has not been any systematic study of this type published in the literature yet.

3.2 Method

3.2.1 Experimental synchrotron X-ray tomography

The experimental data sets analyzed in this work were obtained with two synchrotron X-ray tomography setups at Tomcat beamline (SLS) and PSICHE beamline (SOLEIL) during in situ synchrotron fatigue tests. The scanned specimens with controlled artificial casting defect was made in AlSi7Mg0.6 cast aluminum (more information about material, specimen and fatigue testing device can be found elsewhere [MES 20b; JUN 21; MES 20a]). At SOLEIL (PSICHE), half-acquisition at a voxel size of $1.3\text{ }\mu\text{m}$ has been performed, the energy of the filtered white beam has been set to 29 keV and the object-detector distance has been set at 15 cm. Similar scan conditions have been used at SLS (TOMCAT), but with a different voxel size ($1.6\text{ }\mu\text{m}$) and without half acquisition. The scan conditions can be found in the table 3.1.

Table 3.1: Imaging conditions used at TOMCAT and PSICHE beam-lines (FOV corresponds to the camera size expressed in pixels).

Beamline	Beam Configuration	Energy	Voxel size	Distance detector-object	FOV
TOMCAT	Multilayer	30keV	$1.6\text{ }\mu\text{m}$	15cm	2560×2160
PSICHE	Filtered white beam	29keV	$1.3\text{ }\mu\text{m}$	15cm	2750×2048

3.2.2 Simulation of X-ray phase contrast

A method [LAN 20a] developed by Langer *et al.* was used to simulate phase contrast tomography. The first step consists in using a ray casting procedure in the voxelized object, from which the integral of the refractive index after passing through the object can be obtained. Then the Fresnel propagator is used (Eq 4.2) to simulate the propagation of the x-ray in free space after passing the object from which the Fresnel diffraction patterns (as shown in Figure 3.2b) are generated.

The amplitude of the wave function after free-space propagation along distance D (assuming parallel beam) is as follows:

$$u_D(x, y) = u_0(x, y) * P_D(x, y) \quad (3.1)$$

where the propagator is

$$P_D(x, y) = \frac{1}{i\lambda D} \exp\left(i \frac{\pi}{\lambda D} (x^2 + y^2)\right) \quad (3.2)$$

$u_D(x, y)$ represents the wave function received on the detector, $u_0(x, y)$ is the wave function after the x-ray beam passes through the object, $P_D(x, y)$ represents the Fresnel Propagator in the time domain. In order to simplify the calculation, the convolution operation in the time domain is converted into a multiplication in the frequency domain after Fourier transform.

To implement the simulation; first, a voxelized 3D block containing a model crack (called phantom) was created as shown in Figure 3.2, the rectangular shape of the scanned object is used here to avoid the effect of the jagged edges of the voxelized cylinder which is the sample real shape; secondly, different materials are defined through the gray value of the voxelized phantom (voxels with gray value equal to 0 correspond to the air, voxels with gray value equal to 255 correspond to the AlSi7Mg0.6 alloy); finally the scan conditions must be defined (detector pixel size, distance between object and detector, energy of X-ray beam). The ray-casting class *GateFixedForcedDetectionActor* is used in Gate to implement the Fresnel propagator [LAN 20a]. In order to deal with the partial volume effect [STO 19] at the interface between different materials, we had to remove the bilinear interpolation from the source code of this module and perform pixel oversampling (via the binning factor). A binning factor of 10 has been used in horizontal direction (perpendicular to rotation axis) on the detector. The simulations were implemented on a workstation with 80 CPUs and 250 GB RAM. For a simulation with $1001 \times 1001 \times 1001$ voxels phantom and 1200×1200 detector resolution, the calculation time is about 6 mins per projection (60h for 600 projections/180°). Then the filtered back projection (FBP) as the standard and most popular reconstruction algorithm for parallel beam CT is used in this work.

3.3 Results

3.3.1 Simulation results of flat crack

As mentioned above, internal fatigue cracks in the studied cast aluminum alloy propagate on crystallographic planes inclined with respect to the direction of tension [SER 16]. Therefore, in this section our model crack (phantom) is a flat plane at 45 degrees from the rotation axis (parallel to the load direction), and the sample is a cube ($1\text{mm} \times 1\text{mm} \times 1\text{mm}$) of the AlSi7Mg0.6 as alloy shown in Figure 3.3a. The imaging parameters are those used during the in-situ fatigue experiment performed at PSICHE beam-line [MES 20b] x-ray energy 29 keV, object-detector distance 150 mm, detector pixel size $1.3\text{ }\mu\text{m}$.

First, two different crack opening degrees equal to $5\text{ }\mu\text{m}$ and $1\text{ }\mu\text{m}$ (sub-pixel opening) are studied; the crack length (L) and height (H) are both equal to $100\text{ }\mu\text{m}$. The simulated 3D image of the phantoms is shown in Figure 3.3. When the crack opening is $5\text{ }\mu\text{m}$

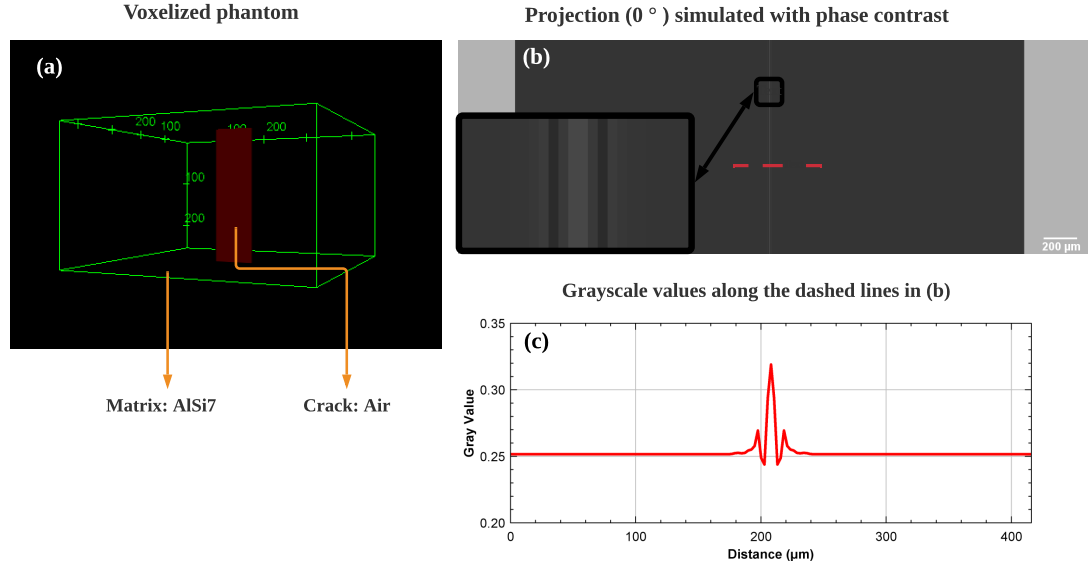


Figure 3.2: (a) Voxalized phantom: Rectangular block of Al-Si alloy with crack (voxel size 1 μm). (b) Simulated projection(0°) with phase contrast, the Fresnel diffraction patterns can be seen on crack interfaces. (c) Distribution of gray scale values along the red dashed line in the projection.

(Figure 3.3c), it can be observed that the crack appears dark, and bright streak artifacts appear at both ends of the crack in the horizontal slice with a slightly divergent shape away from the crack. At the end of the crack those artifacts present a very strong intensity which decreases with distance (Figure 3.3g). In vertical slices, the white artifacts do not appear at the ends of the cracks (Figure 3.3e). When the crack opening is reduced to 1 μm (sub-pixel opening), the contrast in the crack is so weak that the crack can barely be distinguished from the matrix by gray-scale values with respect to noise; however the bright artifacts at the ends of the crack in the horizontal slice remain unchanged compared to those at 5 μm (Figure 3.3b). This seems to indicate that cracks with sub-pixel openings, which cannot be directly observed in horizontal sections, can be revealed by artifacts at both ends, this phenomena will be investigated in the experimental images of the discussion sections. In vertical sections, the cracks remains barely visible and no bright artifacts can be seen at either end (Figure 3.3d). The simulation results of an extended flat crack show therefore that the cracks gray scale values in the reconstructed image are strongly related to its opening, this point is further analysed in the next section.

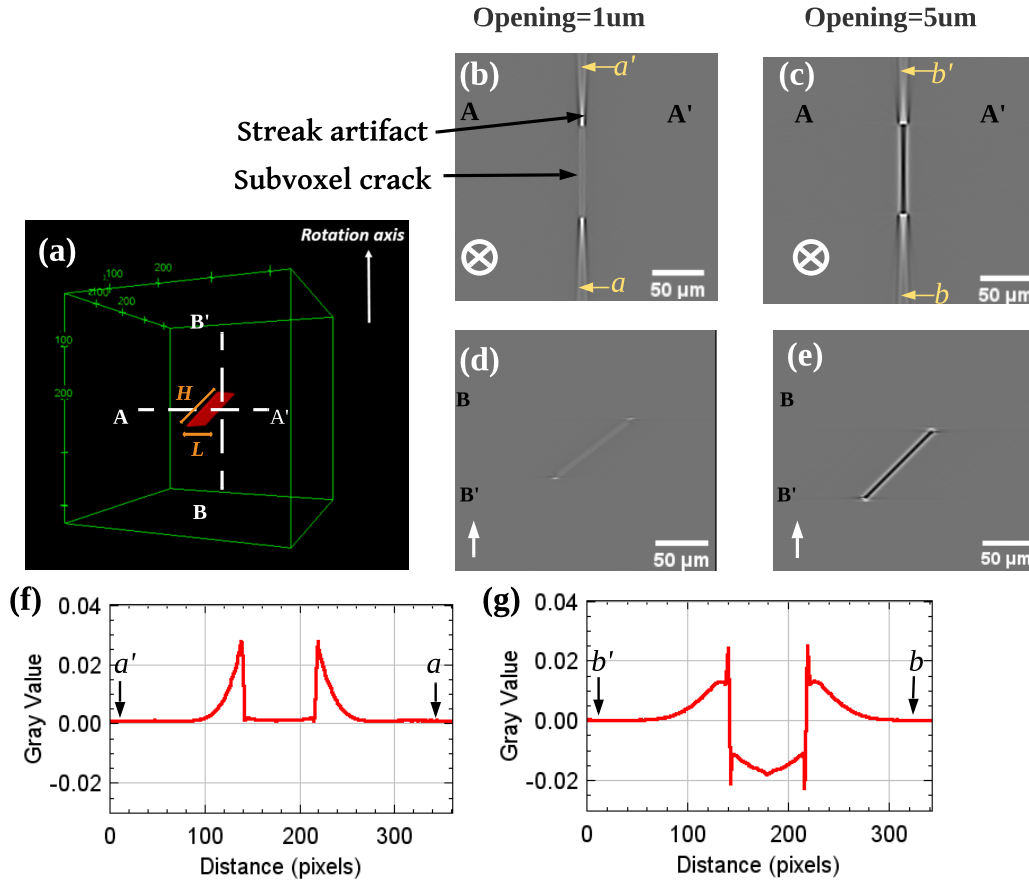


Figure 3.3: Simulated images obtained with the following imaging conditions: x-ray energy 29 keV, object-detector distance 150 mm, detector pixel size $1.3\mu\text{m}$. The crack was assumed to be a plane at 45 degrees to the rotation axis (whose direction is indicated in white in the lower left corner of the images), with a length (L) and height (H) set to $100\mu\text{m}$, two crack openings were investigated: $1\mu\text{m}$ and $5\mu\text{m}$, respectively. (a) Phantom's 3D rendering, the white dashed lines AA' and BB' indicate the position of the horizontal and vertical slices (positioned at the middle of the crack) respectively. (b) Simulated horizontal slice (A-A') of the crack with sub-voxel opening $1\mu\text{m}$; (c) Simulated horizontal slice (A-A') of the crack with opening $5\mu\text{m}$; (d) Simulated vertical slice (B-B') of the crack with sub-voxel opening $1\mu\text{m}$; (e) Simulated vertical slice (B-B') of the crack with opening $5\mu\text{m}$; (f) Distribution of grayscale values along the crack (opening $1\mu\text{m}$) along the (a-a') line in horizontal slices; (g) Distribution of grayscale values along the crack (opening $5\mu\text{m}$) along the (b-b') line in horizontal slices. Bright high-intensity artifacts were observed in both horizontal slices (b) and (c).

3.3.2 Crack gray value in the reconstructed image

To further quantify the relationship between the gray value and the opening degree, the crack's length (L) and crack's height (H) have been both fixed as $100\mu\text{m}$ and the opening degree of the crack varies from 1 to $5\mu\text{m}$ in $1\mu\text{m}$ steps. The results of these simulations

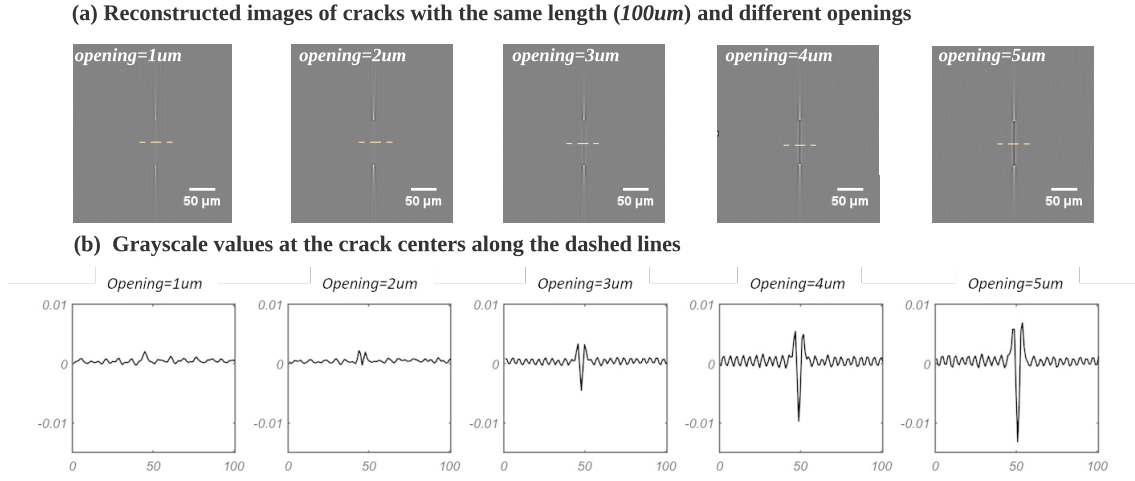


Figure 3.4: All slices are perpendicular to the axis of rotation: (a) Simulated images of cracks with openings ranging from 1 to 5 μm ; (b) Center profile of gray value of each crack: the gray scale value of the crack in the reconstructed image increases as the crack opening increases.

are shown in Figure 3.4; for a fixed length and height of 100 μm , the cracks with openings values equal to 1 μm and 2 μm show a very low contrast in the reconstruction which can hardly be distinguished from the noise. This noise mostly comes from the discretization of the free-space propagation which can experience aliasing artifacts [SYP 03; KIR 20]. As the degree of opening increases, the center of the crack begins to appear dark, and its contrast increases. Meanwhile, the gray values of the streak artifacts hardly change.

Interestingly, it was found that *the gray value in the crack is also related to the crack length*. This is shown in Figure 3.5, where the crack openings is fixed to 1 μm (sub-pixel), the crack height is unchanged (100 μm), and the crack length is gradually changed (10 μm /20 μm /30 μm /40 μm /50 μm). When the crack's length is less than 30 μm , the crack appears dark with relatively strong contrast. With the increase of the crack's length, cracks show an increasingly low contrast until they become invisible. The streak artifacts barely change in the meantime. Different values of crack height (100 μm /200 μm /500 μm) were investigated; but in that case the gray value of the crack in the reconstructed image remain unchanged. In summary, the gray values of cracks in the reconstructed image are related to both its lengths and its openings, narrow and long cracks are less likely to be observed in the reconstructed images.

Various authors have used 3D tomographic images for characterising the opening (closure) of fatigue cracks under mechanical loading as this parameter has a strong influence

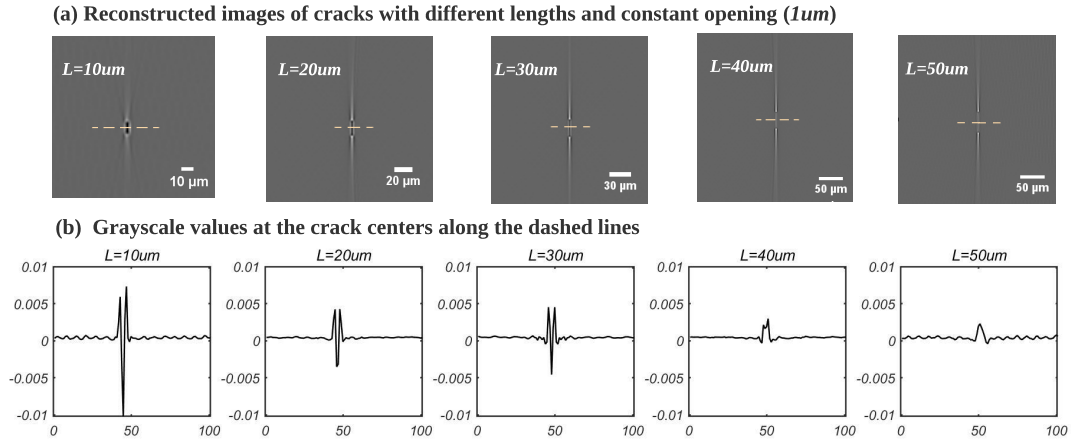


Figure 3.5: All slices are perpendicular to the axis of rotation: (a) The simulated image of cracks with different lengths, 10 to 50 μ m; (b) Center profile of gray value of each cracks: the gray scale value of the crack in the reconstructed image increases as the crack opening increases.

on the ability of the crack to propagate during cycling [RAV 21; CAR 18]. Crack with high levels of closure tend to propagate more slowly during mechanical cycling. Because the gray values in a reconstructed image of a crack are related to both the length and the opening, it is not easy to know the exact value of openings through the gray value. A series of simulation were carried out to quantitatively investigate the effect of the crack size (L and opening parameters) on its visibility. Cracks contrasts are defined (Eq 3.3) as the normalized difference between the intensity at crack center and the intensity of the matrix away from the crack (called I_{crack} and I_{matrix} respectively in Figure 3.6a).

$$\text{Contrast} = \frac{I_{matrix} - I_{crack_center}}{I_{matrix}} \quad (3.3)$$

The results are shown in Figure 3.6 (same scan condition as in Figure 3.3). A large positive contrast value indicates an intense dark in the center of the crack (Figure 3.6b), which corresponds to a large opening and/or relatively short crack length, in which case the crack is easily observed in the reconstructed image. Negative contrast indicates that cracks are not visible and their presence can only be inferred by the streak artifact at both ends (Figure 3.6b). A low contrast (positive) indicates a gray level close to that of the matrix at the center of the crack (larger opening and relatively longer length), whereby the center of the crack is not easily detectable, but it should be noted that a high intensity fringe will still be present at the edges of the crack in all cases. A more detailed analysis about the cracks contrast in the reconstructed phase contrast tomography images is given

in the discussion section.

3.3.3 Simulation results of step-like crack

Internal fatigue crack always present a stepped shape [SER 16] (see for example Figure 3.13i). To better understand these stepped cracks in SRCT image, the simulations of two different step-like shapes have been performed (imaging conditions as in Figure 3.3).

The first simulated results are shown as Figure 3.7. In this case, the cracks are assumed to be in step-like shape at 45 degrees to the rotation axis, the step length of the crack is $50\text{ }\mu\text{m}$ (relatively large compared to crack size), and the crack opening is set to $2\text{ }\mu\text{m}$ or $4\text{ }\mu\text{m}$ (not uniformly, as shown in Figure 3.7b). In the reconstructed horizontal slice (Figure 3.7c), crack segments with an opening of $2\text{ }\mu\text{m}$ appear with low contrast and are barely visible, while bright artifacts appear at each end of these segments. Crack segments with a $4\text{ }\mu\text{m}$ opening, appear dark, again with bright streak artifacts at both ends. Noteworthy, the artifacts have the similar step shape as the cracks, but they are offset from the location of the cracks, which may cause misleading analysis of the experimental crack images. In the vertical re-slice² at the blue dashed line (Figure 3.7d), a dark and a bright segment can be observed: the black part corresponds to the crack (marked as Crack 1), while the bright part corresponds the artifact generated by Crack 2. Equally, the artifacts generated by Crack 1 can be found in vertical slices (re-slice at the red dashed line, see Figure 3.7e). This indicates that the white artifact in the vertical slice comes from the artifact appearing at the end of the crack on the horizontal slice, which represents the presence of a crack in the neighboring slices.

Another simulation with smaller steps ($5\text{ }\mu\text{m}$) of the step-like crack has been carried out, and the results are shown in Figure 3.8. In the horizontal slice (A-A'), crack segments have a length of $50\text{ }\mu\text{m}$ and a opening of $2\text{ }\mu\text{m}$ and they appear with low contrast, while bright streak artifacts still appear at the end of the crack (Figure 3.8b). Interestingly, cracks appear dark when they change direction, which is consistent with the previous observations that the gray value within the cracks increases with decreasing length. In the vertical slice along the red dashed line (a-a') (Figure 3.8c), cracks and artifacts appear very close in location and have the same shape; the difference is that the contrast of the artifacts is much greater than that of the cracks. This indicates that in vertical slices all bright parts with a strong contrast are artifacts.

²orthogonal slice through the defined path within the volume

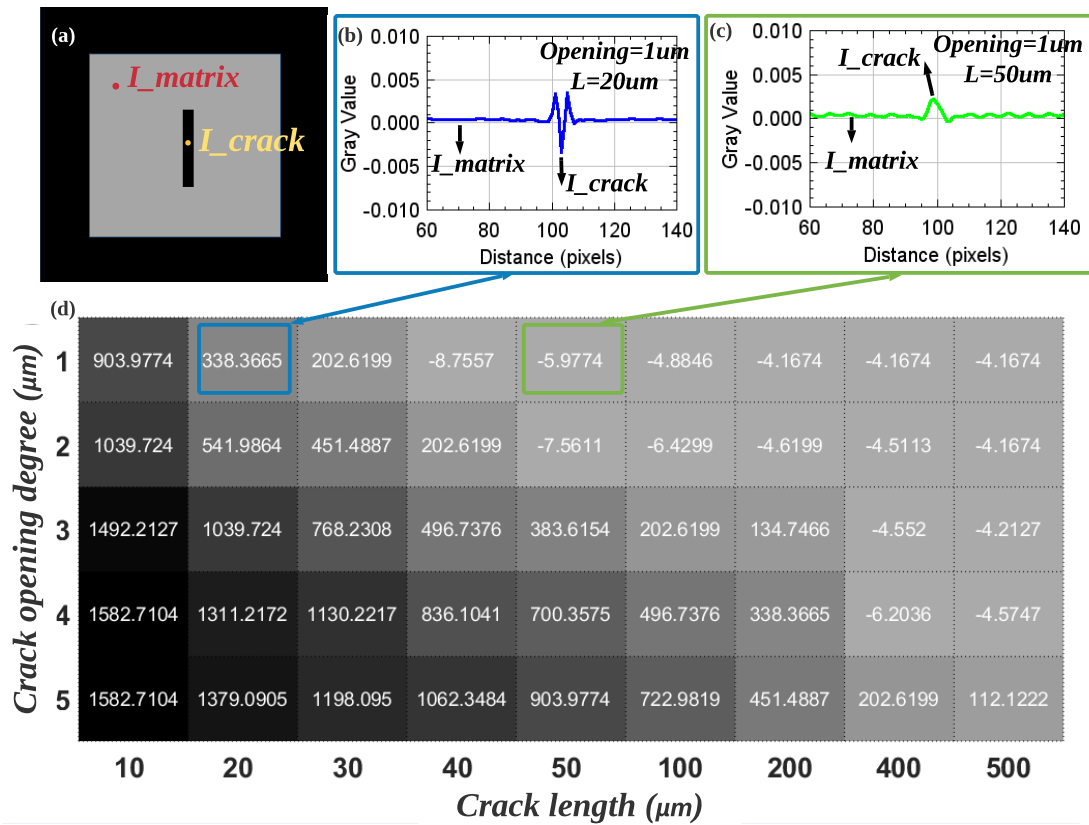


Figure 3.6: Normalized contrast of cracks with different length/opening in reconstructed images (see Figure 3.3 for a definition of the crack geometry). Cracks contrasts are normalized by using the difference between the gray value of the crack center (I_{crack}) and that of the gray value of the matrix (I_{matrix}), divided by the gray value of the matrix (Eq 3.3). (a) Horizontal cross-section of scanned specimen, black represents air, gray represents AlSi matrix; (b)-(c) Gray value distribution along a profile taken at the center of the crack (opening=1 μm length=20 μm /50 μm) in the reconstructed image; (d) Table of the normalized contrast, the darker the gray-level in the cell, the easier the cracks are to observe (see the text for details).

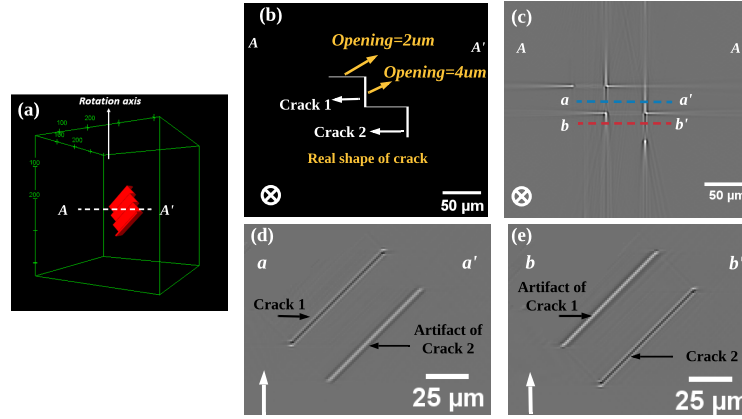


Figure 3.7: Simulation result (scan conditions as in Figure 3.3) of a step-like crack (large steps): (a) Phantom's 3D rendering; 2D section showing the crack in the phantom (b) and in the simulated image (c) on the plane perpendicular to rotation axis going through A-A' line. (c) Horizontal slice (A-A') of the step-like crack, the blue dashed line (a-a') and the red dashed line (b-b') mark the positions of the vertical slices shown in (d) and (e) respectively; (d)-(e) Vertical slices of the step-like crack along the dashed blue line and dashed red line shown in (b), $\uparrow$ and $\otimes$ indicate the rotation axis.

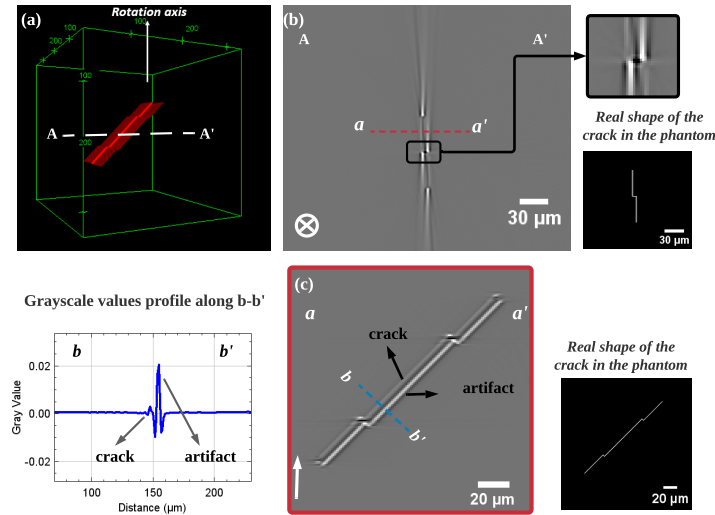


Figure 3.8: Simulation result of step-like crack (the step size is smaller than in the case of Figure 3.7), scan conditions is the same as in Figure 3.3: (a) Phantom's 3D rendering, the white dashed line AA' indicate the position of the horizontal slice; (b) Horizontal slice (A-A') of the step-like crack, the red dashed line (b-b') mark the positions of the vertical slices (c), and the shape corresponding to the cracks is shown next to this image; (c) Vertical slices of the step-like crack along dashed blue line and dashed red line shown in (b), the shape corresponding to the cracks is shown next to this image and the distribution of gray-scale values along the dashed line is displayed on the left side of the current image, $\uparrow$ and $\otimes$ indicate the rotation axis.

3.4 Discussion

3.4.1 Source of streak artifact

Streak artifacts were observed in several studies using SRCT but their exact origin was not clearly identified. Streak artifacts created by the presence of a metallic implant in phase contrast tomography images of the human brain are discussed for example by Croton *et al.* [CRO 18]. Those authors suggest that the main source of the artifacts may be the imperfect response of the detector. For our simulation results, however the streak artifact at the end of the crack is observed *under ideal detector conditions*, which indicates that its origin might be different from that suggested by Croton *et al.*. Similar streak artifacts were also observed by Madonna *et al.* in phase contrast tomography images of rock [MAD 13]. Those authors consider that the source of the artifacts is the exponential edge-gradient effects (EEGE) in FBP reconstruction process. Joseph *et al.* suggest that the streak artifact is created by non-linear error between the recorded projection and the linear spatial averaging of integral of attenuation coefficient [JOS 81]. Furthermore, the magnitude of this non-linear error is related to how fast the projection changes on the detector. Thus streak artifacts are more likely to appear at the edges of sharp, high-contrast heterogeneity.

To further investigate the source of the streak artifacts, we simulate phase-contrast tomography with the Weak absorption Transport of Intensity Equation model (WTIE)³ (Eq 3.4). This relatively simple analytical model has been used in the literature to simulate the propagation of x-rays in free space [BRO 02]. In contrast to the Fresnel Propagator's model (Eq 4.2), the WTIE model requires the following conditions to be respected: near-field diffraction and slow attenuation variation compared to the phase.

For a monochromatic beam of wavelength, in WTIE model the diffracted intensity writes:

$$I_D(\mathbf{x}) = I_0(\mathbf{x}) \exp\left(-\frac{\lambda D}{2\pi} \nabla^2 \varphi(\mathbf{x})\right) \quad (3.4)$$

I_D the intensity recorded by the detector after a propagation distance D , I_0 the corresponding intensity without any propagation, $\nabla^2 \varphi(\mathbf{x})$ the Laplacian of the phase at pixel $\mathbf{x}$.

The simulation results of the Fresnel propagator (implemented in GATE software) and that of the WTIE model with the same phantom and scan conditions are shown and compared in Figure 3.9. Streak artifacts are observed in the reconstructed images simulated using the Fresnel Propagator (Figure 3.9.b), while they are not present in the

³in the WTIE model, the nonlinear Fresnel propagation process is simplified by linearization of the transmittance function via Taylor expansion [WEB 16]

reconstructed images simulated using the WTIE model (Figure 3.9.e). The observation of their first projection (0° , x-ray parallel to the crack direction) reveals that the cracks generates more waves in the projection obtained with the Fresnel propagator simulation, which is consistent with 1D Fresnel diffraction patterns [TAV 10]; in contrast, in the projection obtained with the WTIE model simulation, because of the simplified linearized formulation, only one simple wave trough is observed. Besides, it is worth noting that the distribution of gray values of cracks in the reconstructed image is almost the same for both models (Figure 3.9c and f).

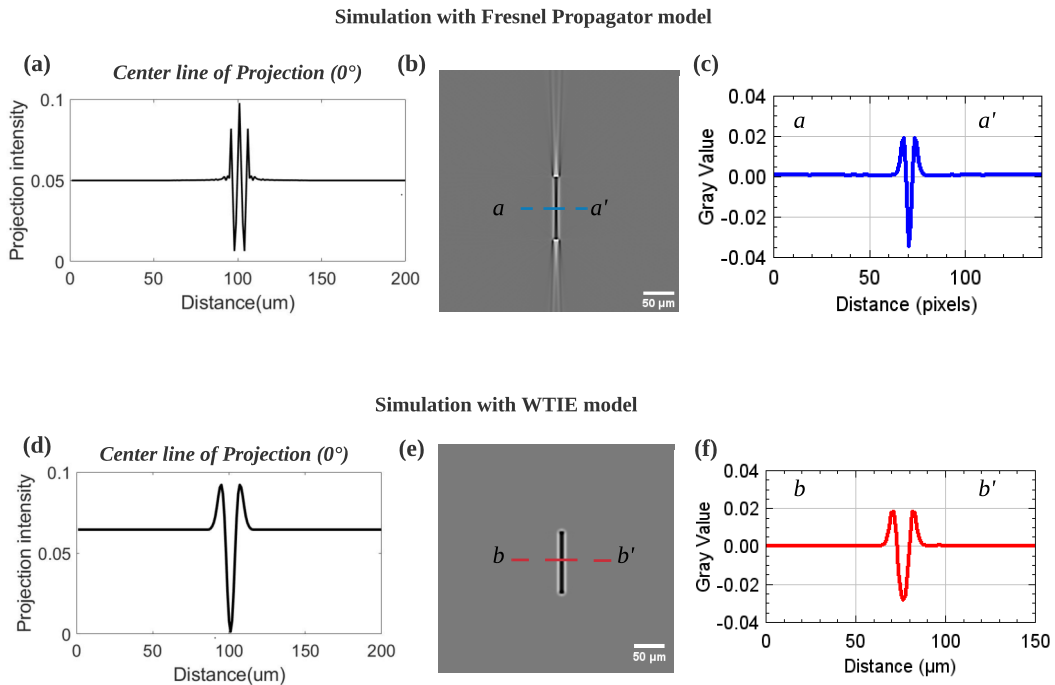


Figure 3.9: Comparison of simulation results of two models for phase contrast formation with the same phantom and scan conditions: (a) Profile of center line of the first projection (0° for which x-ray is incident along the length of the crack) simulated by the Fresnel Propagator method; (b) Reconstructed image of a flat crack simulated by the Fresnel propagator method (same phantom as in Figure 3.3); (c) Distribution of grayscale values along the dashed blue line (a-a') in (b); (d) Profile of center line of the first projection simulated by WTIE model; (e) Reconstructed image of a flat crack simulated by WTIE model (same phantom and scan conditions as (b)); (f) Distribution of grayscale values along the dashed red line (b-b') in (e).

A white (bright contrast) peak can be observed at crack center in the projection orthogonal to the crack length direction (called orthogonal projection) simulated by Fresnel propagator (Figure 3.9.a). The classical FBP was originally designed for the reconstruction of attenuation tomography. The values in the projections represents integration of

the attenuation coefficient, white peak means that the object has a high absorption of photons. This white peak becomes a high intensity white artifact (represent object with strong absorption rate) in reconstructed image. The white peak appears only in limited views around the orthogonal projection (within 10°). A black peak (dark contrast) appears at crack center in the orthogonal projection simulated by WTIE model along crack length (Figure 3.9.d) and no white artifacts appear in the reconstructed image. The projections of one SRCT experiment (obtained at ESRF and under same imaging conditions with Figure 3.1) have been analysed as shown in Figure 3.10. The flat cracks in the projection appear white in the orthogonal projection (Figure 3.10.b), which is consistent with the results of the Fresnel propagator model simulation. And they appear white only in a limited number of views. In projections 4.5° from the front and rear of the orthogonal projection (Figure 3.10.a and b), the flat cracks appear in low-contrast black. This may because a detector with perfect impulse response (same as what we used in Fresnel propagator model) has been used in the experiments (e.g. detector used in ESRF ID06 has a single pixel PSF [CEC 14]). The projection calculated by the WTIE model can be regarded as a result of imperfect response (only main wave was recorded). It should also be noted that flat crack with small openings (typically internal crack) is a special case for the propagation of fatigue cracks. For most of the Model cracks, they appear black in whole projections and have a slight white fringe at edges (as shown in Figure 3.10 and indicated by black arrow). These cracks appear clearly black in the reconstructed images, with white fringe observed only on the edges, and no streak artifacts are observed.

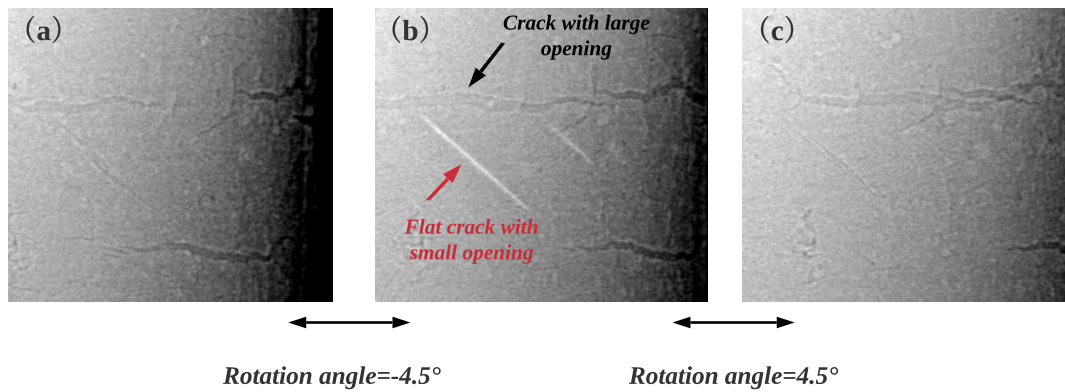


Figure 3.10: Corrected projections of one SRCT experiment (executed in ESRF and under same imaging conditions with Figure 3.1). Flat cracks with small opening appear white within limited view (about 10°) of projections; Rough cracks with larger opening appear black with slight white fringes on edges. (a-c) Projections at different angles: (a), (b) differ from (b) by 4.5° in different directions, respectively.

3.4.2 Gray value of cracks in reconstructed images

In the above results section, it was observed that *the gray value of the crack in the reconstructed image obtained by phase contrast tomography is related to the crack's opening and length*. In the above subsection, it has been found that, even if the presence of the white streaks at the end of the cracks is not reproduced by the WTIE model (Eq 3.4), this model is however able to reproduce fairly accurately gray-scale values at the center of the crack. The pixels gray values in the reconstructed SRCT image given by the WTIE model write:

$$g(x, y, z) = \mu(x, y, z) - D \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) \delta(x, y, z) \quad (3.5)$$

where the first term μ corresponds to the linear attenuation coefficient at voxel (x, y, z) , and the second term is related to the second derivative of the refractive index decrement $\delta(x, y, z)$.

Assuming that the crack is planar and lies in a yz plane, its profile of attenuation coefficient along the x -axis (X-ray direction) is shown in Figure 3.11a. Therefore, the above equation can be simplified to one dimension (equation 3.6),

$$g(x) = \mu(x) - D \left(\frac{\partial^2}{\partial x^2} \right) \delta(x) \quad (3.6)$$

and the refractive index decrement δ can be expressed using a unit step function $U(x)$ (equation 3.7):

$$\delta(x) = \delta_{Al} (1 - (U(x + 0.5a) - U(x - 0.5a))) \quad (3.7)$$

where a is the crack size in the x direction.

In order to avoid discontinuity problem in calculating the derivative, a sigmoid function is used instead of the unit step function (equation 3.8), where w in the sigmoid function represents the slope; the larger the value of w , the closer to the step function U . The simplified curve reproduces equation 3.7 when $w = 100$ (see green curve in Figure 3.11a) and therefore:

$$U(x) \approx \frac{1}{1 + e^{-wx}} \quad \text{when } w \text{ is large} \quad (3.8)$$

The second derivative is calculated using equation 3.8, and the expression of the gray value in the reconstructed image reads:

$$g(x) = \mu(x) - D \delta_{Al} \left(\frac{w^2 \left(e^{-w(x-\frac{a}{2})} - 1 \right) e^{-w(x-\frac{a}{2})}}{\left(1 + e^{-w(x-\frac{a}{2})} \right)^3} - \frac{w^2 \left(e^{-w(x+\frac{a}{2})} - 1 \right) e^{-w(x+\frac{a}{2})}}{\left(1 + e^{-w(x+\frac{a}{2})} \right)^3} \right) \quad (3.9)$$

Here δ_{Al} is the refractive index decrement of aluminum at 29 keV, $\mu(x)$ is the attenuation coefficient, its value in the air is taken equal to 0. Supposing $w = 100 \mu\text{m}^{-1}$, we then draw the profile of $g(x)$ when the crack size a takes different values.

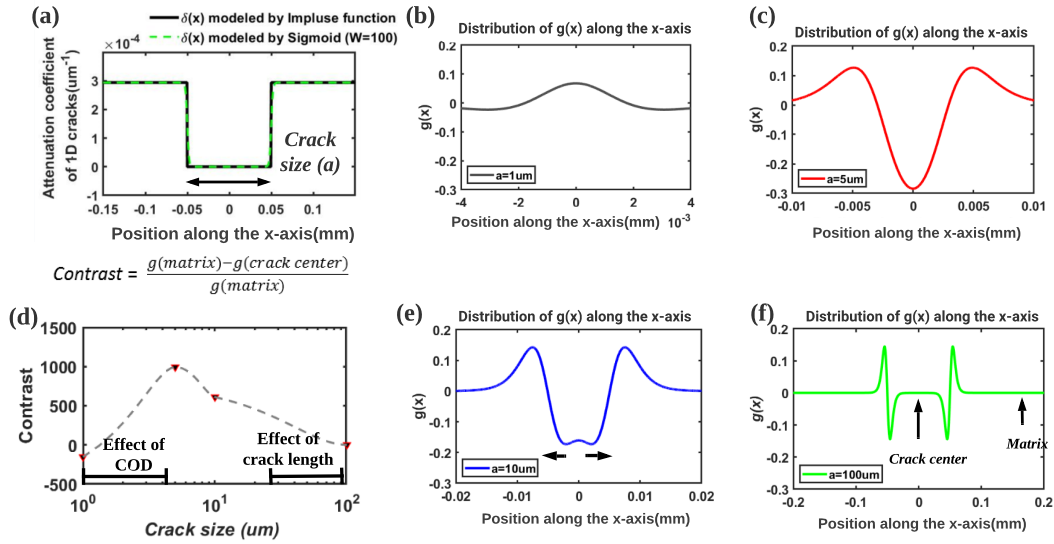


Figure 3.11: The simplified one-dimensional solution of WTIF model (Eq 3.6) is used to discuss the relationship between the crack gray-scale values and the crack size. (a) Attenuation coefficient of a one-dimensional crack along the X-axis: the black line is the ideal case (modeled by impulse function), the dashed green line is the simplified case (modeled by a Sigmoid function with $w=100$); (b) Distribution of $g(x)$ along the x-axis (crack size= $1 \mu\text{m}$); (c) Distribution of $g(x)$ along the x-axis (crack size= $5 \mu\text{m}$); (d) Normalized contrast (Eq 3.3) of crack center for different crack sizes; (e) Distribution of $g(x)$ along the x-axis (crack size= $10 \mu\text{m}$); (f) Distribution of $g(x)$ along the x-axis (crack size= $100 \mu\text{m}$).

The result is shown in Figure 3.11: when the crack size is small compared to the detector pixel size (e.g. $a = 1 \mu\text{m}$), the scanned object can be almost regarded as a homogeneous object with very small values of second derivative of the refractive index. Therefore, the gray value at the crack center in the reconstructed image is close to that of the matrix (Figure 3.11b). This explains why the cracks are invisible when the crack opening is sub-pixel. When the crack size increases to several times of the pixel of the detector (e.g. $a = 5 \mu\text{m}$), the second derivative of the step function at both edges (called sharp signals in the following) of the crack seems to have an effect on the center of the crack (Figure 3.11c), and the closer to the center, the more significant the contrast. At this stage, the larger the crack's opening, the larger the gray value in the reconstructed image (Figure 3.11b and c). As the crack size continues to increase (e.g. $a = 10 \mu\text{m}$), it can be

observed that the sharp signals generated by the crack edge begin to separate, whereby the contrast in the center of the crack begins to decrease (Figure 3.11e). When the crack size continues to increase to several hundred times of the detector pixel ⁴ (e.g. $a = 100 \mu\text{m}$), the sharp signals are far enough from the crack center to produce a contrast at crack center close to the attenuation coefficient of air (ie about 0). In this case, the normalized contrast (Eq 3.3) in Figure 3.6 will be 1. However, the sharp signals appear at the two edges of the crack can help to observe the crack edge (Figure 3.11f). This may explain that the gray value of cracks in the reconstructed image decreases with the increase of crack length. In a nutshell as shown in Figure 3.11d, the contrast at the crack center increases with increasing size and decreases when the size of the crack is in the range of several tens of pixels.

The signal generated by the edges of the crack on the detector during the acquisition of the projections can intuitively explain the surprising decrease of the crack gray-scale value with increasing crack length shown previously. In phase contrast tomography, interference patterns related to Fresnel diffraction appears on the detector (called sharp signal and marked using red dashed line in Figure 3.12a) at the edge of the object [BRO 02]. As explained above, in case of crack phase contrast imaging, the intensity on the detector varies with the distance between the sharp signals generated at the two edges of the crack. During the rotation, the distance between the sharp signals for the projection at angle θ is shown in Eq 3.10:

$$d = e \cos \theta + L \sin \theta \quad (3.10)$$

where e denotes the crack opening, L denotes the crack length and θ denotes the angle between x-ray and crack length direction (Figure 3.12). When two sharp signals are in close proximity to each other (at a distance d of about a few pixels), interference between the sharp signals occurs which render the crack in the projection with a high dark contrast. The smaller the crack length L , the greater will be the proportion of projections (ie a larger range of θ values) for which interference between the ends of the crack will occur. In contrast, when the sharp signals are far from each other, no interference between the sharp signals takes place and the detectors record only the attenuation of the matrix which causes a decrease in the gray value of the cracks in the reconstructed image. For the internal fatigue cracks (flat crack) we are discussing, the crack length is much larger than the crack opening: when the crack length increases, fewer projections will show interferences between the crack edges and the gray value of the crack in the reconstructed image will tend towards that of the matrix. As shown in figure 3.12b, the projections

⁴when the distance between the two crack surface becomes large, it should be called crack size instead of crack opening

recorded by the detector (simulated by the Fresnel propagator model) for different crack lengths ($L=10\text{ }\mu\text{m}/20\text{ }\mu\text{m}/100\text{ }\mu\text{m}$) demonstrate the decrease in the intensity of the crack center as the length increases.

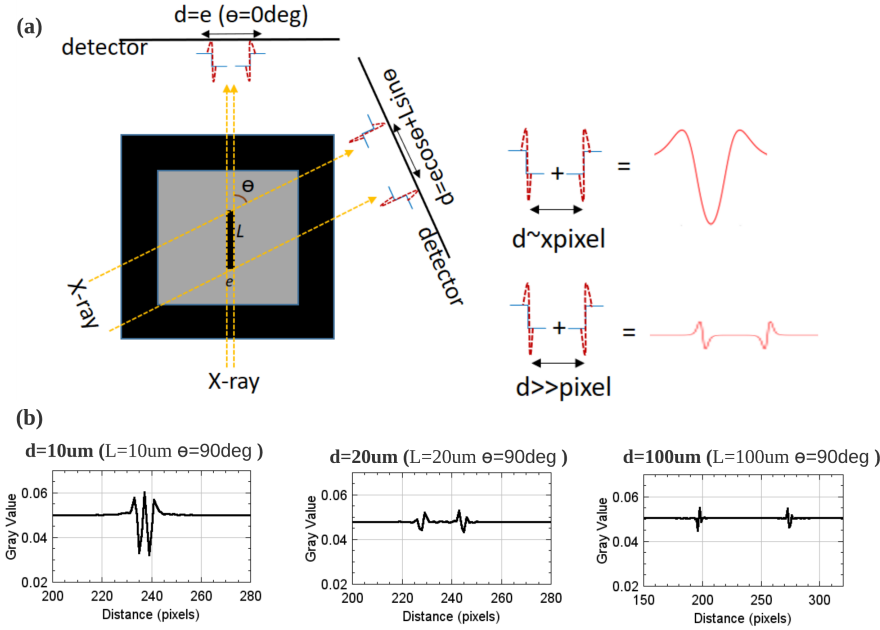


Figure 3.12: Qualitative explanation of the effect of crack length on the gray-scale values of the cracks in the reconstructed images. (a) Schematic diagram of a crack acquisition during scan. In phase contrast tomography, the edges of the crack (marked in blue) generate sharp signals on the detector (marked in red), and an interaction when they are close, causing a high intensity on the detector (at the center of the crack); (b) Simulated intensity signals generated at the detector for a given angle ($\theta=90^\circ$) and different lengths of cracks ($L=10\text{ }\mu\text{m}/20\text{ }\mu\text{m}/100\text{ }\mu\text{m}$, $e=3\text{ }\mu\text{m}$).

3.4.3 Re-analysis of internal cracks in experimental images

In the previous sections, flat cracks as well as stepped cracks have been simulated. By observing the specimen fracture surface using SEM (Figure 3.13h), it was found that the crack surface are extremely flat. They propagate from an internal defect until the specimen fracture. With the help of the simulation results, the experimental images (obtained at SOLEIL PSICHE beamline and SLS TOMCAT beamline, detailed scan conditions can be found in method section) can be better interpreted. First we analyze the cracks and artifacts in horizontal slices (i.e. perpendicular to the rotation axis): as shown as Figure 3.13a (same image as in the introduction section), based on the simulation results it is determined that the dark parts of the image are cracks, and the bright parts with strong contrast (located at the ends of the cracks) are artifacts. It can be seen that the gray-scale value of the crack segment is variable, for example the crack marked with a

red arrow has a lower contrast than the neighboring crack segments. This lower contrast could be interpreted as a locally smaller opening, but the simulation results show that the decrease in contrast may also equally be due to the local planar shape of the crack on a relatively long distance. This clearly shows the difficulty in trying to assess local crack closure levels from tomography specially on such flat cracks. When the size of the flat crack increase, the simulation result show that the crack almost disappears in the reconstructed image. This is observed in Figure 3.13b, where one can nevertheless detect the crack presence from the streak artifacts which appears at both ends (as in Figure 3.13c). The length of this crack segment can be obtained by measuring the distance of the artifacts on both sides (102 μm); based on Figure 3.6, a maximum opening of the crack of 3 μm can be inferred.

Equally, step-like cracks with different sizes can be found in the experimental images. As shown in Figure 3.13d and e (obtained at SLS), the above simulation results (Figure 3.7) help us to explain that the particularly bright parts in horizontal slices are all artifacts although they present a step shape similar to that of the crack and the actual cracks segments appear between every two streak artifacts. Similar step-like cracks were also found in the SEM observation of the fracture surfaces of the tested specimens (Figure 3.13i). Figure 3.13f is a horizontal slice obtained at another synchrotron x-ray source (SLS) for another AlSi7 specimen also containing an internal fatigue crack, the scanning conditions are almost similar to those of the simulation. Small-scale step-like cracks are present in this reconstructed horizontal slice: before obtaining the simulation results (Figure 3.8), all bright segments in this slice were considered as cracks; nevertheless, the invisible flat cracks (marked as red segments in Figure 3.13g) are now positioned in between the series of streak artifacts, with a certain offset; eventually the crack size is smaller than what was first assumed. In summary, with the help of the simulation results, the fatigue cracks can be more accurately identified in horizontal slices and *even invisible cracks (due to small openings/large length) can be identified*, which may make it possible to accurately determine the crack front.

By the above simulation results (Figure 3.8), it can be found that the streak artifact behave differently in horizontal slices and in vertical slices. Therefore, subsequently, vertical slices of the same experimental images obtained at SOLEIL were analyzed. On Figure 3.14a, the bright streak artifacts in the vertical slice do not appear at the ends of the flat crack segments but parallel to it. In ROI1 (Figure 3.14c), the flat crack appears black, and then bright streak artifacts appear on both its left and right sides. With the help of simulation results (Figure 3.7d and e), it is known that streak artifacts in a vertical slice indicate the presence of cracks with the identical geometry in the corresponding location of its adjacent vertical slice. Consistently, the source of the artifact on the left side

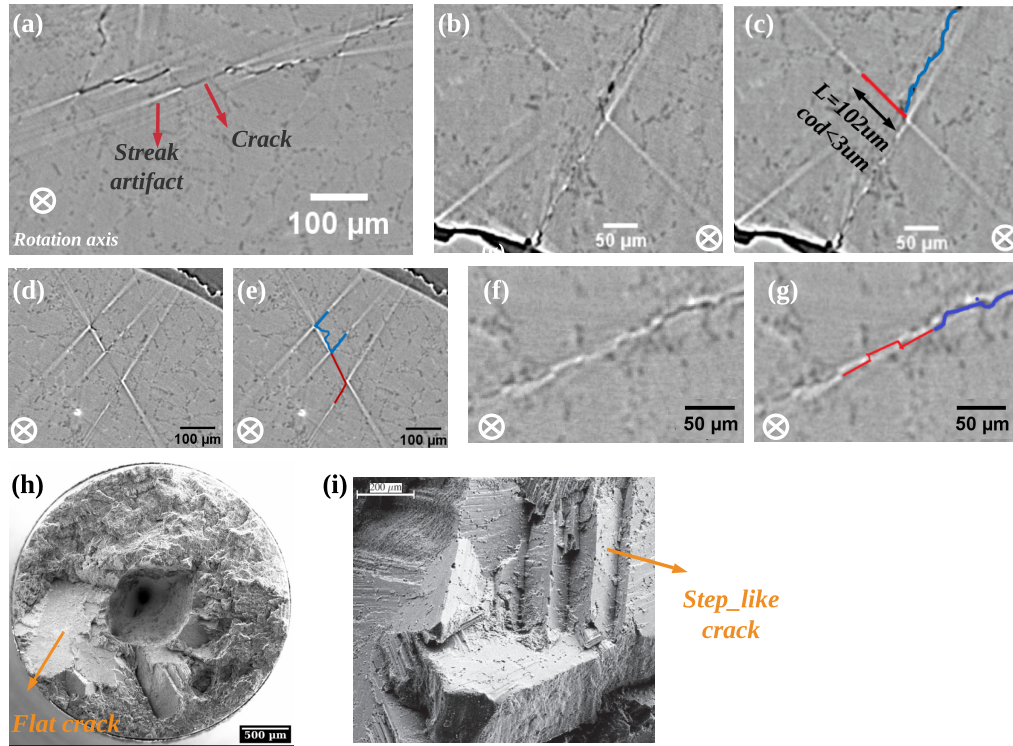


Figure 3.13: Analysis of cracks and artifacts in horizontal slices of experimental scans: the experimental SRCT images of a cracked AlSi7 specimen which have been obtained at SOLEIL PSICHE beamline (a-e) and SLS TOMCAT beamline (Fig.f-g) show the same streak artifacts as in the simulated image. The scans conditions of (a)-(e) are completely identical as Figure 3.3; the scans conditions of (f-g): energy 30 keV, distance between the sample and the detector 15 cm and voxel size 1.6 μm . All slices are horizontal slices (perpendicular to the rotation axis). (a) the same 2D experimental horizontal slice as in Figure 3.1b, flat crack with dark and white streak artifact at the ends of the crack can be observed. Tomography images of various parts of the crack are shown in b) d) and f. On these images a red line has been added to indicate (based on the simulation results) that a crack is present in the sample (c),e) and g) and blue lines have been added to the crack segments which can be unambiguously determined (black voxels). (h)-(i) SEM observation of the fracture surfaces of the fatigue tested specimen at two different magnifications.

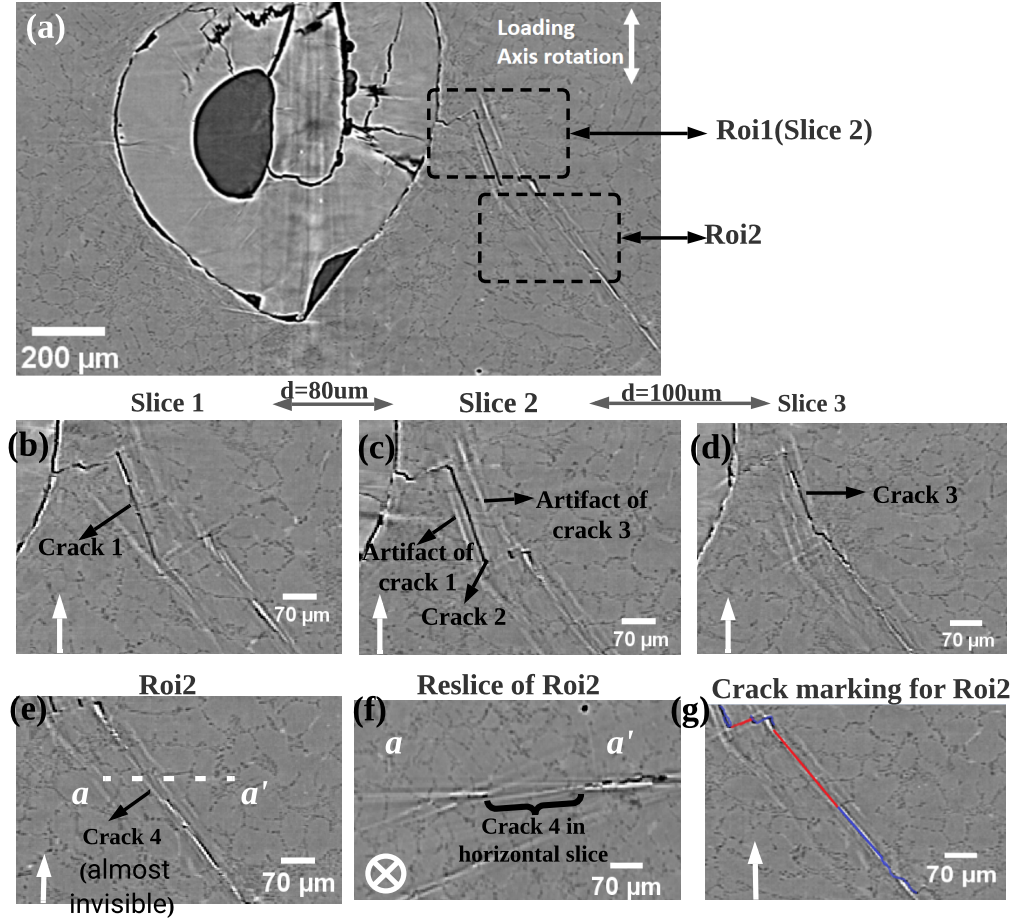


Figure 3.14: Analysis of cracks and artifacts in vertical slices of experimental scans: experimental SRCT images of cracked AISi7 specimens which have been obtained at SLS TOMCAT beamline. The scans conditions are completely identical as Figure 3.3. (a) A 2D experimental vertical slice, two ROIs were analyzed, in ROI1 the cracks appear dark and in ROI2 the cracks are invisible; (b)-(d) Enlarged view of ROI1: (c), the slice in front of (c) at a distance of 80 μm: (b) and behind it at a distance of 100 μm: (d); (e) Enlarged view of ROI2; (f) Horizontal re-slice of white dashed line (a-a') which shows that there is invisible crack (named crack4); (g) Crack marking for Roi2: markings in blue indicate a crack containing dark voxels and in red indicate an invisible crack whose presence needs to be confirmed by artifacts in horizontal slices.

of the dark crack is found in a slice 80 μm away from the current slice (called crack 1 in Figure 3.14b) and the source of the artifact on the right side is found in the vertical slice 100 μm from the current slice (called crack 3 in Figure 3.14d). Similar streak artifacts in vertical slices can be found in publications using phase contrast synchrotron tomography: in Al-Si cast alloys [SER 17] ; in additively manufactured Inconel [RAV 21]; in Ti alloys [BAB 14]. Our simulation results can help in distinguishing cracks from artifacts.

Another interesting case is shown in Figure 3.14e. On this image, it is not clear whether a crack is present or not (indicated as crack 4). Its presence is proved by analysing an horizontal slice taken passing through the a-a' line (Figure 3.14f) which shows a sub-voxel crack only signalled by the streak artifacts at its ends. The correct interpretation of the image is given by the red line in Figure 3.14g. *Therefore, for internal fatigue cracks (at a certain angle e.g. 45 degrees to the tensile direction), horizontal slices may be more convenient for complete determination of the crack tip.* To summarize, only pixels with a dark contrast can be unambiguously identified as belonging to a crack in the SRCT reconstruction image; pixels with a strong white contrast should be interpreted as streak artifacts; some cracks disappear in the image because of their small opening and large length. It can be concluded from this that extracting/segmenting the complete 3D crack image from the SRCT volumes requires some observer judgment and therefore should be quite difficult to automatize. Machine learning based methods may be an effective way to automate crack segmenting from such SRCT volumes [XIA 21a].

3.4.4 Re-segment internal cracks in experimental images

With the help of the above simulation results, cracks are more accurately identified from the streak artifacts and even invisible cracks (due to small openings/large length) can be recognized by the streak artifacts at their ends. In chapter 2, a deep learning based method (U-net) for crack images segmentation has been introduced. At that time, the only way to distinguish real cracks from artifacts relies on the user-judgement, based on what can be expected from the crack in terms of crack propagation direction (propagating from internal defects to free surface). Some white streak artifacts are identified as cracks in the above chapter, and in this section to obtain more exact binary images of the cracks, the U-net network has been retrained by using the features of the crack contrast obtained through simulations. The volume segmented here has been obtained by synchrotron tomography in a cast Al sample (same with chapter 2) at ID19 beamline of synchrotron ESRF, the energy of the beam is 29keV, the voxel size=1.3 μm and distance between specimen and detector=15cm. As shown in Figure 3.15a and b, cracks segments with dark contrast have been distinctly labeled (e.g. crack1); meanwhile the invisible cracks segments have been labeled by the streak artifacts at their ends (e.g. crack2). 120 slices (out of 1200 for the

whole image) were manually segmented by using the newly understood crack features like above. By retraining the U-net model using these 120 images (learning rate=0.0005, batch size=100, number of epochs=100), the segmentation results of the cracks can be found in Figure 3.15c and d: the dark contrast crack was undoubtedly detected, and the invisible crack (e.g. crack3) was also successfully detected.

Overall, the segmented cracks obtained using the new criteria are more realistic, but the continuity of the cracks is reduced by view of 3D rendering (some holes appearing on the crack faces: Figure 3.15e), which may be because the new criteria make it more difficult for U-net to identify the cracks, or because some cracks with low openness and without streak artifacts at both ends are not detected. Another point worth mentioning is that in the simulation results of this chapter, it can be found that the contrast of the crack in the reconstructed image is related to both opening and length of the crack; therefore, during labeling the crack, the crack opening cannot be taken into account (the openings of all labeled cracks are the same), and the opening of the crack in the segmented image does not represent the opening of the real crack.

3.5 Conclusions

The aim of the present chapter was to better identify and characterize internal fatigue cracks and artifacts in an Al alloy in SRCT images by simulating the phase contrast contribution in the reconstructed 3D images. In the studied material, fatigue cracks grow along crystallographic planes; their surfaces form very planar facets with dimensions of the order of several 100 micrometers⁵. Through the simulation results, streak artifacts with shapes similar to flat cracks that cause difficulties in accurate identification of cracks were investigated. The streak artifacts always appear on both ends of the flat crack segments even when the crack is invisible. Further, in changing the size of the cracks in the simulation it has been found that the length/opening of the crack has little effect on the streak artifact and determines the gray value of the crack in the reconstructed image. The contrast in the gray value of the crack increases with the crack opening, and decreases with the crack length. Therefore, *it is very difficult to quantitatively analyze the opening degree of flat cracks through gray values*. Simulations of step-like cracks were performed and were found in good agreement with the experimental images.

The WTIE model was used to simulate the same phantom flat crack; the streak artifacts were not found on horizontal slices while they were observed when the Fresnel Propagator model was used. The larger number of diffraction fringes observed when the latter model

⁵cracks initiated from the surface, which has been often reported in the literature have a less planar shape for which the present analysis is less relevant

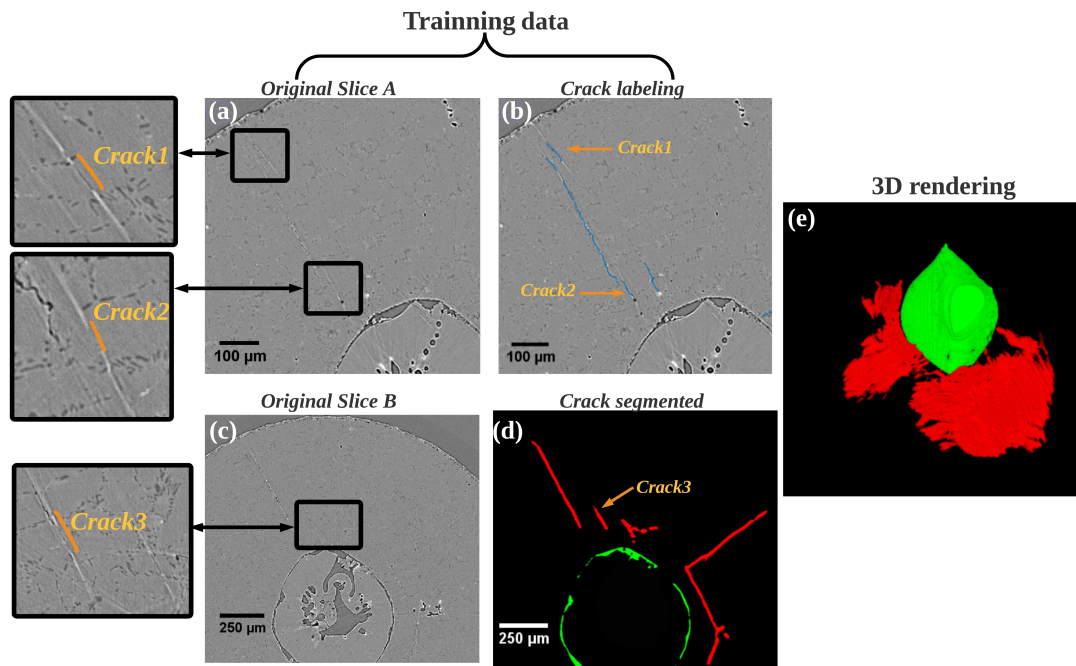


Figure 3.15: Segmentation results obtained with the retrained U-net model (newly understood crack features have been applied in crack labeling), volume obtained at ESRF beamline of synchrotron ID19: energy 29keV, distance between specimen and detector=15cm, voxel size=1.3 μm . (a) A 2D experimental horizontal slice (named slice A), two ROIs of cracks were zoomed, crack1 appears slightly dark with streak artifacts at end and crack2 is INVISIBLE with streak artifacts; (b) Crack labeling in Slice A; (c) Another 2D experimental horizontal slice (named slice B), crack3 with invisible contrast has been marked; (d) Segmentation results of Slice B, crack3 has been successfully detected; (e) 3D rendering of cracks.

is used might be the reason of this difference. The gray-scale values in the cracks in the reconstructed images are consistent for the two models mentioned above. Thus, the simplified WTIE model is used for the analytical analysis of the crack gray-scale values in the reconstructed image to explain the variation of crack gray-scale values with length and opening.

Eventually, the experimental images were reanalyzed by using the results obtained from the simulation. Cracks in horizontal slices appear as dark or low contrast to the point of invisibility, and the strong white contrast parts that appear at their ends are all artifacts. The presence of those artifacts can however help to locate invisible cracks segments. The experimental step-like cracks are in good agreement with the simulation results found in the experimental horizontal slices. In vertical experimental slices, streak artifacts no longer appear at the ends of the flat crack segments; instead, they appear in the same position in the adjacent slices, and have the same shape as the crack.

3.6 Appendix: Details about Fresnel Propagator in 'Gate'

In this chapter, the simulation of phase contrast tomography is done based on Fresnel Propagator, and here in this section, the principle of Fresnel Propagator and the implementation in Gate will be introduced.

The simplest phase contrast set-up is propagation-based phase contrast imaging (PB-PCI) also known as free space propagation phase contrast. It consists in letting a spatially coherent beam propagate after passing through a sample. If the detector is close to the sample “at contact plane”, an absorption image of the object is recorded. Phase contrast can be achieved by moving the detector downstream. As shown in Figure 3.16a, the intensity recorded by the detector changes markedly as the propagation distance changes, and in the near-field region they are closer to the intensity at the time of the attenuation-contrast (homogeneous Material has the identical attenuation coefficient), enhancing the contrast only at the edges of the object [BRO 02]. A 3D view of a typical near-field Fresnel diffraction can be found in Figure 3.16b, interference fringes are generated at the material-air interface. In single-distance propagation-based imaging (PBI, which we talked about in this work), the propagation distance will be limited in near-field region, a criterion is shown in Eq 3.11:

$$\lambda D |a|^2 \ll 1 \quad (3.11)$$

Where λ is the wavelength of X-ray, D is the distance between the sample and detector, and a is the size of scanned sample.

For the calculation of near-field Fresnel diffraction, first, the X-ray wave function after passing through the object should be calculated. The interaction between the object and the X-ray wave can be described as a transmittance function $T(\mathbf{x})$ (we consider a parallel beam configuration, propagating in the z -direction. The projection plane (x, y) can also be referred by $\mathbf{x} = (x, y)$, involving the projections of the attenuation $B(\mathbf{x})$ and the phase shift $\varphi(\mathbf{x})$:

$$T(\mathbf{x}) = \exp(-B(\mathbf{x}) + i\varphi(\mathbf{x})) \quad (3.12)$$

where $B(\mathbf{x})$ and $\varphi(\mathbf{x})$ are projections of the absorption index and refractive index decrement, respectively, perpendicular to the propagation direction of the beam:

$$\begin{aligned} B(\mathbf{x}) &= \frac{2\pi}{\lambda} \int \beta(\mathbf{x}, z) dz \\ \varphi(\mathbf{x}) &= -\frac{2\pi}{\lambda} \int \delta_n(\mathbf{x}, z) dz \end{aligned} \quad (3.13)$$

Thus, if $u_{inc}(\mathbf{x})$ denotes the incident wave front, and u_0 the wave front right after the sample (i.e. at contact plane), we obtain:

$$u_0(\mathbf{x}) = T(\mathbf{x})u_{inc}(\mathbf{x}) \quad (3.14)$$

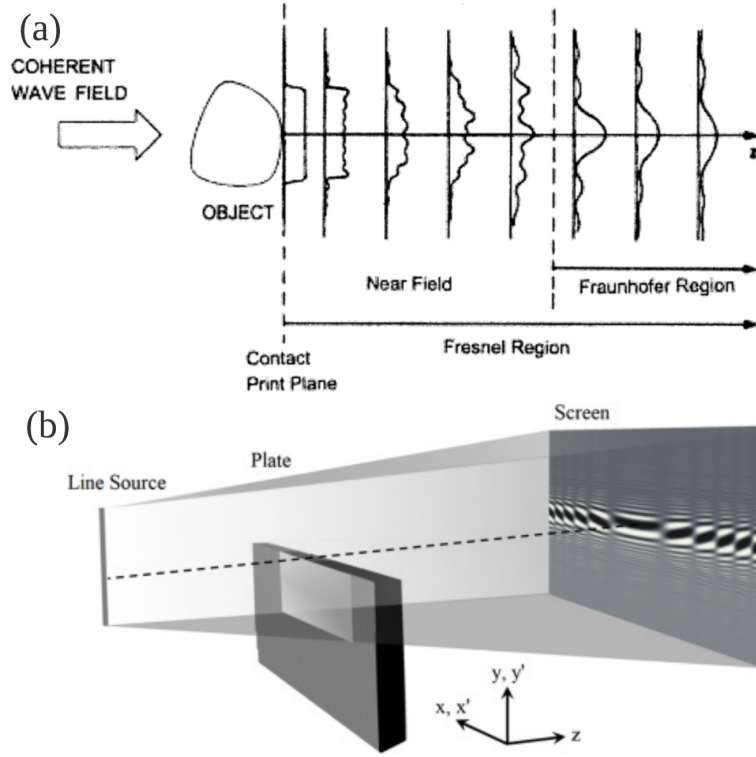


Figure 3.16: Principle of coherent imaging based on phase contrast. (a) X-ray diffraction pattern on detector with different propagation distance. The phase-contrast images are observed in the near field of the Fresnel diffraction region (image from [BRO 02]). (b) A 3D view of Fresnel diffraction pattern on detector (image from [GHO 20]).

The corresponding intensity recorded by the detector, without any propagation, is:

$$\begin{aligned}
 I_0(\mathbf{x}) &= |u_0(\mathbf{x})|^2 \\
 I_0(\mathbf{x}) &= |T(\mathbf{x})u_{inc}(\mathbf{x})|^2 \\
 I_0(\mathbf{x}) &= e^{-2 \cdot B(\mathbf{x})} |u_{inc}(\mathbf{x})|^2 = e^{-2B(\mathbf{x})} I_{inc}(\mathbf{x})
 \end{aligned} \tag{3.15}$$

which corresponds to the standard Beer-Lambert law used in attenuation CT. In Gate software, the 'Xraylib' library provided by ESRF gives the absorption index and refractive index of the defined material (defined by Atomic composition and density). Therefore, the pixelated intensities without any propagation can be calculated through a integral solver.

In the case of propagation, the diffraction pattern observed at a distance D from the object can be calculated by a convolution of the exit wave $u_0(\mathbf{x})$ and the Fresnel propagator $P_D(\mathbf{x})$ [GOO 05]. The Fresnel transform can be written as the convolution of the exit wave front $u_0(\mathbf{x})$ with the propagator $P_D(\mathbf{x})$. $u_D(\mathbf{x})$ denotes the wave front at a distance D

from the sample:

$$u_D(\mathbf{x}) = P_D(\mathbf{x}) * u_0(\mathbf{x})$$

$$\text{Where } P_D(\mathbf{x}) = \frac{1}{i\lambda D} \exp\left(i\frac{\pi}{\lambda D}|\mathbf{x}|^2\right) \quad (3.16)$$

In Gate implementations, the propagator is applied in the Fourier domain, since there it becomes a multiplication instead of a convolution in the spatial domain. The equivalent of Equation in the Fourier domain is:

$$\tilde{u}_D(f) = \tilde{P}_D(f)\tilde{u}_0(f)$$

$$\tilde{P}_D(\mathbf{f}) = \exp\left(-i\pi\lambda D|\mathbf{f}|^2\right) \quad (3.17)$$

After obtaining $\tilde{u}_D$ in frequency domain, the inverse Fourier transform will be applied to get u_D in real time:

$$u_D(\mathbf{x}) = \mathcal{F}^{-1}\left(\tilde{P}_D\mathcal{F}[u_0]\right)(\mathbf{x}) \quad (3.18)$$

In Gate, the Fourier transform and the inverse Fourier transform have been implemented by using the image convolution filters in the ITK library. The two ITK filters used are 'ComplexToComplexFFTImageFilter' and 'MultiplyImageFilter'.

Chapter 4

Investigation of wrinkled artifact in phase contrast CT image via simulations and experiments

The aim of this chapter is to investigate the origin of an artifact (wrinkled artifact) which is found on the images of crack edges and to find ways to avoid or reduce it. Phase contrast tomography simulations (using GATE software) as well as experiments were performed to understand this artifact. It was found that, the source of the artifacts is the two-dimensional interference of x-rays (2D Fresnel Patterns) on the detector; it can be diminished by reducing the phase contrast intensity (smaller objet-detector distance/higher x-ray energy), or by simply inclining the crack to avoid the 2D interference. This chapter has been written for publication in the journal of Materials Characterization as an article entitled "Investigation of wrinkled artifact in phase contrast synchrotron tomography image of metallic fatigue cracks via simulations and experiments" written by C. Xiao, J.Letang, W.Ludwig J.Buffiere.

4.1 Introduction

Synchrotron Radiation Computed Tomography (SRCT) delivers better visibility than laboratory CT for studies of damage in metals. This is in part due to the high lateral coherence of the synchrotron sources. Images reconstructed with the classical Filtered Back Projection (FBP) algorithm show interference fringes whenever a phase discontinuity appears in the studied sample allowing for example to detect cracks with small (especially sub-voxel) opening [CLO 97] [CLO 99]. In practice, however, the presence of irregular diffraction fringes (called wrinkle artifact in this work) can somewhat complicate

the quantitative analysis of the 3D images as we can see in Figure 4.1a extracted from Buffière *et al.* [BUF 06]. The scans were recorded at ESRF ID19 with a monochromatic beam (30keV), a voxel size of $0.7\text{ }\mu\text{m}$, detector-sample distances: 35 mm and 5mm. Ob-

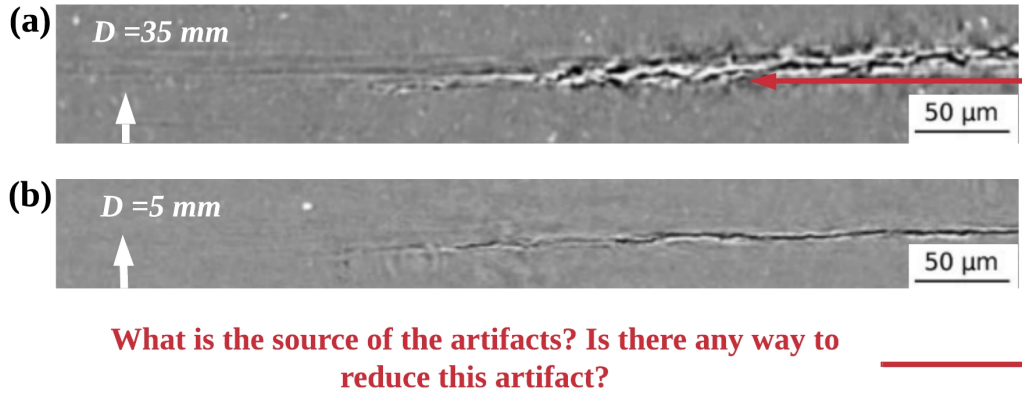


Figure 4.1: Wrinkle artifacts in a vertical reconstructed SRCT slice (parallel to the rotation axis) of cracked aluminum alloy sample at different distances – (a) 35 mm and (b) 5 mm – obtained at ESRF (ID19) with energy 30 keV and voxel $0.7\text{ }\mu\text{m}$. Images from Buffière *et al.* [BUF 06]. They showed that those artifacts can be reduced by making the propagation distance smaller. $\uparrow$ indicate the rotation axis.

viously, reducing the sample-to-object distance D can reduce this artifact. Nevertheless reducing D to very small distances (5 mm in that case) is generally not possible in the case of in-situ experiments because the scanned sample is typically held under load by a mechanical rig within a polymer tube [BUF 10], and this tube and/or the geometry of the machine generally imposes that D is of the order of 5 to 10 cm. This type of wrinkle artifact is often observed in 3D images recorded during in-situ experiments, *e.g.* in Ti alloys [BIR 09] [CHA 15] [YOS 16], in Al alloys [PRO 06] [WIL 13] making quantitative analysis of cracks (*i.e.* their opening) difficult. Beside playing on the x-ray propagation distance to reduce the wrinkle artifacts, making the wavelength of the photons smaller (*i.e.* increasing the energy of x-rays) should equally lead to a reduction of the wrinkle artifacts since the propagation distance and the wavelength are homologous in the relative absorption-contrast intensity [BRO 02], but this assertion should be verified in simulations and experiments.

In some experimental SRCT images of fatigue cracks, it can be found that the visibility of a crack is determined by its relative orientation with respect to the plane defined by the source trajectory. Wrinkle artefacts always appears stronger along cracks normal to the rotation axis (named here horizontal cracks), but much less in the vicinity of inclined

cracks. This is illustrated in Figure 4.2, which shows two images extracted from a single SRCT volume of a fatigue crack in an aluminum alloy sample. It can be seen on the figure that the edges of the inclined crack are perfectly visible (Figure 4.2a), while those of the horizontal ones appear blurred, due to the presence of wrinkle artifacts (Figure 4.2b). The

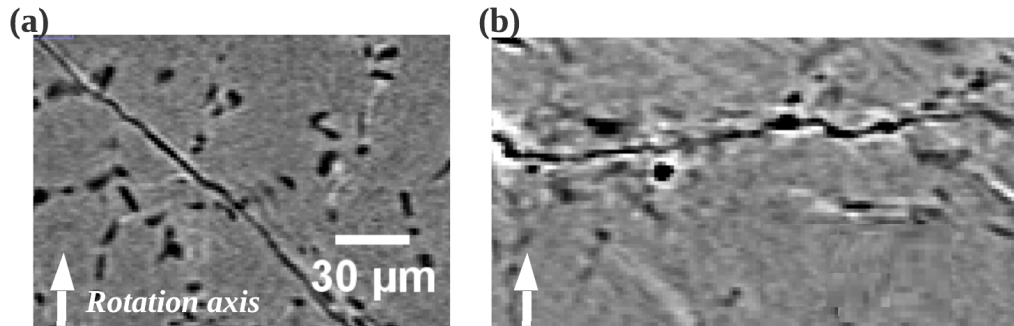


Figure 4.2: Two regions of interest in a reconstructed SRCT slice (containing the rotation axis) of a cracked aluminum alloy sample obtained at ESRF (ID11) with energy 29 keV, voxel $1.3\text{ }\mu\text{m}$, detector-object distance 140 mm. The sample is held under mechanical load during the scan to maintain the cracks. (a) ROI of an inclined crack without wrinkle artifact; (b) ROI of horizontal crack (has similar opening to the former one) with wrinkle artifact (same scale-bar for the two images).

vast majority of the papers showing 3D tomographic images of fatigue cracks recorded in-situ show cracks growing nanoscopically in Mode I [SCH 09]. As the loading axis is always set parallel to the rotation axis, the observed fatigue cracks therefore always lie perpendicular to the rotation axis. As a result, wrinkle artifacts are likely to appear along fatigue cracks and cause degradation of imaging quality.

This work provides a systematic sensitivity study of the formation of wrinkle artifacts with respect to tomographic acquisition settings that are likely to influence the crack measurement, namely the x-ray energy, the propagation distance and the crack inclination with respect to the plane defined by the source trajectory. The method proposed by Langer *et al.* [LAN 20a] using the Fresnel propagator for generating diffraction patterns is used to simulate phase contrast tomography with different acquisition settings and SRCT experiments are performed at ESRF ID11 to support the simulation results.

The contribution this work is to provide some useful insight into how SRCT acquisition parameters affect metallic fatigue crack characterization.

4.2 Method

4.2.1 Simulation of X-ray phase contrast

The wave function $u_D(x, y)$ impinging upon the detector can be modeled as the convolution of the wave function $u_0(x, y)$ after the sample with the Fresnel propagator $P_D(x, y)$ as follows

$$u_D(x, y) = u_0(x, y) * P_D(x, y) \quad (4.1)$$

where

$$P_D(x, y) = \frac{1}{i\lambda D} \exp\left(i \frac{\pi}{\lambda D} (x^2 + y^2)\right) \quad (4.2)$$

The implementation proposed by Langer *et al.* [LAN 20a] in the Monte Carlo platform GATE [SAR 14] was used to compute the wave propagation. Its principle is first to use a ray casting procedure from which we can obtain the x-ray wavefront $u_0(x, y)$ by integrating the complex refractive index in the voxelized sample. Then the Fresnel propagator (Eq 4.2) is used to simulate the propagation of the x-ray wave in the free space after passing the sample, and the Fresnel diffraction intensity patterns $|u_D(x, y)|^2$ are generated. In order to simplify the calculation, the convolution operation is expressed in the frequency domain after Fourier transform.

4.2.2 Simulated test cases

The sample geometry of all test cases is a cube $1 \times 1 \times 1 \text{ mm}^3$ composed of $1001 \times 1001 \times 1001$ voxels. We first consider a voxelized 3D block in AlSi7Mg0.6 alloy with different crack models (consisting of air), namely simple geometries such as flat, triangular and step-like shapes:

- Starting with a simple case, the crack is first considered as flat (crack length $100 \mu\text{m}$, crack width $100 \mu\text{m}$, crack opening $5 \mu\text{m}$). The same settings than the in-situ fatigue experiment (Figure 4.2) were set.
- Two triangular cracks (different lengths) with decreasing opening along the crack length have been used. The cracks lengths were set to $200 \mu\text{m}$ and $100 \mu\text{m}$ respectively, the width of these two crack is fixed to $100 \mu\text{m}$, the maximum value of cracks opening is set to $5 \mu\text{m}$ and the crack opening decreases uniformly along crack length until $1 \mu\text{m}$ (sub-voxel).
- For step-like shapes, the step length of the crack is first set to $100 \mu\text{m}$ and the crack opening $5 \mu\text{m}$. Then, the crack step length and the crack opening are reduced to $20 \mu\text{m}$ and $1 \mu\text{m}$ (sub-voxel) respectively. Finally, two different step lengths of the crack are set, $5 \mu\text{m}$ and $10 \mu\text{m}$, with a constant crack opening of $1 \mu\text{m}$ (sub-voxel).

Subsequently, in order to simulate a more realistic case, two cracks in the same kind of metallic alloy were segmented in experimental datasets:

- The first one from a SRCT experimental data (voxel size of $1.6\mu\text{m}$) and used as input phantom for simulations. Figure 4.3a shows such a crack. SRCT data have been obtained by Serrano-Munoz *et al.* [SER 17] at the Swiss Light Source (SLS). The scanned sample suffered a tensile fatigue test (more information about this

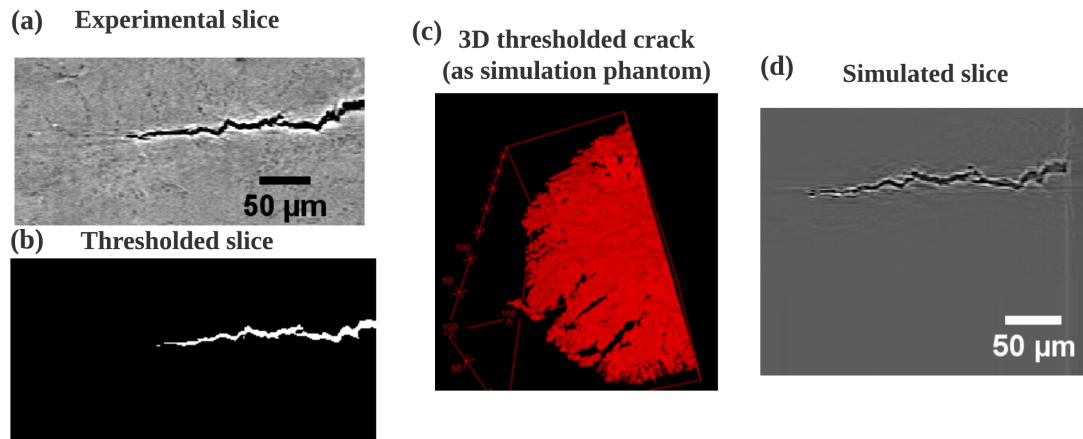


Figure 4.3: Simulation of 'real crack' by thresholding experimental SRCT volumes. The experimental SRCT has been obtained at the Swiss Light Source (SLS) with energy 25 keV, voxel size $1.6\mu\text{m}$, detector-sample distance 70mm. The scanned sample is made of an AISi7 alloy and suffered a tensile fatigue test. (a) Vertical slice in the experimental SRCT images, the black dots in the background correspond to the Si particles present in the alloy (size: $1\text{--}5\mu\text{m}$), they have been omitted in the simulation; (b) Thresholding of (a) by using OTSU algorithm in Fiji software; (c) 3D rendering of the thresholded crack; (d) Simulated slice under the same scan settings.

experimental can be found in [SER 17]). The crack has been extracted from the reconstructed images by using OTSU algorithm in Fiji software (Figure 4.3b), and will be referred as 'tensile fatigue crack'. Different settings have been used in the 'real' crack test case: incident energy either 25 or 42 keV, sample-to-detector distance either 70 or 150 mm, crack inclination either 0 or 45° .

- The second one comes from a rolling-contact fatigue test scanned with our laboratory tomograph (voxel size of $1.3\mu\text{m}$). This simulated crack will be referred as 'rolling-contact fatigue crack'. It has been segmented by Hessian matrix based method resulting that small openings cracks are more continuous and have a uniform opening [XIA 21a]. Therefore, the uniform opening of this crack can be varied by the dilation/erosion algorithm (as shown in Figures 4.9a-b) to investigate the effect of wrinkle artifacts on cracks with different openings.

Finally, the filtered back projection (FBP) algorithm which is the standard and popular reconstruction algorithm for parallel beam CT is used to reconstruct simulated images. These simulations were implemented on a workstation with 80 CPUs and 250 GB RAM. For a simulation with a $1001 \times 1001 \times 1001$ voxels phantom and 1200×1200 detector resolution, the calculation time is about 6 mins per projection (60 hours for 600 projections/ 180°).

4.2.3 Experimental data

Experimental phase contrast SRCT have been carried out on the ID11 beam line at the European Synchrotron Radiation Facility (ESRF), Grenoble, France. The voxel size was $1.22 \mu\text{m}$ with a 2048×2048 low noise CDD detector. The purpose of the experiments was to support the simulation results on the effect of the different scanning settings (x-ray energy, sample-to-detector distance and inclination angle) on wrinkle artifacts:

- Two different sample-to-detector distances have been tested, 70 mm and 140 mm. Typically, 70 mm is about the minimum distance considering the presence of fatigue devices in in-situ experiments.
- The photon energy was set to 29 keV (minimum energy achievable by ESRF ID11) and 42 keV in order to study the effect of photon wavelength.
- For the inclination angle, the rotating stage in ID11 allows the scanned to be tilted by up to 20° in both directions (see Figure 4.4). A sample base with a 20° inclination was machined in order to give the cracks a bigger range of angles at which they could be tilted. Inclination of 0 and 35° have been considered.

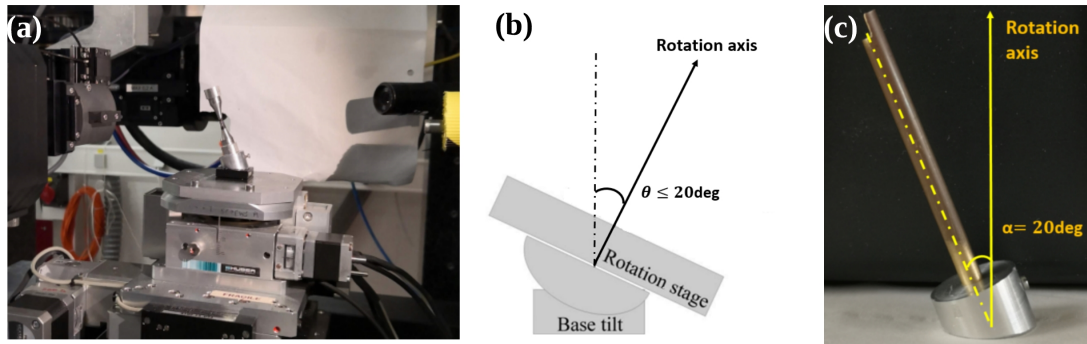


Figure 4.4: (a) Picture of the experimental synchrotron tomography setup as installed at ESRF ID11; (b) Schematic diagram of the rotating stage of ID11, maximum rotation angle of 20° ; (c) Inclined base (20°) for installation of specimens.

Two samples with different materials have been scanned in this work. The first one is provided by Nizery *et al.* [NIZ 15] which is made in Al-Cu-Li alloys and was submitted to a 36k fatigue cycles test with a maximum stress of 450 MPa (more information about this sample can be found in the reference, where the sample name is 7-6-1). The second one is provided by Junet *et al.* [JUN 21] which is made in TiAl6V4 and was submitted to 180k fatigue cycles test with a maximum stress of 800 MPa.

4.3 Results

4.3.1 Simulated test cases

4.3.1.1 Flat crack

When the perfectly flat crack is parallel to incident x-ray beam (called horizontal crack), as shown in Figures 4.5a-c, crack corners can be observed with a dark contrast but the center parts of cracks are invisible in central vertical slices (along dashed white line $A - A'$), some bright artifacts appear at the end of crack. In the horizontal slice (along dashed white line $a - a'$), crack surface presents a complex geometrical patterns (grid-like).

When the crack is rotated 45 degrees and tilted with respect to the incident x-ray beam (called inclined crack) under same scan settings, as shown in Figures 4.5e-f, the planar crack appears very differently in the reconstructed images. In central vertical slices (along dashed white line $B - B'$), the crack shows dark contrast and there are white streak artifacts appearing at the crack tips. This streak artifact has been observed experimentally at the end of very flat fatigue cracks in the experimental SRCT images [LUD 03]; and it has been discussed in another work [XIA 21b]. Compared to the previous case, the crack is well reconstructed as a dark flat plane in slices along length direction of the crack ($b - b'$).

The first results using very simple shapes show that the orientation of crack has a significant effect on the reconstructed images of crack, quantitative analysis of this horizontal planar crack in reconstructed images can become problematic due to the complex interference fringes which appear in the crack surface (grid-like pattern in Figure 4.5c). Same interference fringes are however not found in experimental images what we have, this may due to the fact that experimentally cracks are almost never perfectly flat¹. However, such grid-like fringes can be considered as a source of wrinkle artifacts, as discussed further in section 4.4.1.

¹This can happen if cracks grow along crystallographic planes for very long distances as in the case of internal cracks growing in vacuum as discussed in [MES 20b; XIA 21b]

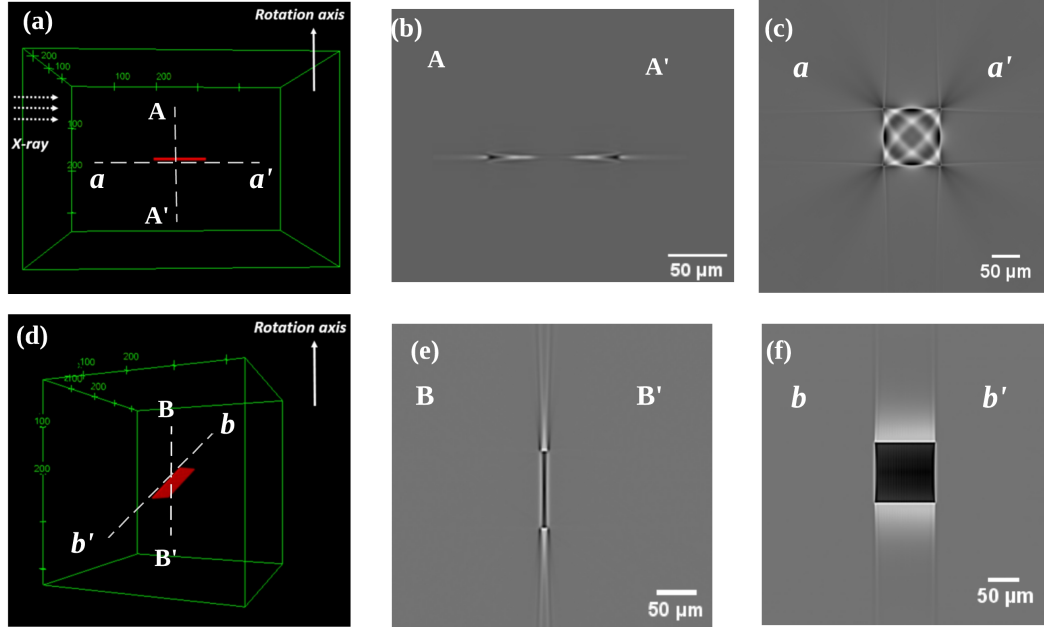


Figure 4.5: Simulated results of a flat crack (crack length 100 μm , crack width 100 μm , crack opening 5 μm) with two different orientations, the simulated images are obtained with the same scan settings as Figure 4.2. (a) 3D rendering of a flat crack parallel to incident x-ray beam (called horizontal crack); (b) Vertical reconstructed slice (along A-A') of horizontal crack; (c) Horizontal reconstructed slice (along a-a') of horizontal crack; (d) 3D rendering of a flat crack inclined at 45° with respect to the incident x-ray beam (called inclined crack); (e) Vertical reconstructed slice (along B-B') of inclined crack; (f) Reconstructed slice (along b-b') of inclined crack.

4.3.1.2 Triangular crack

The opening of a fatigue crack open in mode I and propagating from a free surface decreases when going from the crack mouth (surface) to its tips (bulk) [SCH 09] to reproduce such a shape, cracks with a triangular shape have been used in the phantom. In the simulation results with the same settings as Figure 4.5, it can be clearly found that when the two triangle cracks are parallel to the incident x-rays (Figure 4.6b), the cracks show dark contrast (black) at a larger opening (greater than 3 μm). When crack opening decreases, the cracks begin to appear bright (white) with high contrast and bright (white) artifacts appear at tips of cracks. Moreover, the wrinkle artifacts showing black and white mixed, studied in this work, appear on crack edges, which makes them jagged.

In contrast, for cracks inclined at 45° with respect to the beam direction, the cracks' edges appear much sharper and the wrinkle artifacts disappeared (Figure 4.6e); crack parts with openings larger than 2 μm appeared dark and the crack tips with sub-voxel

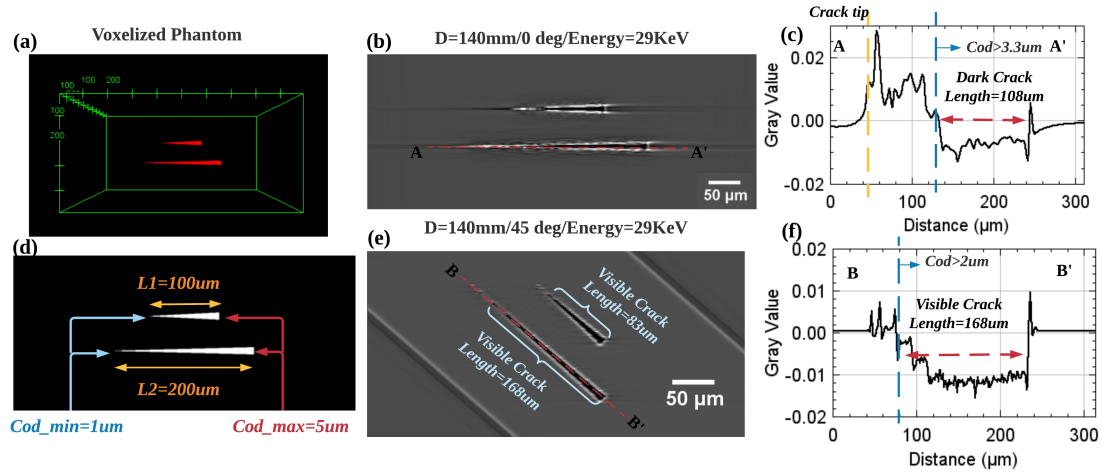


Figure 4.6: Simulated results of triangle crack (crack length 200 μm and 100 μm , maximum crack opening at end 5 μm , minimum crack opening at tip 1 μm , crack width 100 μm) in AlSi7 block with different orientations, the simulated images are obtained at same scan settings as Figure 4.2. (a) 3D rendering for horizontal triangle crack; (b) The vertical reconstructed slice of horizontal triangle crack; (c) Distribution of grayscale values along the direction of length (AA') for long cracks in (b); (d) 2D vertical slice of phantom, white pixels correspond to triangle cracks; (e) The vertical reconstructed slice of inclined (45°) triangle crack; (f) Distribution of grayscale values along the direction of length (BB') for long cracks in (e).

opening were almost invisible. In summary, in both horizontal and inclined cracks' images, the dark contrast (black) voxels can be surely considered as crack. While, in horizontal cracks' images, the bright (white) voxels cannot be distinguished as crack or artifact. For horizontal and inclined cracks, quantitative analysis of the crack length measurements from reconstructed images was performed. As shown in Figure 4.6c, the identifiable (black contrast) length is 108 μm for the horizontal crack with a length of 200 μm . As a contrast, the identifiable (black contrast) length of the inclined crack is 168 μm (Figure 4.6). Inclined cracks have a smaller error between the true length and the measured value.

4.3.1.3 Step-like crack

Fatigue cracks do not remain specially flat during propagation within the metal and can take on a step-like shape ² when it interacts with the grain boundary [RAV 21; SER 16]. The same simulation settings as Figure 4.6 have been used here, and the results are shown in Figure 4.7. Firstly, the interior of crack in the reconstructed image shows dark (black) contrast with clearly defined edges, and the wrinkle artifacts appear only at the turnings

²the magnitude and the frequency of those steps depend on the crack growth mechanisms, see for example [KRU 07]

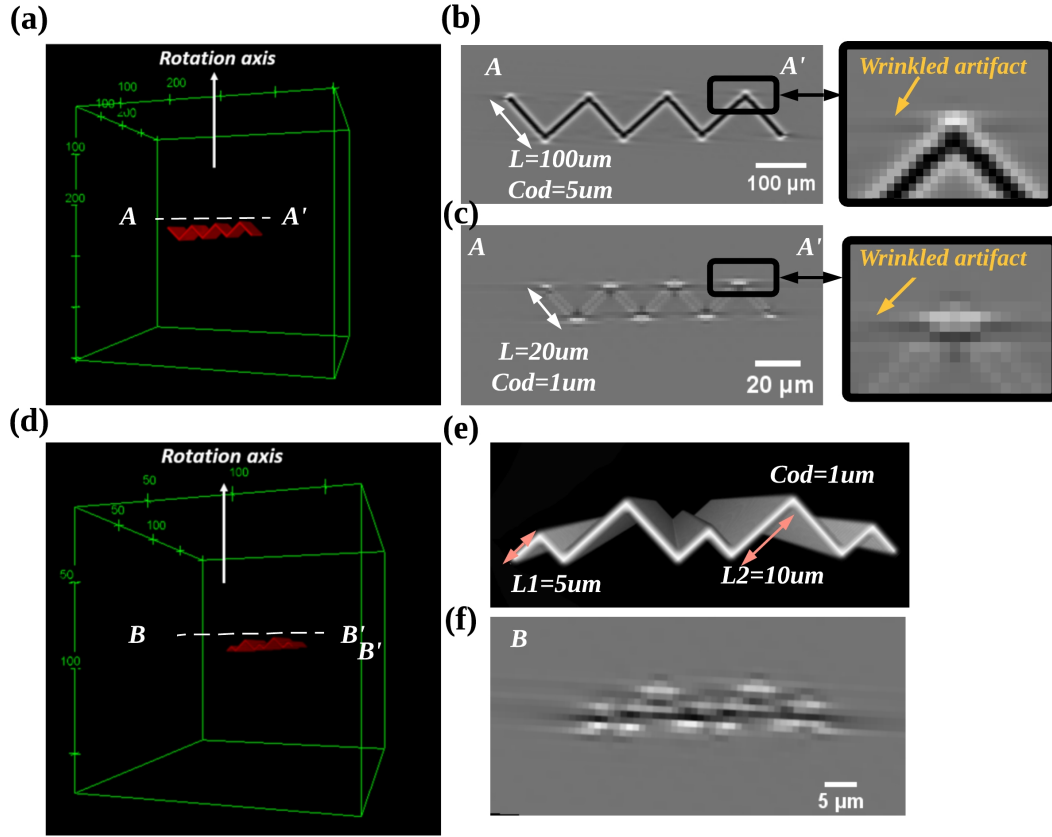


Figure 4.7: Simulated results obtained for step-like cracks in AISi7 phantom with different step sizes and geometries, the simulated images are obtained at same settings as Figure 4.6. (a) 3D rendering for a step-like crack with constant step length; (b) Vertical reconstructed slice (along A-A') of a wide step-like crack (step length 100 μm , crack opening 5 μm); (c) Vertical reconstructed slice (along A-A') of a thin step-like crack (step length 20 μm , crack opening 1 μm); (d) 3D rendering for a step-like crack with variable step lengths; (e) Definition of the step sizes; (f) Vertical reconstructed slice (along B-B') of the crack with variable step lengths.

of the crack (Figure 4.7b). When the crack step length and the crack opening are reduced, crack appears in extremely low contrast and barely visible in the reconstructed image; the wrinkle artifacts are more noticeable around this thin crack (Figure 4.7c) compared to the wide step-like crack (Figure 4.7b). When the crack opening remains at 1 μm (sub-voxel) as shown in Figures 4.7e-f, the crack appears as irregular bright (white) and dark (black) mixed patterns similar to wrinkle artifacts in experimental images, which makes the crack shapes difficult to be recognized. The above simulation results show that the wrinkle artifacts are more prominent to step-like cracks with smaller opening and more irregular geometry.

4.3.1.4 Tensile fatigue crack

The thresholded crack has been initially set approximately parallel to the incident x-ray as shown in Figure 4.8a and then different detector-sample distances and different x-ray energies were tested. For an x-ray energy of 25 keV, the wrinkle artifacts around

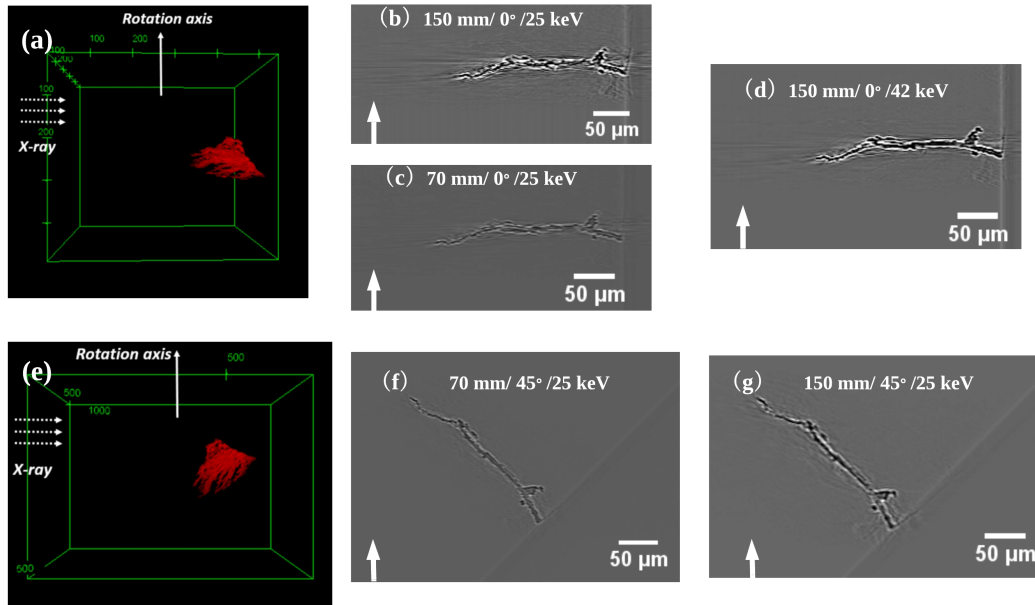


Figure 4.8: Simulation results of the tensile fatigue crack. Voxel size of detector is fixed at $1.6\mu\text{m}$. All the reconstructed slices are vertical slices (parallel to rotation axis). (a) 3D rendering of the crack with the mechanical loading direction (parallel to x-ray beam, called horizontal crack); (b) A slice of the horizontal crack at sample-to-detector distance 150 mm, energy 25 keV; (c) at sample-detector 70 mm, energy 25 keV; and (d) at sample-to-detector distance 70 mm, energy 42 keV. (e) 3D rendering of the crack tilted by 45° (called inclined crack); (f) the same slice of the inclined crack at sample-to-detector distance 70 mm, energy 25 keV; and (g) at sample-detector 150 mm, energy 25 keV. $\uparrow$ indicate the rotation axis.

the cracks are significantly reduced in the simulated image at 70 mm sample-to-detector distance (Figure 4.8c) compared to the image at 150 mm (Figure 4.8b). As the energy was increased (see Figure 4.8d), the wrinkle artifacts were reduced, allowing the crack edges with larger openings to be clearly identified. There are still some wrinkle artifacts at the tip of the crack though.

For the inclined crack (Figure 4.8g) at long propagation distance (150 mm) and low energy (25 keV), the wrinkle artifacts were reduced compared to Figure 4.8b, even compared with the image of horizontal crack simulated at higher energy (Figure 4.8d). The similar phenomenon (Figure 4.8f) can be found in the simulation of short sample-to-detector

distance (70 mm).

4.3.1.5 Rolling-contact fatigue crack

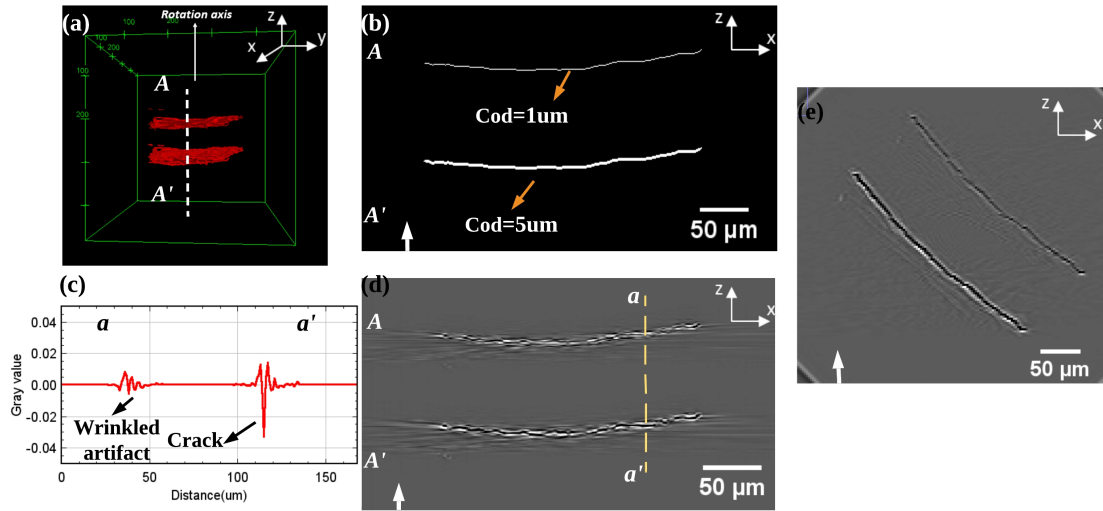


Figure 4.9: Simulation results of the rolling-contact fatigue crack. Scan settings: sample-detector 70 mm, energy 25 keV, voxel size $1.3\mu\text{m}$. All the reconstructed slices are vertical slices (containing the rotation axis). (a) 3D phantom containing two segmented crack with opening $1\mu\text{m}$ and $5\mu\text{m}$; (b) A vertical slice of phantom along A-A'; (c) The gray-scale distribution along the yellow dashed line (a-a') in (d); (d) Reconstructed image of slice A-A' shown in (b); (e) same as (d) but with a 45° tilt of the crack in the phantom. $\uparrow$ indicate the rotation axis.

For the rolling contact fatigue crack, the thresholded cracks are placed horizontally and simulated under the following settings: sample-detector 70mm, energy 25 keV, voxel size $1.3\mu\text{m}$. In the reconstruction images (Figure 4.9d), the wrinkle artifact appears on both cracks. For the crack with larger opening ($5\mu\text{m}$), the central part of the crack still appears dark (black) and can be surely identified; for the crack with sub-pixel opening ($1\mu\text{m}$), it cannot be identified from the artifacts (see Figure 4.9c: the distribution of gray-scale level along dashed yellow line (a-a')). In accordance with section 4.3.1.2, wrinkle artifacts appear at the interface of large opening cracks resulting in jagged crack edges, and make cracks with small opening difficult to be characterized. When the two cracks are tilted by 45 degrees and simulated with the same settings, Figure 4.9e shows that wrinkle artifacts are significantly reduced and the imaging quality is improved for both cracks.

4.3.2 First conclusions from simulations

We have seen that crack measurement is likely to be affected by wrinkle artefacts (too strong diffraction patterns), which are mainly driven by three parameters: the propagation distance, the x-ray energy and the crack inclination with respect to the x-ray beam. Several indications can be drawn from all these simulations:

- In order to reduce diffraction patterns, increasing the energy is one option [AMI 07] but for light materials (*e.g.* Al alloys), excessive energy will also make the specimen more transparent to x-rays resulting in unfavorable imaging quality.
- Another way to avoid diffraction patterns being too strong is to limit the propagation distance. However, regarding in-situ fatigue tests, the diameter of the fatigue machine is usually of the order of the tens of centimeters, therefore making it difficult to reduce the propagation distance [BUF 06].
- Under these constraints, it seems rather interesting to avoid situations where the crack surface is parallel to x-ray beam. Thus, the inclination of the crack avoids the appearance of such wrinkle artefacts degrading its characterization but still makes it possible to take advantage of the diffraction patterns for better visualization as is desired in particular for sub-voxel cracks.

4.3.3 Experimental verification

4.3.3.1 Al-Cu-Li alloy

In the above simulation results, it can be found that reducing the sample-to-detector distance, increasing the x-ray energy, and tilting the sample/cracks are effective ways to reduce wrinkle artifacts. To support these assertions, experimental phase contrast tomography scans were performed at the European Synchrotron Radiation Facility (ESRF) at beamline ID11.

First, a fatigue specimen (in Al-Cu-Li alloys) containing a mode I crack has been scanned without any applied load and with the specimen axis (along which the fatigue stress is applied), placed at 70 mm from the detector and the x-ray energy is set to 42 keV. As shown in Figure 4.10c, no obvious wrinkle artifacts were observed around the crack. When the sample-to-detector distance is increased to 140 mm with the same x-ray energy (see Figure 4.10b), some wrinkle artifacts appear at the crack mouth (which has a larger opening) and make crack edges appear jagged. In addition, the crack tips are slightly blurred by wrinkle artifacts, therefore a portion of the crack tip can not be clearly determined. Therefore, the effect of increasing the sample-to-detector distance on the presence of wrinkle artifacts has been confirmed in this experiment: longer propagation

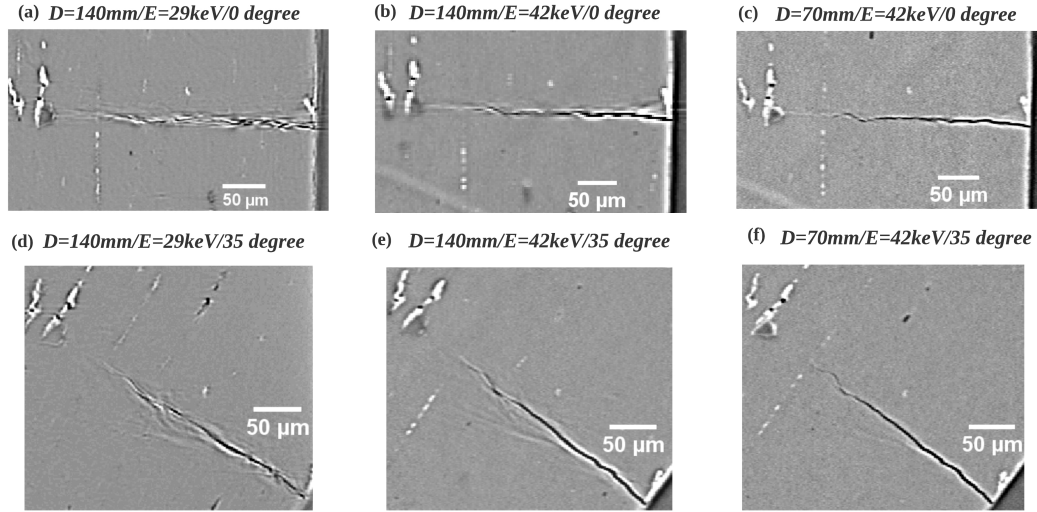


Figure 4.10: Experimental SRCT image of a fatigue specimen made of an Al alloy obtained at ESRF with different inclinations, sample-to-detector distances and x-ray energies. The voxel size is $1.22\text{ }\mu\text{m}$. All slices correspond to the same location within the specimen and are vertical (contain the rotation axis). (a) No inclination (0°), 140mm and 29 keV; (b) No inclination (0°), 140 mm and 42 keV; (c) No inclination (0°), 70mm and 42 keV; (d) With inclination (35°), 140 mm and 29 keV; (e) With inclination (35°), 140mm, and 42 keV; (f) With inclination (35°), 70mm and 42 keV.

distance produces more wrinkle artifacts. This observation depends however on the energy used: when the x-ray energy is decreased to 29 keV (Figure 4.10a), the crack becomes discontinuous in the reconstructed image due to the formation of strong wrinkle artifacts. In this case, the cracks can hardly be identified or measured from this SRCT image. Comparing Figures 4.10a and b, it could be confirmed that higher x-ray energy can reduce artifacts which is also consistent with the simulation results (Figure 4.8b and f).

For each distance and energy settings illustrated in Figures 4.10a-b-c, a new scan has been recorded with the specimen axis inclined at 35° . Comparing Figure 4.10d and Figure 4.10a, wrinkle artifacts are significantly reduced in the reconstructed images of the tilted specimen, from which the crack could be more easily characterized. In Figure 4.10e, wrinkle artifacts are reduced compared to Figure 4.10b, especially at the crack end. In Figure 4.10f, the wrinkle artifacts have completely disappeared and the crack boundary is smooth, moreover the crack tip is slightly more clearly defined when comparing to Figure 4.10c. Comparisons of these three pairs of experimental images are consistent with the simulation results (Figure 4.8 and 4.9) that tilting the sample to avoid cracks parallel to the x-ray is an effective and simple way to reduce wrinkle artifacts.

4.3.3.2 Ti-Al-V alloy

As shown in Figure 4.11, for the crack parallel to the x-ray beam (0° case) the intensity of the wrinkle artifacts becomes stronger with increasing distance, but the crack can still be well identified and only the tips of the crack (especially on the right side) are discontinuous (Figure 4.11b). Comparing Figure 4.11b and d, the wrinkle artifact intensity has been reduced by inclining the specimen. Wrinkle artifacts seem to have lower intensity and less effect on crack visibility at the same scanning settings compared to the Al specimens shown in Figure 4.10. Further explanations about this results can be found in Section 4.4.1.

4.4 Discussion

4.4.1 Source of wrinkle artifacts

In the flat crack simulations, 'peculiar' (grid-like) interference patterns were observed on the surface of the horizontal crack (Figure 4.5). To investigate the origin of those patterns, the projections recorded by the simulated detector with different angles have been checked. The results of this analysis is shown in Figure 4.12. The classical Fresnel diffraction fringes (one central black fringe bordered by white fringes called 1D Fresnel diffraction patterns in [TAV 10]) are observed at the crack surface in the projection when the crack plane is orthogonal to the x-ray (Figure 4.12a). This 1D Fresnel diffraction patterns will become

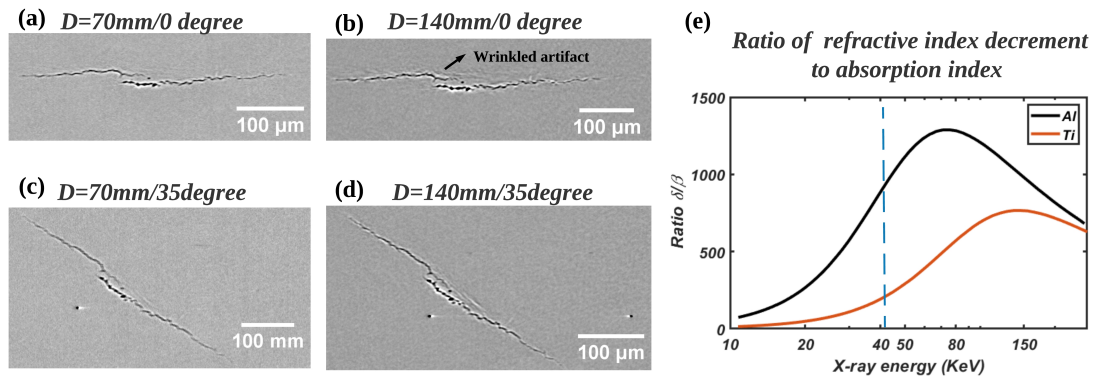


Figure 4.11: Experimental SRCT images of a fatigue tested Ti-Al-V alloy specimen obtained at ESRF with different sample-detector distances and orientations. The energy is fixed to 42 keV and voxel size is fixed at 1.22 μm. The images (a-d) are vertical experimental slices at same location in the specimen. (a) No inclination (0°) and 70 mm; (b) No inclination (0°) and 140 mm; (c) With inclination (35°) and 70 mm; (d) With inclination (35°) and 140 mm; (e) The ratio of refractive index decrement (δ) to absorption index (β) of Ti and Al.

bright (white) fringes on the crack edges after reconstruction.

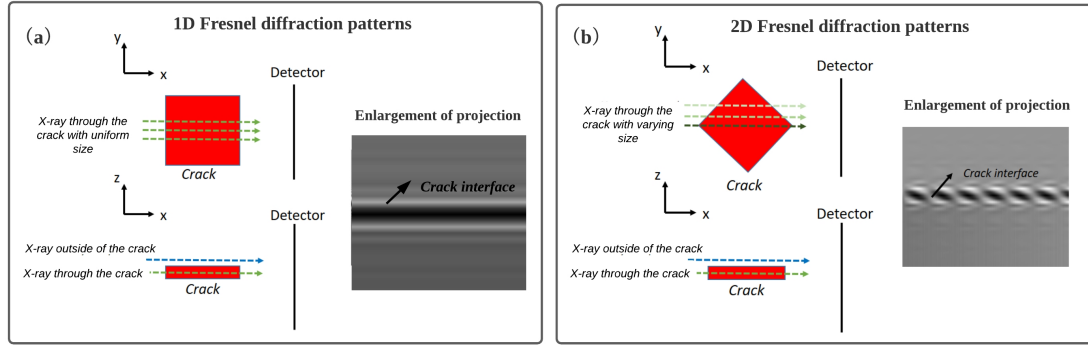


Figure 4.12: Explanation of the formation of the grid-like artifacts in a planar crack parallel to the x-ray beam (Figure 4.5c). (a) When the square crack is facing the x-ray beam, the x-ray attenuation length is constant along the crack; therefore, the interference occurs only in the direction normal to the crack plane, which generates a 1-dimensional Fresnel pattern. (b) During the acquisition, the relative orientation of the crack will change, and the x-ray attenuation length becomes variable along the detector line where the crack is projected. Therefore, the interference pattern is now 2-dimensional: (i) between the nearby x-rays that do not pass through the crack (blue) and the x-rays that pass through the crack; (ii) between the x-rays that pass through different distances (green with different brightness).

Interestingly during the acquisition scan, a black and white braid-like interference pattern is produced on the detector when the crack front makes a 45° angle with respect to x-ray beam (Figure 4.12b), which might cause the grid-like patterns in reconstructed images. In fact, this braid-like interference fringe (called 2D Fresnel diffraction patterns) has been discussed in [TAV 10; SAL 17]. It was observed at the interface of a wedge shape sample illustrated by a coherent laser light [TAV 10]. We believe that the wrinkle artifact observed on the simulated images is a result of this 2D Fresnel diffraction patterns. Obviously, cracks are never perfectly aligned perpendicular to the rotation axis so the reconstructed image will not show extended complex patterns such as the one shown on Figure 4.5c. However it is likely that those 2D Fresnel diffraction patterns can occur at a local scale on planar parts of the cracks and generate some wrinkle artifacts.

For tilted cracks, the wrinkle artifact intensity decreases because the x-ray penetration distance does not vary much along detector lines (parallel to the plane of the source trajectory) onto which the crack is projected during the whole scan.

Wrinkle artifacts are related to the diffraction fringes, which in turn depend on the magnitude of phase shift induced by the crack [CLO 99; BRO 02]. The model proposed by Paganin *et al.* [PAG 02] can be used to understand the difference in phase artifacts between Ti and Al alloys. They showed that the ratio of refractive index decrement (δ)

to absorption index (β) directly affects the strength of the phase shift. For a 42 keV x-ray energy, Figure 4.11e shows that this δ/β ratio of Al is much larger for Al than Ti. This can explain why fewer wrinkle artifacts are visible in SRCT images of Ti specimen for comparable acquisition settings (orientation, sample-to-detector distance and x-ray energy).

4.4.2 Quantitative analysis of cracks

As we have mentioned in the results section, the presence of wrinkle artifacts poses difficulties for the quantitative analysis of cracks. Measuring crack length/opening from tomography images is the main purpose of 3D characterization of cracks, and segmenting cracks from the matrix by a gray-scale level thresholding is a common method for crack quantitative analysis [BUF 17]. One key parameter which is often discussed in the literature about 3D fatigue cracks is the evaluation of crack closure/opening from the reconstructed SRCT images [KHO 06; CAR 18; RAV 21].

To better appreciate the effect of wrinkle artifacts on the quantitative analysis of cracks, a classical segmentation method, namely Isodata (as default method in *Fiji* software), was used to segment the cracks imaged in the Al alloy at different detector-sample distances, x-ray energies and orientations (Figure 4.10). Crack opening maps were obtained from the binary images by integrating in the direction perpendicular to the crack of the binary image. Based on the above simulation results (Figure 4.6), it can be found that only pixels with black contrast can confidently be identified as belonging to a crack in the reconstructed phase contrast tomography images. Therefore, in this work, the segmented crack is only defined by the voxels with black contrast.

Comparing Figure 4.13a and d, the projected crack tip is basically identical in the tilted and horizontal cases (dashed white line indicates the projected crack tip of (d) which is the best imaging case). However, a large discrepancy appears in the above estimated crack opening: for the inclined case (Figure 4.13d) it is about 15-20 μm *ie* twice the value obtained for the horizontal cracks (about 7 μm). An estimate of the expected opening of such a Mode I crack can be computed using the following equation:

$$\begin{aligned} COD &= \frac{8K_I}{E} \sqrt{\frac{r}{2\pi}} && (\text{plane stress}) \\ COD &= \frac{8K_I(1-\nu^2)}{E} \sqrt{\frac{r}{2\pi}} && (\text{plane strain}) \end{aligned} \quad (4.3)$$

r

where for this sample, the stress intensity factor K_I during fatigue test is about 12.7 $\text{MPa}\cdot\text{m}^{1/2}$, the Young's modulus of this Al-Cu-Li alloy is about 66 GPa (more details

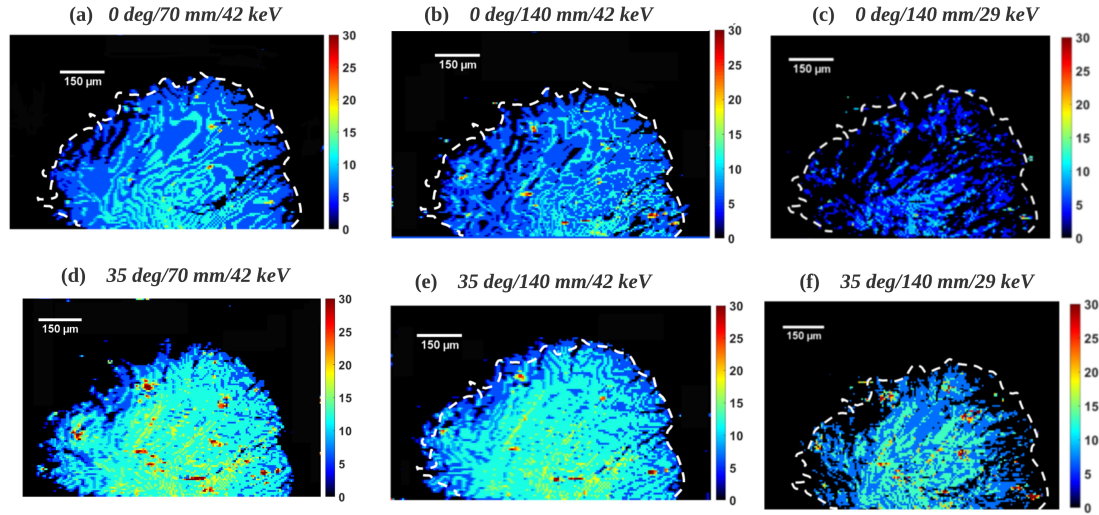


Figure 4.13: Comparison of quantitative analysis of crack opening maps under different scanning settings: experimental data in Figure 4.10 have been thresholded to estimate the crack opening maps. The dashed white line is the crack front obtained with the best image quality (Figure 4.10f). (a) Horizontal crack (0°) at 70 mm and 42 keV; (b) Horizontal crack (0°) at 140mm and 42 keV; (c) Horizontal crack (0°) at 140 mm and 29 keV; (d) Inclined crack (35°) at 70mm and 42 keV; (e) Inclined crack (35°) at 140mm and 42 keV; (f) Inclined crack (35°) at 140mm and 29 keV.

can be found in [NIZ 15]), and the crack length is about 0.6 mm (r in Eq 4.3 indicates the distance to the crack tip). Therefore, the estimated value of crack mouth's opening (plane stain) is $15.9\mu\text{m}$ which is in good agreement with measured crack opening in inclined case (Figure 4.13d). Smaller measured crack opening in the horizontal case (Figure 4.13a) may be due to jagged crack edges (which can be found in simulation results Figure 4.6b and experimental results Figure 4.10a) caused by wrinkle artifacts.

When the detector-sample distance is increased to 140 mm and the x-ray energy is kept constant, some discontinuities (holes) appear in the crack opening map of the horizontal case (Figure 4.13b). In fact, these holes do not physically make sense (they would have caused large stress concentrations), but have been caused by the wrinkle artifacts which noise-disrupt the crack surfaces with small opening in the reconstructed image. For the inclined case (Figure 4.13e), the crack opening map is almost unchanged by comparing with Figure 4.13d. This shows that even after increasing the detector-sample distance, the wrinkles artifact remains low intensity for the inclined case.

When the x-ray energy is decreased to 29 keV and the propagation distance is kept large (140 mm), the crack opening map is extremely discontinuous for the horizontal case

(Figure 4.13c). Only less than half of the crack extent has been detected open in this case. Some more sophisticated segmentation methods, such as U-net neural networks [XIA 21a], could extract more completely the cracks, but it greatly increases the post-processing time and risks of some erroneous labeling of crack pixels still persists. For inclined case under same distance and x-ray energy, more than 80 percent of the crack was detected (Figure 4.13e). The missing part is mainly the crack front with small opening. Comparing Figure 4.13c and e, for long propagation distance and low x-ray energy, tilting scanned specimen is an effective way to reduce wrinkle artifacts. Being able to image the sample under load would change the values displayed in Figure 4.13 but we believe that the tendencies reported above would still be valid.

4.5 Conclusions

The aim of the present work was to investigate wrinkle artifacts in phase contrast synchrotron tomography via simulations and experiments. Firstly, through simulations of cracks with simple geometry (flat, triangular, step-like crack), wrinkle artifacts were progressively identified in the simulated reconstructed images: grid-like patterns on the flat crack surface (Figure 4.5c), when the crack is parallel to the incident light; jagged (noise-like) patterns in triangular crack edges (Figure 4.6b) leading to problems in the length/opening measurements of the cracks; a few wrinkle artifacts appeared at the turn of large scale step-like crack, as the step length changes and the crack opening decreases, the intensity of the wrinkle artifacts increases sharply to the point where the crack shape becomes illegible (Figure 4.7).

Then, by checking the simulated projections of the flat crack, 2D Fresnel diffraction patterns (discussed in [AMI 07; TAV 10; SAL 17]) were observed when the lengths crossed by the x-rays at the level of the crack are not constant (Figure 4.12b), which is considered to be the origin of the wrinkle artifact in the reconstructed image. Therefore, avoiding an incident beam parallel to the crack surface (by inclining the specimen) can prevent 2D Fresnel diffraction patterns from appearing on the detector, resulting in fewer wrinkle artifacts in the reconstructed image. In addition, the intensity of the interference caused by the propagation of x-rays in free space increases with the propagation distance and the wavelength of x-rays [AMI 07]. Thus, reducing the detector-sample distance and increasing the energy (reducing the wavelength) are also ways to reduce the wrinkle artifacts. In practice, the detector-sample distance is sometimes limited by the size of in-situ instruments [BUF 06]. Inclining the specimen might be a simple but efficient method for decrease the wrinkle artifact when the distance and energy cannot be changed easily.

Thresholded cracks from experimental images were used as input to the simulations

to get a more realistic characterization of the effect of the scanning settings (x-ray energy, propagation distance and orientation) on the wrinkle artifacts (Figure 4.8). The advantage of this simulation is to better control a change in scan settings compared to real experiments and a known crack structure (thresholded crack) can be compared to the crack in the reconstructed image. An experimental crack thresholded by a Hessian-matrix based method [XIA 21a] with uniform openings has been used to investigate the effect of different openings on the presence of wrinkle artifact (Figure 4.9): wrinkle artifacts create jagged edges for cracks with large opening and almost impede an accurate identification of cracks with small opening.

Finally, experimental phase contrast SRCT of cracked specimens in Al alloys (Al-Cu-Li) and Ti alloys (Ti-Al-V) have been performed at ESRF ID11 under different free-propagation distances, beam energies and inclinations. In the Al specimen, wrinkle artifacts were confirmed to be reduced by reducing sample-to-detector distance, increasing x-ray energy and tilting the crack (Figure 4.10). The effect of wrinkle artifacts on the quantitative analysis of cracks was studied by thresholding volumes in Figure 4.10 and calculating crack opening maps. It was found that, the presence of wrinkle artifacts leads to inaccurate crack opening measurements and can hinder crack front detection in some cases (Figure 4.13). In addition, for the same scan settings, fewer wrinkle artifacts were observed in the Ti specimen (Figure 4.11), this may be explained by the fact that Ti has a lower ratio of refractive index decrement (δ) to absorption index (β), resulting in a smaller phase shift [PAG 02], thus low interference intensity. The presence of wrinkle artifact problem will therefore be dependent on the material studied.

Chapter 5

Characterization of internal fatigue cracks in nodular cast iron using Digital Volume Correlation of laboratory X-ray tomography images.

This chapter is dedicated to the evaluation stress intensity factors of internal fatigue cracks in nodular graphite cast iron by using digital volume correlation (DVC) of laboratory X-ray tomography images. DVC is a method that can measure displacement fields at the sub-voxel scale in samples of cast iron under load thanks to the graphite nodules which can be used as an internal natural marker. Fatigue samples containing controlled internal defects have been produced in a nodular cast iron without changing the micro-structure and the nominal mechanical properties of the material. Specimens with internal cracks and surface cracks were characterized by laboratory tomography at different loads after different number of fatigue cycles. The displacement fields close to the cracks were calculated by the DVC method, from which stress intensity factor values were extracted using Williams series; based on those results the closure level of internal cracks and surface cracks was analysed and discussed.

5.1 Introduction

In the previous chapters it was shown that thanks to phase contrast and provided that imaging conditions are optimised, synchrotron tomography offers a better detection of fatigue cracks in metals than laboratory tomography. The latter technique is however easier to access. To overcome the limited spatial resolution, as shown in Chapter 2, optimised thresholding methods can be used. Another way of detecting cracks in metals is to look at them through their displacement fields when they are submitted to some mechanical loading. This approach first developed in 2D at the surface of cracked sample via Digital Image Correction (DIC) measurements [CHU 85] has been extended in the last ten years in 3D using tomographic images [RAN 10]. Like in 2D, the displacement field induced by a crack is measured by comparing two volumes of a cracked sample submitted to different mechanical loads. This technique called Digital Volume Correlation (DVC) does not require a very high spatial resolution as only the displacement of some markers in the sample are tracked (with a sub-voxel resolution). Hence, provided the markers can be detected, Lab CT can be used for characterize fatigue cracks with sub-voxel opening. In this chapter, the DVC technique is used to study quantitatively internal fatigue cracks in cast iron using Lab CT.

In cast iron, fatigue cracks are known to initiate at casting defects such as microshrinkages or dross defects. In the high cycle fatigue regime, for positive R ratios, near surface defects are much more prone to crack initiation than internal defects and therefore they control the fatigue limit. Life-time prediction through the use of Paris' laws for surface crack and internal crack have been developed [NAD 97a; NAD 04]. For accurately developing such crack propagation laws, fatigue crack closure assessment is essential. Since its discovery in the 70s, several methods have been developed to measure crack closure. The most used ones are based on macroscopic compliance measurements (see for example [VAS 94]). Researchers have also developed more local technique involving for example DIC analysis close to the crack tip. For example, in-situ experiments using a small series of load cycles in a four point bending device installed within a SEM has been performed to observe surface crack closure in nodular cast-iron [HEI 18]. The main drawback of this type of work is that it uses a 2D visualization of the crack. The cracks opening may not be uniform in the direction of specimen width/thickness. To assess to crack closure in 3D, X-ray tomography can in principle be used. As mentioned in chapter 3, direct measurement of crack openings through gray-scale images can be quite inaccurate, but DVC can accurately calculate crack openings at the sub-pixel scale [LIM 09]. It suffices to use a material containing markers to extract the displacement fields, cast iron is therefore well adapted to the DVC method because the graphite nodules can be used as a natural

marker. Limodin has studied the closure of surface cracks in a nodular graphite cast iron using DVC and laboratory X-ray micro-tomography. An estimation of the opening stress intensity factor (K_{op}) for a mode I crack has been found to be of the order of $6MPa\text{m}^{1/2}$. However in Limodin's work, the studied samples (section $1.6 \times 1.55\text{mm}^2$) are cut from a larger pre-cracked specimen (section $6 \times 4\text{mm}^2$) and stress relaxation is suspected to occur during simple preparation casting some doubts on the quantitative analysis of closure ¹.

As explained before, fatigue cracks tend to initiate from the surface of fatigue samples [SCH 09]. However, the presence of 'big' defects in the bulk of large castings is not uncommon ². The harmfulness of such defects with respect to fatigue is difficult to assess for obvious reasons. One way to tackle this problem is to integrate propagation laws to predict the fatigue life of the component assuming that the internal defect is equivalent to an initial crack and that no initiation stage exists. However imperfect this approach might be, it can give some estimations. One remaining issue however is that propagation laws for internal fatigue cracks (which propagate in vacuum, at least theoretically) are badly known. Researchers have carried out crack propagation tests under vacuum as a first approach [NAD 97a] [BIL 04], but the validity of those laws for real internal cracks is quite difficult to check. To add some complexity for this problem, in spite of being of paramount importance for crack propagation, as explained, the phenomenon of crack closure has never been characterised directly and quantitatively for internal cracks.

Most of the (rare) studies on the propagation of internal cracks in metals up to now deal with natural internal defects and/or natural cracks: for example in cast iron [TOM 18], titanium alloy [YOS 16] or Al-Si cast alloys [SER 17]. Using natural internal defects for internal crack initiation has the advantage of being representative of the behaviour of the real cast component, however the shape and size of the defects cannot be controlled and locating the defects precisely into the fatigue specimens is not easy. A method for producing internal artificial defects was presented in [SER 16] for a Al cast alloy. The size of the defects produced is relatively large (hole with ~ 1 mm diameter) which i) imposes a large size on the sample and ii) cannot avoid crack initiation on neighboring microshrinkages (if some are present) unless very low stress levels are used [MES 20b]. Another method for fabricating internal artificial defects by diffusion bonding plates containing a laser machined sharp notch was successfully developed to study the fatigue propagation of internal

¹In the case of plasticity induced closure the crack tip is submitted to compressive stress induced by the plastic zone

²A shrinkage is a void which appears at the end of the metal solidification process. If the last pockets of liquid which solidify are not in contact with the surface, a void appears because of the volume reduction during the liquid to solid phase transition. Because such voids form between dendrites of solid metal, they have a complex 3D shape which creates a region of stress concentration [SER 16] which is very detrimental to fatigue resistance.

cracks in a titanium alloy [JUN 19]. In that case, the crack initiation period was always less than 10 % of the fatigue life and occurred systematically at the internal notch for all the stress levels investigated.

This chapter describes the application of this method to nodular cast iron. After a brief description of the procedure used to produce the samples, the microstructure and mechanical properties of the material containing the defects are studied. The propagation of fatigue cracks from the notches has been characterised ex-situ using lab CT in the case of surface and internal defects. After describing the method used for performing the DVC analysis, quantitative results on stress intensity factors, crack growth rates and closure levels are presented. The limits of the method are discussed in a final section.

5.2 Materials and experimental methods

5.2.1 Initial Materials

The nodular cast iron employed in this study is used for producing car components, it was provided by Pr.Yves NADOT; its fatigue properties have been extensively studied [NAD 97b]. Its micro-structure contains a ferrite matrix including less than 5% of pearlite. The mean ferrite grain size is about 50 μm . The bulk matrix exhibits a homogeneous distribution of graphite nodules with a mean diameter of 15 μm . The material Young's modulus, yield stress, fracture stress and Poisson's ratio are equal to 178 GPa, 380 MPa, 510 MPa and 0.27, respectively. More details on the microstructure and mechanical properties of the material can be found in [NAD 04].

5.2.2 Fatigue specimens

5.2.2.1 Internal defects

To produce artificial internal defects inside metallic tomography fatigue samples, a method combining femtosecond laser machining and Spark Plasma Sintering (SPS) Welding is used. This method was proposed by A.Junet *et al.* and has been applied in a Ti alloy [JUN 19]. As shown in Figure 5.1, first, a cast iron plate is cut into two parts by Electrical Discharge Machining (EDM); then a thin notch is machined in one of the two plates by femtosecond laser machining. The laser machining has been performed by Prof. A.Weck from Ottawa University [WEC 07]; after mechanical polishing of the plates down to 1 μm diamond suspension and ultrasonically cleaning up with acetone, the notched plate was welded with the unmachined plate using a Spark Plasma Sintering (SPS) device (HP D 25 of FCT Systeme Company). A compressive load of 11.17kN applied by two punches on the two cast iron plates resulting in a pressure of 9.6 MPa. The thermal cycle consisted

in a fast heating rate of 300 °C/min up to 780 °C, followed by a slow heating rate of 100 °C/min up to the soaking temperature at 880 °C, a holding time of 120 min and finally a cooling stage at 15 °C/min down to 400 °C. Finally, the welded plates were naturally cooled down to room temperature.

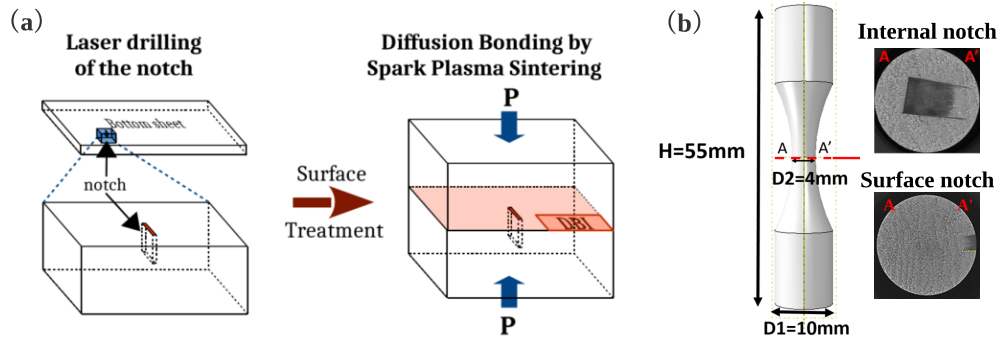


Figure 5.1: Production process of fatigue specimens with artificial internal and surface notches. (a) left: Femtosecond Laser machining of the notch; right: Spark Plasma Sintering (SPS) diffusion bonded artificial internal crack. (b) Schematic drawing of a cylindrical fatigue specimen; tomography slices showing internal and surface notches. Adapted from [JUN 19].

5.2.2.2 Post-weld materials

In order to verify that the SPS process does not modify the material properties in terms of microstructure and mechanical properties, post-weld materials were cut, mechanically polished down to 1 μm , chemically attacked using Nital 4% and characterized using an optical and a scanning electron microscope (SEM). The microstructure of the post-weld material is shown in Figure 5.2a and b, no large voids were found around the weld interface which is made visible in the optical micrography by the etching solution. Ten different areas (0.4mm*0.4mm) were selected to measure the ferrite grain size and the nodular size of the post-weld material by optical microscopy: the average grain size was found equal to 43 μm with a standard deviation of 6.81 μm ; the average nodular size is 21 μm with a standard deviation of 4.23 μm . Those values are in very good agreement with those obtained using the same method on the initial material respectively: 45 μm with a standard deviation of 9.72 μm and 23 μm with a standard deviation of 8.17 μm . The Vickers hardness of the ferritic matrix was measured (10 indentations with a pressure of 5Kg): for the initial material a value of 168.1HV with a standard deviation of 12.54HV was found; for the post-weld material, the measured value is again in good agreement with the value measured before welding: 163.4HV with a standard deviation of 8.69HV.

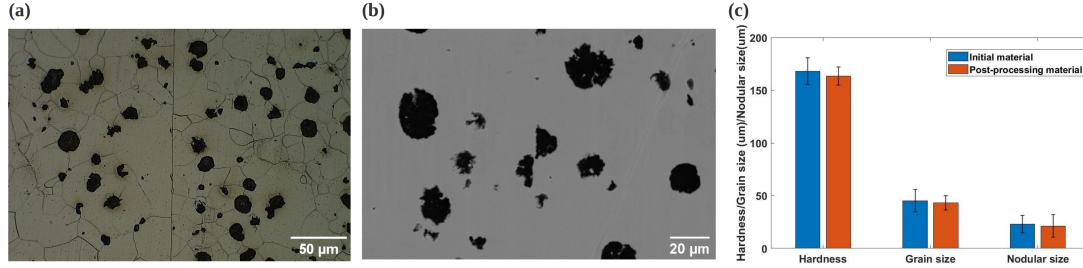


Figure 5.2: Optical micrography of the micro-structure of post-weld materials after chemical etching in 4% Nital. (a) The thin vertical line corresponds to diffusion bonded interface by the etching solution. (b) SEM image of the same interface. (c) Comparison of the hardness, grain size and nodular size of post-weld materials with the initial material.

A tensile test was carried out at a constant strain rate of $2 \times 10^{-4} s^{-1}$ (tensile stress along the welding interface) for the post-weld material. A standard test specimen (Figure 5.3) was machined with a central-section of $2mm \times 2mm$. The quasi-static mechanical properties show good consistency with those of the initial material ($\sigma_{e0.2} = 355$ MPa vs $\sigma_{e0.2} = 380$ MPa [NAD 04]). The fractography in Figure 5.3c shows the ductile behavior of the post-weld material; the weld interface (vertically oriented) is not visible.

From all those analysis, it was concluded that the SPS process used in this work does not change the microstructure nor the mechanical properties.

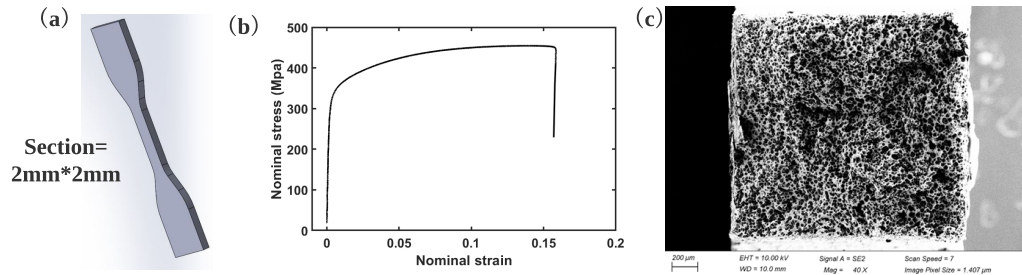


Figure 5.3: Characterisation of the tensile properties of the post-weld material. (a) Diagram of the specimen used with a minimum cross section of $2mm \times 2mm$. (b) Tensile curve ($\dot{\epsilon} = 2 \times 10^{-4} s^{-1}$). (c) SEM image of the fracture surface after tensile testing, the welding interface cannot be detected.

5.2.2.3 Fatigue specimen dimensioning

The design of the crack size and fatigue specimen dimensions is limited by the following:

- the cast iron studied in this work has excellent fatigue resistance, with a stress intensity factor threshold of approximately $10 \text{ MPa}\sqrt{m}$ for internal crack propagation in vacuum [NAD 99]. The stress intensity factor variation during a cycle for internal cracks of diameter a can be estimated from Eq 5.1 [NAD 97a]. The maximum stress σ_{max} used during fatigue ($R=0.1$) and the size of the initial notch have been determined in order i) to avoid plasticity in the section of the notch and ii) to induce a ΔK level large enough (assuming that the notch is a crack, and based on a Kitagawa diagram of the material [NAD 04]) to be above ΔK_{th} , the SIF threshold for crack propagation in vacuum. In this study, two different batches of samples have been prepared corresponding to two different notch sizes, $1.7\text{mm} \times 1.7\text{mm}$ and $1\text{mm} \times 1\text{mm}$. The typical 3D geometry of the notch is shown in Figure 5.39 (in Appendix 5.8).

$$\Delta K = 0.7 \Delta \sigma \sqrt{\pi a} \quad (5.1)$$

- In the study of closure phenomena and the propagation laws of cracks, the theory of Linear Elastic Fracture Mechanism (LEFM) is used. The condition of confined plasticity can be assumed if the radius of the plastic zone at the crack tip does not exceed 10 to 15% of the crack size. This radius can be estimated from Eq 5.2. In our case, for a crack size of 1.7mm, the maximum fatigue stress ($R=0.1$) was chosen to be 280 MPa to achieve a plastic zone size of 0.10mm. Elastic FE simulation using Abaqus software (Figure 5.4) gives a plastic zone size of the order of 16%.

$$r_y = \frac{1}{\alpha \pi} \left(\frac{K}{\sigma_Y} \right)^2 \quad (5.2)$$

Where σ_Y is the yield stress, $\alpha = 2$ for plane stress and $\alpha = 6$ for plane strain.

- The size of the voxel for laboratory tomography depends on the size of the scanned object. Cast-iron exhibits a strong x-rays attenuation; for the machine currently in use (VTOMOX), 10 mm is the maximum thickness through which x-rays can pass allowing a minimum 10% transmission. The minimum radius (middle) of the fatigue specimen was therefore determined to be 2mm in order to be able to use a voxel of $2.5 \mu\text{m}$ during scanning (Figure 5.1.b).

The diffusion bonded plates were cut into cylindrical fatigue specimens which dimensions are shown in Figure 5.1.b. In order to compare the behaviour of internal cracks with those of surface cracks, two notch-free plates have been diffusion bonded by SPS and machined into cylindrical fatigue specimens (Figure 5.5d) at the surface of which surface notches (Figure 5.5c) were created using the same method (femtosecond laser machining).

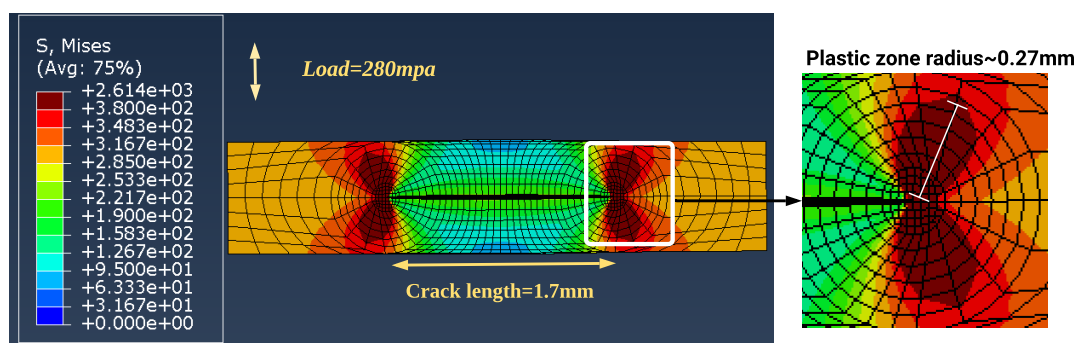


Figure 5.4: FE simulation of a circular internal crack/notch with 1.7mm diameter submitted to a tensile load of 3516.8N. The color-bar show the Von Mises stress distribution around the internal crack: with dark red colour indicating a Von Mises stress larger than the material yield stress, therefore. The value of the plastic zone radius is of the order of 0.3mm.

5.2.3 EX-situ Fatigue tests

5.2.3.1 Fatigue tests

The fatigue test specimens were mechanical polished by SiC-paper to remove surface scratches. The fatigue machine used in [LAC 15] which allows to perform cyclic test inside the tomograph has a limited tensile capacity of 2000N. Therefore it was decided to *perform the fatigue test outside the tomograph* where only constant tensile loading of the cracked samples was performed. The list of the samples investigated is given in Table 5.1. The fatigue tests have been performed at room temperature using a servo-hydraulic INSTRON 8516 fatigue testing machine. Constant amplitude stress controlled uni-axial tests were carried out with a frequency of $f=10$ Hz (sinusoidal wave form) and a stress ratio $R=0.1$. To reduce the misalignment of the tension axis, the specimens have been fixed in the INSTRON hydraulic clamps by attaching two rectangular steel blocks with M5 screws as shwon in Figure 5.6.

5.2.3.2 In-situ loading for DVC

After a certain number of fatigue cycle, X-ray tomographic scans were performed using the tomography system V-Tomex previously described in chapter 1.2). In this part of the thesis a 140 kV acceleration voltage was selected to ensure a 10% transmission of the X-ray beam through the 4mm diameter cross-section. The specimen was fixed using long M5 threaded rods (Figure 5.7) in the aluminum tube of an in-situ tensile machine which was placed on the rotating stage in the tomograph chamber between the X-ray source and the detector.

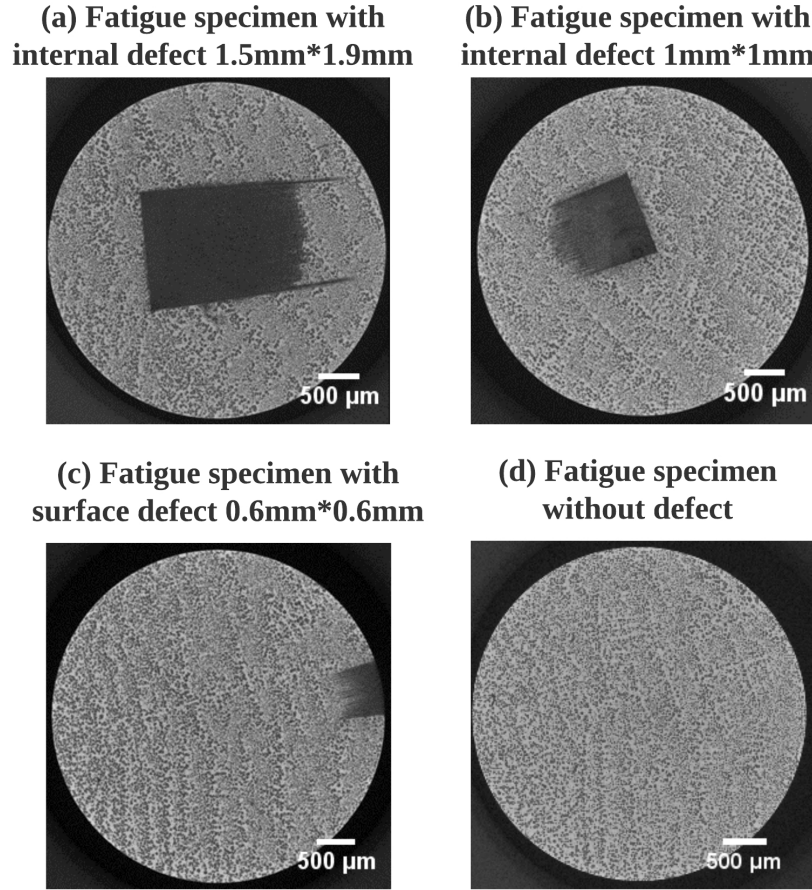


Figure 5.5: Lab.CT slices at the center of fatigue specimens containing different defects: (a) internal defect $1.5\text{mm} \times 1.9\text{mm}$ (named *Sample – internal – 1*); (b) internal defect $1\text{mm} \times 1\text{mm}$ (named *Sample – internal – 2*); (c) surface defect $1\text{mm} \times 1\text{mm}$ (named *Sample – surface – 1*); (d) without defect ((named *Sample – without – 1*)).

The distance between the sample and the source has been reduced as much as possible (11.27mm) resulting in an image voxel size $2.5\mu\text{m}$. A set of 1200 radiographs were taken while the sample was rotated through 360° along its vertical axis. With an acquisition time per image of 667 ms one scan lasted about 56 min. The scans were recorded at different loads in order to study crack closure/opening (Table 5.1). Reconstruction of the tomographic data was performed with a filtered back-projection algorithm using the `datos|x`-acquisition software developed by Phoenix.

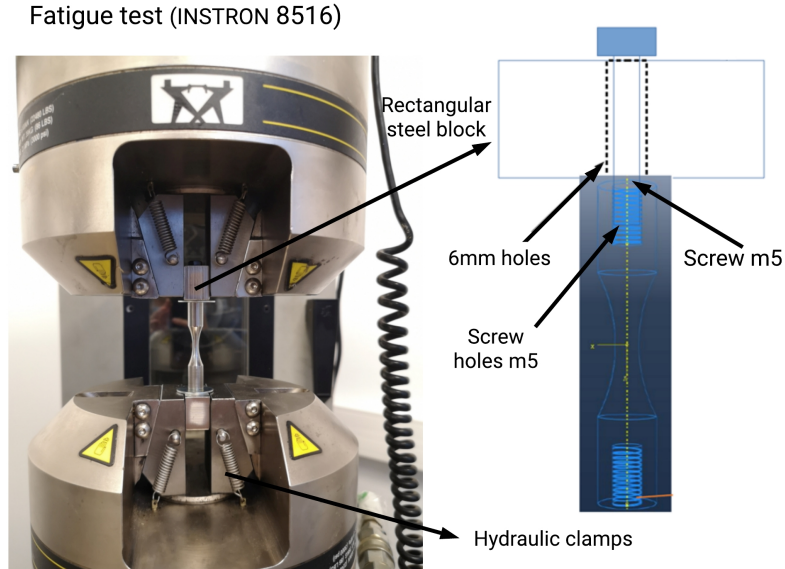


Figure 5.6: Photograph of the specimen assembled in the fatigue test machine: Two rectangular steel blocks with 6 mm holes are attached to the ends of the specimen by M5 screws and are fixed in the INSTRON hydraulic clamps.

Table 5.1: Ex-situ fatigue test parameters: maximum stress and number of cycles in fatigue test; value of the load applied during the tomographic scan (the order represents the increase or decrease of loads)

Sample name	Defect size	Max. fatigue stress	Number of fatigue cycles	Scan load	Crack propagation
<i>Sample – internal – 1</i>	1.5mm×1.9mm	280Mpa	0	100N 3500N	No
	1.5mm×1.9mm	280MPa	4100	100N 1400N 2330N 2800N 3500N	No
	1.5mm×1.9mm	280MPa	7100	3500N	No
	1.5mm×1.9mm	280MPa	12100	3500N	No
	1.5mm×1.9mm	280MPa	20100	3500N	Yes
	1.5mm×1.9mm	280MPa	30100	3500N	Yes
	1.5mm×1.9mm	280MPa	40100	3500N	Yes
	1.5mm×1.9mm	280MPa	50100	3500N 2640N 2000N 1400N 100N	Yes
<i>Sample – internal – 2</i>	1mm×1mm	300mpa	0	without load	No
	1mm×1mm	300MPa	8600	100N 3800N	No
	1mm×1mm	300MPa	16600	100N 3800N	Yes
<i>Sample – surface – 1</i>	0.6mm×0.6mm	300mpa	0	without load	No
	0.6mm×0.6mm	300MPa	8600	100N 1422N 2330N 3050N 3800N	Yes
	0.6mm×0.6mm	300MPa	10600	3800N	Yes
	0.6mm×0.6mm	300MPa	12600	3800N 3050N 2330N 1422N 100N	Yes

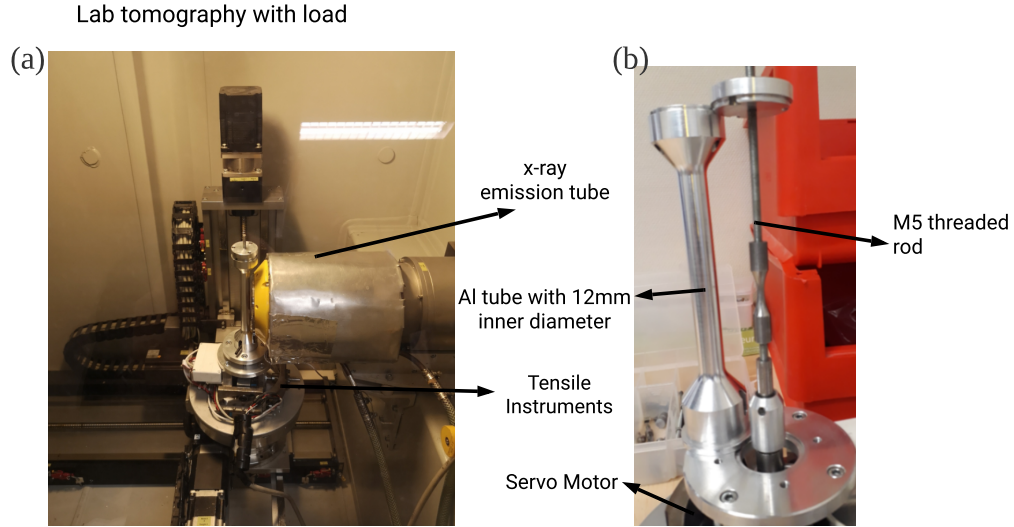


Figure 5.7: Photography of the specimen assembled in tensile instrument which has been placed on the rotating stage in tomography chamber. (a) in-situ loading stage inside the Tomograph, (b) Al tube used to transmit the load and specimen mounted with M5 screws

5.2.4 Digital image correlation

A multiscale DVC algorithm is used to compute the displacement fields in the loaded specimen. Details of the method can be found in [LAC 15]. A ROI of $800 \times 800 \times 400$ voxels in the 3D images was binned (2×2 binning, equivalent to a voxel size of $5 \mu\text{m}$) and centered within the $1850 \times 1850 \times 1200$ voxels original image. Three kinds of mesh have been used in this work, first, eight node cubic elements (element size 64 pixels/32 pixels/16 pixels) are used to compute the displacement fields as a initial value for subsequent calculations, an example of the calculated displacement fields from tomography images loaded at 100N and 1422N of 'Sample-surface-1' after 8600 cycles is shown in Figure 5.8a. External forces are equal to zero at the free surface, therefore, a free-surface hexagonal mesh was created to account for this boundary condition. The gray level tomography images were filtered using a median filter (radius=50 pixels) in the direction containing rotation axis (called z direction in this work) to remove the nodules and crack (as shown in Figure 5.9b), after thresholding to obtain the specimen envelope. The hexagonal mesh was generated from the 3D thresholded image by using the Hypermesh software (Figure 5.9c). The displacement fields calculated by with cubic mesh as the initial value and the free-surface mesh are shown in Figure 5.8a.

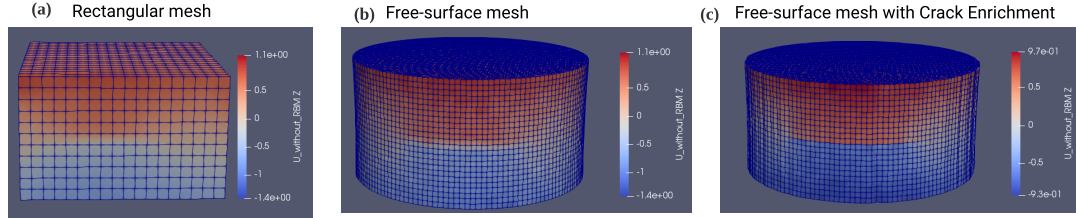


Figure 5.8: Displacement fields calculated from tomography images loaded at 100N and 1422N of 'Sample-surface-1' after 8600 cycles: (a) displacement fields calculated with a rectangular mesh (element size = 32 voxels); (b) displacement fields calculated using a free-surface mesh (element size = 16 voxels); (c) displacement fields calculated using a free-surface mesh with crack enrichment (element size = 16 voxels).

To take into account the presence of a crack in the mesh, the eXtended Finite Element Method (X-FEM [BEL 99]) has been used. It allows to enrich the mesh elements containing the crack with additional terms (the discontinuity due to the crack) by Heaviside type enrichment functions. More details about the enrichment of the cracks can be found in [LAC 15]. Here, the crack is assumed to be lying on a plane (ie, small scale roughness is ignored), its circular crack front is defined using the z-project function of Fiji software (minimum value) of 60 CT slices surrounding the crack (Figure 5.9d). The 2D mesh (plane where the crack is located) after enrichment is shown in Figure 5.9e: the blue part is the crack zone, and its mesh nodes use Heaviside type enrichment functions [DOL 00]. The displacement fields calculated by using crack-enrichment mesh are shown in Figure 5.8c. From above displacement fields the stress intensity factor values along the crack front can be calculated using Williams series [WIL 21]. The principle of this method is to compare the displacement field measured by DVC at the crack front with the field described by the Williams series in a plane normal to the crack front, and then minimizing the difference between them to determine SIF. More details about this method can be found in [LAC 15].

In addition to this, the SIF can be measured by crack opening map. As shown in Eq 5.3, the crack opening varies with the distance from the crack tip (r), so the SIF (K_I) can be fitted by least squares method from the crack tip opening displacement (CTOD) profile. However, this method can only be used at a few discrete location along the crack front and not all along the entire crack front. In our work, this method is mainly used to compare with the results of the Williams series calculation in some specific cases.

$$CTOD = \frac{8K_I}{E} \sqrt{\frac{r}{2\pi}} \quad (\text{plane stress})$$

$$CTOD = \frac{8K_I(1-\nu^2)}{E} \sqrt{\frac{r}{2\pi}} \quad (\text{plane strain}) \quad (5.3)$$

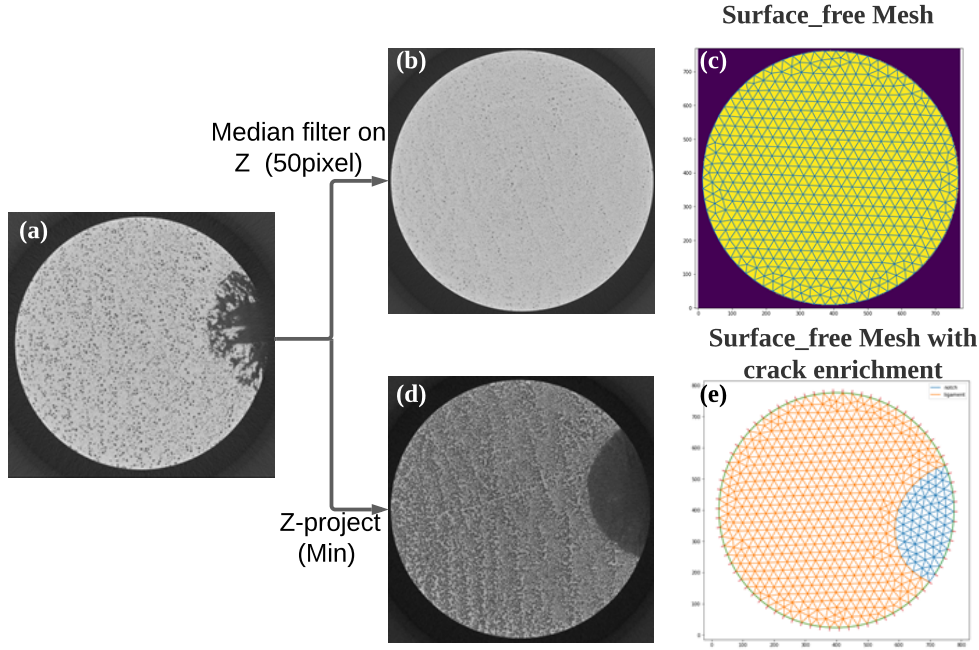


Figure 5.9: Generation of free-surface mesh without and with crack enrichment: (a) reconstructed slice of 'Sample-surface-1' after 8600 cycles loaded at 3800N showing a fatigue crack ; (b) same slice in the sample reconstructed volume after applying a median filter ($r=50$ pixels) in z direction; (c) 2D free-surface mesh; (d) Min- z -project of 60 middle slices showing a projected view of the crack; (e) crack enriched mesh for X-FEM calculation, blue elements indicates the cracked area with enriched nodes.

5.3 Results and Analysis

5.3.1 Crack closure

5.3.1.1 Crack closure assessment for a surface crack

In order to validate our method, the surface crack was studied first and compared to the work of N.Limodin *et al.* on the same type of material [LIM 09]. A crack has been detected in *Sample – surface – 1* after 8,600 fatigue cycles at $\sigma_{max} = 300MPa$. The sample was removed from the fatigue rig and installed inside the in-situ tensile machine to be scanned under load. The cracked sample was submitted to increasing levels of

tensile loads between 100 and 3800N (see Table 5.1). It was found that recording the scans at increasing loads induced some plastic/non-linear behaviour of the sample which altered the SIF extraction procedure. When this was realised the *Sample – surface – 1* sample was submitted to 4000 supplementary fatigue cycles (12,600 in total) and then the tomographic scans were performed *under decreasing loads* for which the SIF extraction was found to give reasonable results. In this section we present the results obtained with decreasing loads after 12,600 cycles. SIF values obtained at increasing loads after 8,600 cycles are presented and discussed in section 5.4 of this Chapter.

Five different loads (3800N/3050N/2330N/1422N/100N) were used for the scans. As shown in Figure 5.10, after 12,600 cycles a surface crack has initiated from the notch and propagated over almost 500 μm in the bulk of the sample (initial notch size 600 μm). Qualitatively it can be observed that the crack opening at different loads did not vary much in the reconstructed tomography images; values of the order of 20-30 μm are recorded which is significantly larger than the 6 to 20 μm values reported by Limodin *et al.* [LIM 09] probably because of the larger crack size and σ_{max} values used.

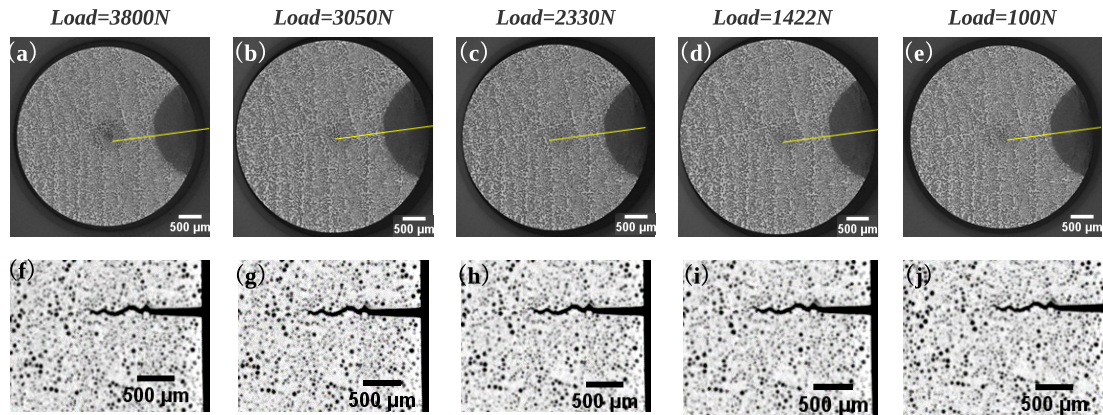


Figure 5.10: Laboratory tomography results of *Sample – surface – 1* after 12,600 cycles of fatigue testing under different loads (imaging conditions can be found in section 5.2.3.2). (a)-(e) Projected images of the minimum value of 60 horizontal slices (perpendicular to rotation axis) centered on the crack of *Sample – surface – 1* under 3800N/3050N/2330N/1422N/100N loading; (f)-(j) Vertical slices (parallel to the rotation axis) through the yellow lines marked in the Min-z-projects in (a)-(e).

Volume correlations

These intra-cycle tomography images (Figure 5.10) were used to calculate the displacement field around the crack using the DVC method developed by Lachambre *et al.* [LAC 14]. An element size of 16 voxels was chosen as a good compromise between dis-

placement uncertainty and spatial resolution of the displacement fields. For the element size used, the displacement uncertainty was about 0.09 voxel. More details about the methodology of uncertainty evaluation can be found in [LAC 14]. In the results (shown in Figure 5.11), the variation of crack opening displacement (COD) can be observed: the maximum displacement value decreases from 1.36 pixel ($6.8\mu\text{m}$) to 0.74pixel ($3.7\mu\text{m}$) as the load decreases. Figure 5.12 shows the distribution of strain around the crack. As the measurements are obtained for decreasing applied loads, those strains correspond to elastic strains. As expected, the regions with the largest strain level are clearly confined to the crack region.

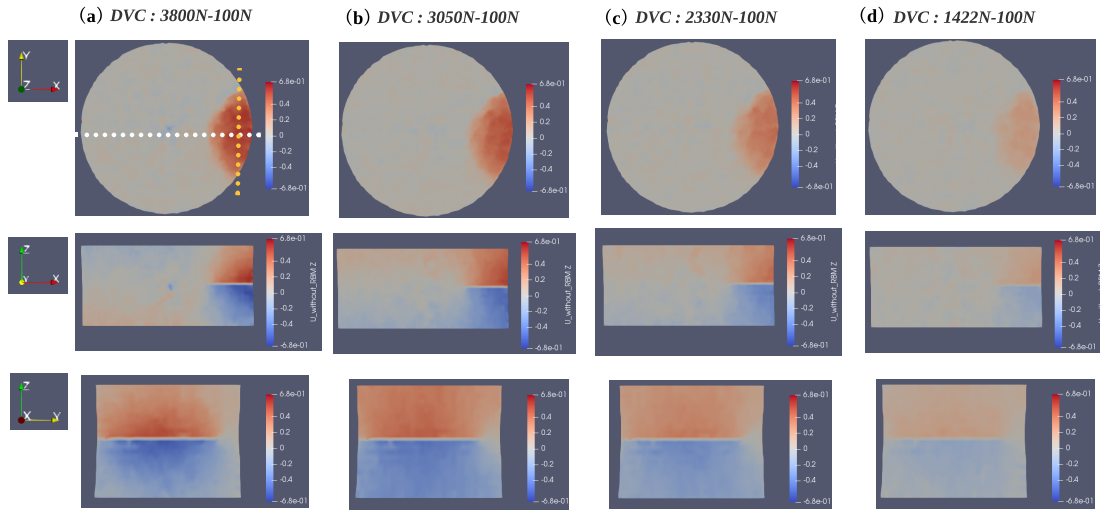


Figure 5.11: Displacement fields in z direction (tensile direction) calculated by the DVC method from 5 intra-cycle CT images (shown in Figure 5.10), the 3D image at minimum load has been used as reference. (a)-(d) corresponding to the four different loads: 3800N/3050N/2330N/1422N, in each group of images: the top image shows the displacement field in the x-y plane (perpendicular to the rotation axis), at the center of the sample; the middle image is in the x-z plane (parallel to the rotation axis), along the dotted white line; the bottom image is in the y-z plane (parallel to the rotation axis), along the dotted yellow line.

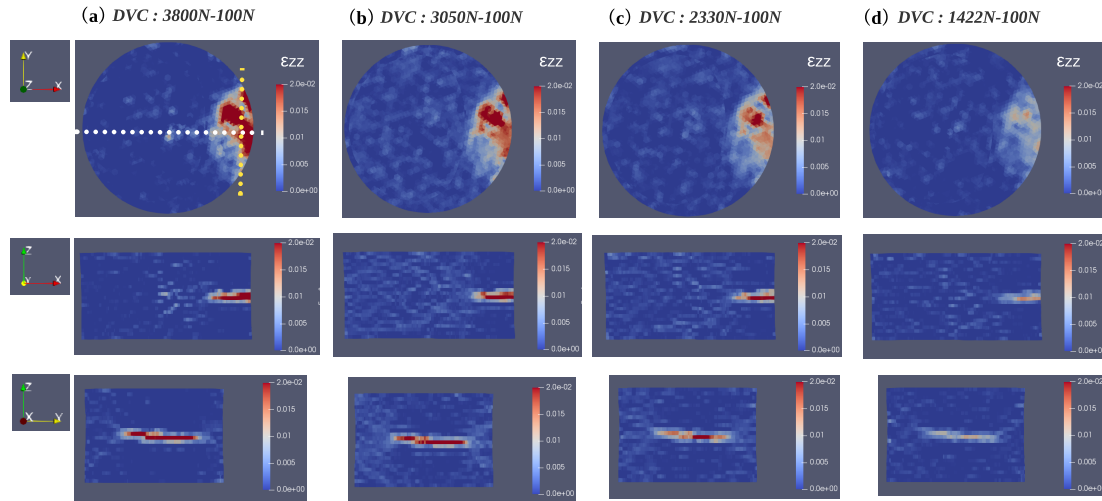


Figure 5.12: Strain fields (ϵ_{zz} , z corresponding to the tensile direction) calculated by the DVC method from 5 intra-cycle CT images (shown in Figure 5.10), the 3D image at minimum load has been used as reference. (a)-(d) corresponding to the four different unloading loads: 3800N/3050N/2330N/1422N, in each group of images: the top image shows the strain field in the x - y plane (perpendicular to the rotation axis), at the center of the sample; the middle image shows the strain field in the x - z plane (parallel to the rotation axis), along the dotted white line; the bottom image shows the strain field in the y - z plane (parallel to the rotation axis), along the dotted yellow line.

SIF extraction

The displacement fields measured by the DVC method can be used to compute the SIF values at the crack front by fitting some Williams series. The procedure is illustrated on Figure 5.13 for the surface crack observed after 12,600 cycles. Figure 5.13 also shows the SIF values at maximum load (3800N): from the lower part to the middle part of the crack front, K_I values of the order of $20 \text{ MPa}\sqrt{\text{m}}$ are measured; the upper part of the crack front has smaller K_I values with some scatter, the minimum value being about $15 \text{ MPa}\sqrt{\text{m}}$. The stress intensity factor values for mode II and mode III are much lower. K_{II} being very close to zero and K_{III} varying between -5 on $5 \text{ MPa}\sqrt{\text{m}}$ with some scatter. The SIFs for the other three loads (3050N/2330N/1422N) are given in appendix 5.6, while the values of K_I for different loads at the middle (30th Williams plane) of crack can be found in Table 5.2.

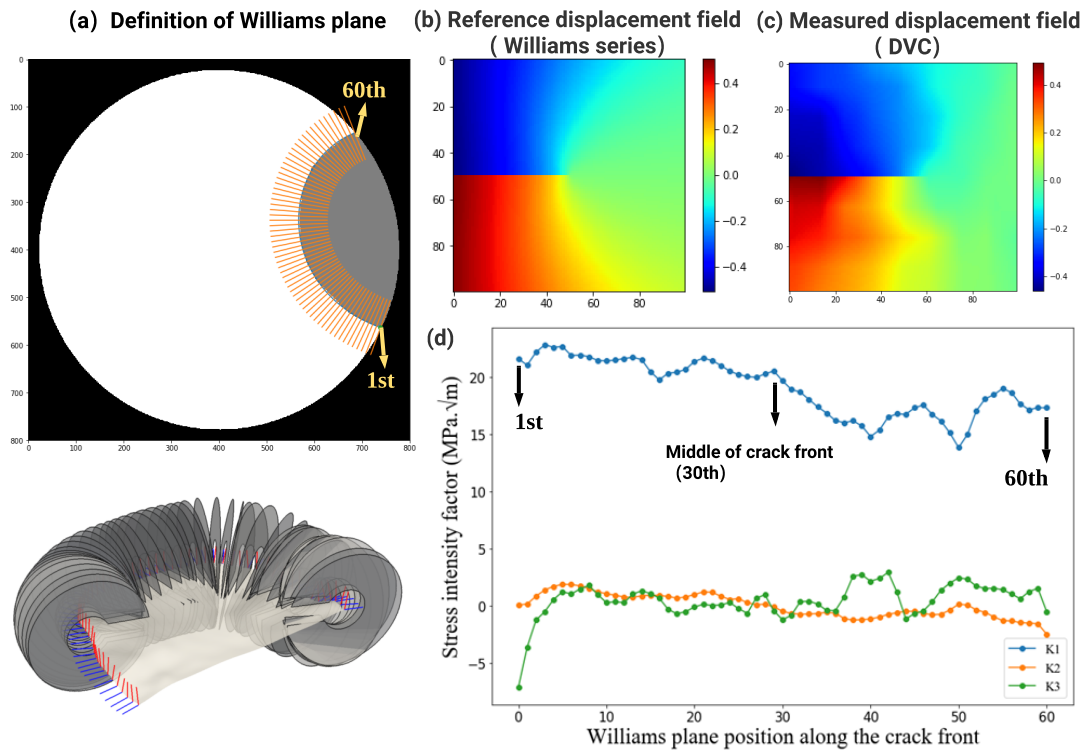


Figure 5.13: Stress intensity factor values for maximum load (3800N) computed along the crack front by Williams series. (a) 60 planes (radius 60pixel) normal to crack front are defined (Williams plane), a 3D schematic of the Williams plan as can be seen in the bottom image; (b) displacement field at the middle of the crack front in the crack propagation direction (corresponding to $Mode_I$) calculated by the Williams series; (c) displacement field at the middle of the crack front in the crack propagation direction (corresponding to $Mode_I$) measured by the DVC method; (d) Stress intensity factor values along the crack front.

The displacement field in Mode I (U_z) as shown in Figure 5.11 is discontinuous around the crack, thus the Crack Opening Displacement (COD) can be obtained by calculating the displacement jump (ΔU_z) from the difference between the U_z values in two slices taken parallel to the crack plane on both sides of it. The resulting COD maps (for a region of interest containing the crack) under different loads have been plotted in Figure 5.14. The ΔU_z profiles from crack mouth to crack tip were extracted for each loading step at the middle of the crack front (along the dashed white lines drawn in Figure 5.14). The values of COD measured should be a square root function of distance to the crack tip (Eq 5.3 in case of plane strain) if linear elastic behavior prevails in the vicinity of the crack tip [LIM 09]. By fitting the ΔU_z profiles with such a function the K_I values can be extracted. The values obtained by this method vary from 17.94 to $7.63 MPa\sqrt{m}$ as the load decreases, which is consistent with the values calculated by the Williams method (see Table 5.2).

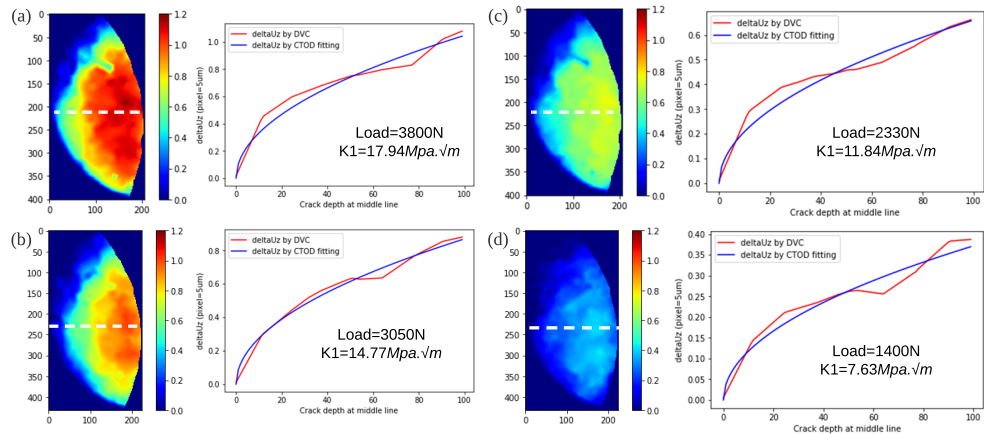


Figure 5.14: (a-d) Left: maps of crack opening displacement (COD) with decreasing loads, right: SIF (K_I) fitting by CTOD method (introduced in section 5.2.4), red curve corresponds to COD profile along dashed white line, blue curve corresponds to fitted curve with obtained K_I .

An elastic finite element simulation of the surface crack shown in Figure 5.13a with the same geometry under a load of 3800N was carried out in Abaqus software; the SIF values along the crack front were extracted from this simulation in order to verify the SIF values calculated by the Williams series. As shown in Figure 5.15, the K_I values calculated by the contour integral method from the FE simulation varies between 11 and $20 MPa\sqrt{m}$, the values at the part of the crack front intersecting the surface are larger than in the bulk. K_{II} and K_{III} values found in this simulation are on the order of $10^{-2} MPa\sqrt{m}$. Compared to the results calculated using the Williams series, values of K_I exhibit a similar maximum

value ($20 \text{ MPa}\sqrt{m}$) at the end of the crack front; the major difference lies around the middle part of the crack front (15th - 45th Williams plane) which may be caused by the roughness of the crack. The study of V.Maurel *et al.* [MAU 20] has shown that rougher cracks usually have larger SIF values than flat crack at the same tensile load. In the FE simulation, the crack is defined as a flat semi-circle while the experimental crack appears more irregular in the CT images (Figure 5.10j). The K_I values at the middle of the crack front obtained from the FE simulation for the different loading steps can be found in Table 5.2.

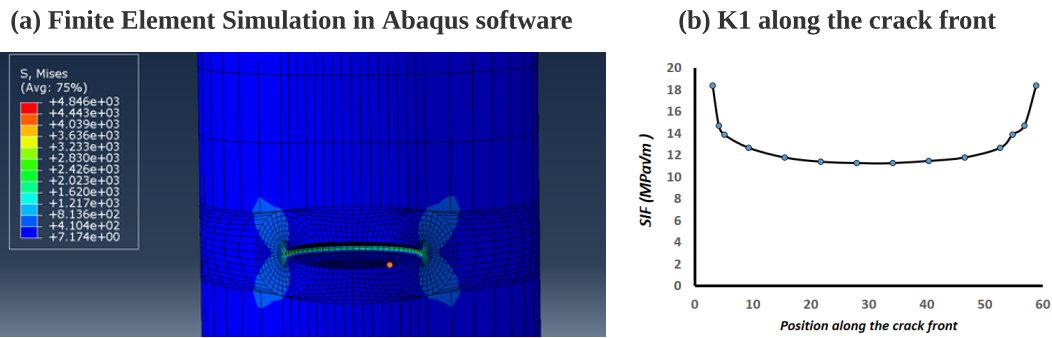


Figure 5.15: Finite element simulation for the surface crack shown in Figure 5.13a with the same geometry under a load of 3800N. (a) 3D view of the simulated stress field (Von-Mises); (b) Stress intensity factor values (K_I) along the crack front.

In summary, the K_I values obtained in the middle of the crack front using the Williams series and CTOD method are in agreement for the different (decreasing) loads investigated. Discrepancies with the elastic 3D FE simulation might be the result of crack roughness and/or a not perfectly aligned sample which might not be loaded under pure tension. In the rest of this section, we believe that the SIF values calculated by the Williams series are reasonable for the experimental/not perfectly flat crack.

Table 5.2: Stress intensity factor values (K_I) at the middle of the surface crack front under different loads calculated by three different methods (FE simulation/ Williams series/ CTOD)

Loads	K_I ($MPa\sqrt{m}$)	K_I ($MPa\sqrt{m}$)	K_I ($MPa\sqrt{m}$)
	FE simulation	Williams series	CTOD
3800N	11.5	18.9	17.9
3050N	9.2	15.2	14.8
2330N	6.9	12.5	11.8
1422N	4.1	6.1	7.6

Crack closure analysis

The surface-free mesh (introduced in Figure 5.9c) without crack enrichment has been used in the DVC calculation using intra-cycle tomography images to obtain COD maps which have not an *a priori* defined cracked area. The resulting COD maps are shown in Figure 5.16 for decreasing load levels. Values of ΔU_z larger than three times the standard uncertainty (0.27 voxel) are considered as 'real' crack opening, so that dark blue area in Figure 5.16 correspond to closed crack area. At 1400N (Figure 5.16d), the closed areas can be observed all along the crack front except for a small portion of the lowermost part, and the corresponding K_I values range from 2 to 9 $MPa\sqrt{m}$. At 2330N, no obvious closed area can be found at crack front, and the K_I values along the crack front vary from 8 to 16 $MPa\sqrt{m}$. Therefore, the value of opening SIF (K_{op}) of such surface crack can be estimated close to 8 $MPa\sqrt{m}$ (plotted as dashed red line in Figure 5.16). For larger loads (3050N versus 3800N), the measured K values increase approximately linearly with the load (except at the 50th williams plane), which can be interpreted as the fact that the crack front is fully open since the 2330N load was attained.

The K_{op} value obtained in this work is larger than that measured by Limodin *et al.* (6 $MPa\sqrt{m}$) [LIM 09]. The following factors can be listed to account for this discrepancy:

- in Limodin's work, the studied samples (section $1.6 \times 1.55mm^2$) were cut from a larger pre-cracked specimen (section $6 \times 4mm^2$) and stress relaxation is suspected to occur during simple preparation which may cause the reduction of the plastic zone resulting in a smaller K_{op} measured;
- in Limodin's work, the studied crack has a length of 350 μm which is smaller than our case (900 μm), and a maximum stress intensity factor used in her work is less than 12.8 $MPa\sqrt{m}$ which is also smaller than our case (20 $MPa\sqrt{m}$).

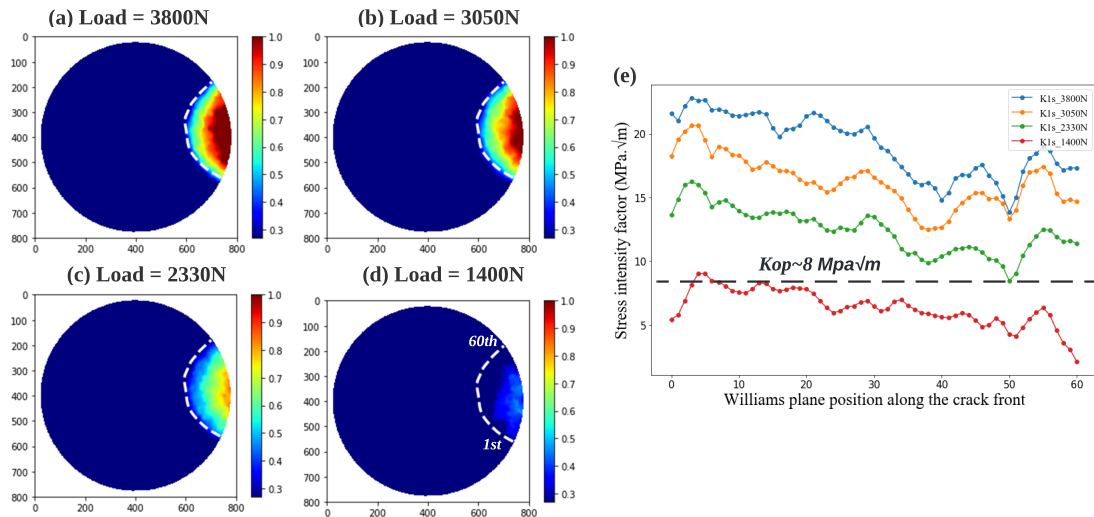


Figure 5.16: (a-d) Maps of crack opening displacement (COD) computed from the surface-free mesh (Figure 5.9c) for decreasing loads (3800N/3050N/2330N/1400N). The crack front is thresholded directly from the projected view of the crack at maximum load (Figure 5.10a) and drawn as a dashed white line. (e) K_I values along crack front calculated by Williams series method for decreasing loads (3800N/3050N/2330N/1400N).

5.3.1.2 Crack closure assessment for an internal crack

An internal artificial defect with a size of 1.7mm has been fabricated in *Sample – internal – 1* by diffusion bonding plates containing a laser machined notch. The crack (initiated from the internal defect) has been first detected in *Sample – internal – 1* after 20,100 cycles at $\sigma_{max} = 280MPa$. In order to obtain a well propagated internal crack, a total of 50,100 cycles were carried out with a scan under maximum load (3500N) every 10,000 cycles. Similar to the case of the surface crack, recording the scans at increasing loads induced some plastic/non-linear behaviour of the sample. Therefore, in this section we present the results obtained with decreasing loads after 50,100 cycles. SIF values obtained at increasing loads ³ after 4,100 cycles are presented and discussed in appendix 5.7 of this Chapter.

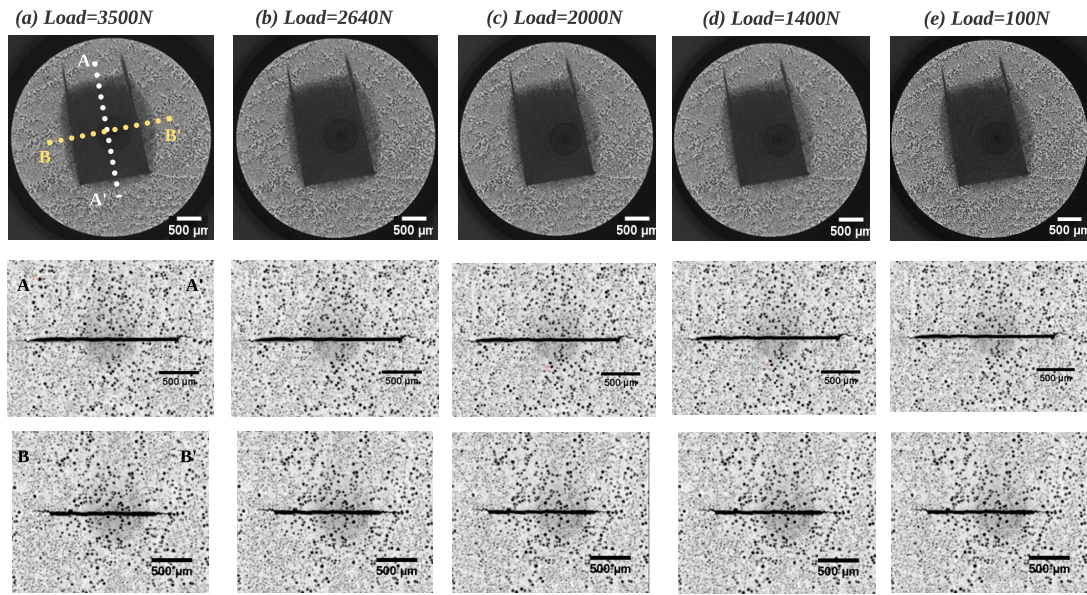


Figure 5.17: Laboratory tomography results of *Sample – internal – 1* after 50,100 cycles of fatigue testing under different loads (imaging conditions can be found in section 5.2.3.2). (a)-(e) Top: projected images of the minimum value of 60 horizontal slices (perpendicular to rotation axis) centered on the crack of *Sample – internal – 1* under a load of 3500N/2640N/2000N/1400N/100N; Mid: vertical reconstructed slices (parallel to the rotation axis) through the dotted white lines (A-A'); Bottom: vertical reconstructed slices (parallel to the rotation axis) through the dotted yellow lines (B-B').

Five different loads (3500N/2640N/2000N/1400N/100N) were used for the scans. As shown in Figure 5.17, after 50100 cycles, the internal crack has initiated from the notch

³where the crack has not yet propagated, but the flat and thin notch can be seen as a crack

and propagated of almost 350 μm along direction B-B'; on the other side, the internal crack has propagated over almost 240 μm along direction A-A' (laser entering from A'). The variation of crack opening at different loads is not obvious. From the gray-scale images, the crack opening of such internal crack is much smaller than the one observed to the surface crack in *Sample – surface – 1* after 12,600 cycles in spite of having similar ΔK_{max} level in both sample ⁴.

Volume correlations

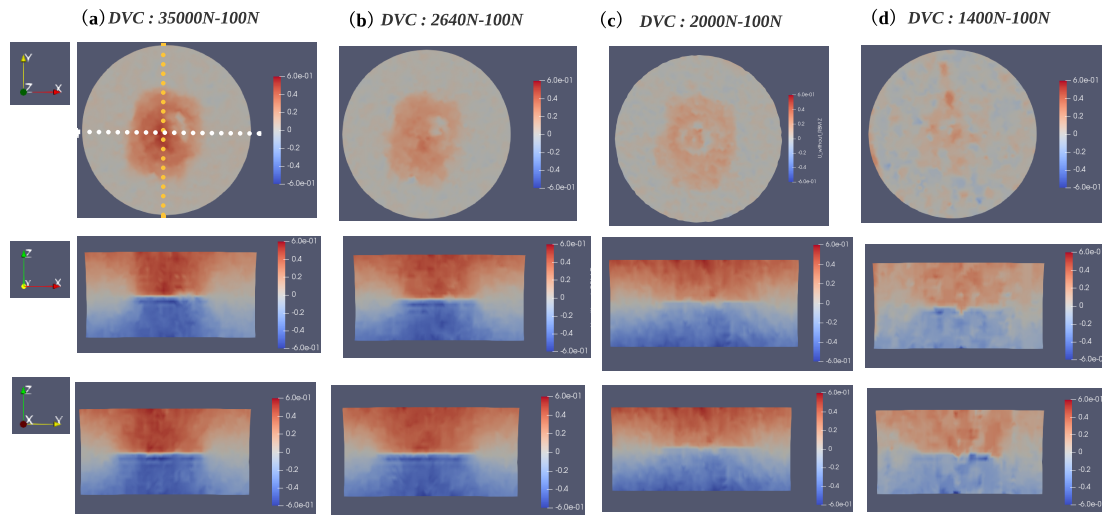


Figure 5.18: Displacement fields in z direction (tensile direction) calculated by the DVC method from the above 5 intra-cycle CT images (shown in Figure 5.17), the 3D image at minimum load has been used as reference. (a)-(d) four different decreasing loads: 3500N/2640N/2000N/1400N, in each group of images: the top image shows the displacement field in the x-y plane (perpendicular to the rotation axis), at the center of the sample; the middle image is in the x-z plane (parallel to the rotation axis), along the dotted white line; the bottom image is in the y-z plane (parallel to the rotation axis), along the dotted yellow line.

The displacement fields around the internal crack can be calculated by the DVC method from the intra-cycle tomography images. The 3D image obtained under minimum load has been used as reference, the results can be found in Figure 5.18. The variation of crack opening displacement (COD) can be observed: the maximum displacement value decreases from 1.21 pixel (6.05 μm) to 0.62 pixel (3.1 μm) as the load decreases. Figure 5.19 shows the distribution of strain around the internal crack. Like in the case of the surface crack, the obtained strains are found to correspond to elastic strains; the regions with the largest strain level are confined to the crack region.

⁴the internal crack has a similar ΔK_{max} (estimated by analytical calculation) as the surface crack

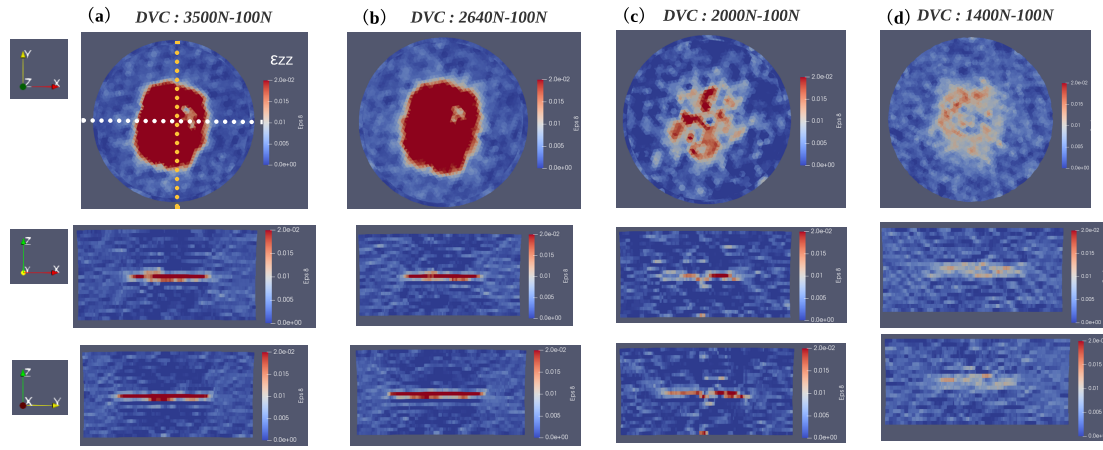


Figure 5.19: Strain fields (ε_{zz} , z corresponding to the tensile direction) calculated by the DVC method from the 5 intra-cycle CT images (shown in Figure 5.17), the 3D image at minimum load has been used as reference. (a)-(d) four decreasing loads: 3500N/2640N/2000N/1400N, in each group of images: the top image shows the strain field in the x - y plane (perpendicular to the rotation axis), at the center of the sample; the middle image shows the strain field in the x - z plane (parallel to the rotation axis), along the dotted white line; the bottom image shows the strain field in the y - z plane (parallel to the rotation axis), along the dotted yellow line.

SIF extraction

The Williams series method has been used to extract the SIF values at the front of the internal crack. Figure 5.20 shows the SIF values at maximum load (3500N), K_I varies between $5-18 \text{ MPa}\sqrt{\text{m}}$. The internal crack exhibits almost a rectangular shape, locally smaller values of K_I can be found at the four corners (B,D,F,H on figure) and locally larger values can be found at the midpoints of the four sides (A,C,E,G on figure), which might explain why the internal crack propagation is faster at the middle of the notch sides and slower at the corners (this can be clearly observed in Figure 5.24a). The values of K_{II} and K_{III} are much lower. K_{II} varying from -2 to $1 \text{ MPa}\sqrt{\text{m}}$ and K_{III} varying from -4 to $4 \text{ MPa}\sqrt{\text{m}}$ with some fluctuations. The SIFs for the other three loads (2640N/2000N/1400N) are given in appendix 5.6, while the values of K_I for different loads at the two mid-points of crack front (A,G marked in Figure 5.20a) can be found in Table 5.3 ⁵.

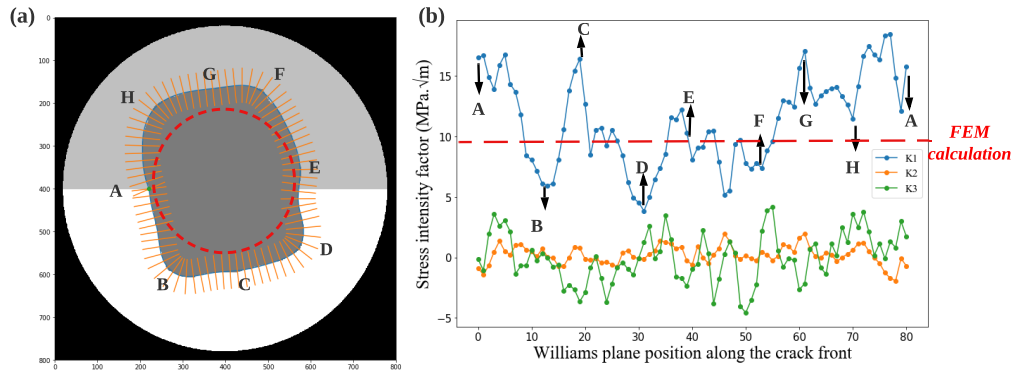


Figure 5.20: Stress intensity factor values corresponding to the maximum load (3500N) along the internal crack front have been computed by Williams series. (a) 80 planes (radius 60pixel) normal to crack front are defined (Williams plane), 4 corners are marked as B,D,F,H and 4 midpoint of the 4 sides are marked as A,C,E,G; (b) Stress intensity factor values along the crack front. The dashed red line in (a) represents the circular crack with a diameter of 1.7 mm in the finite element simulation; the dashed red line in (b) indicates the K_I values along crack front calculated by FEM simulation.

To verify the plausibility of the SIF values along the internal crack front obtained by Williams series, elastic finite element simulations of internal cracks were performed in Abaqus software. Directly using the shape of thresholded crack as input model for simulation increases the complexity of the simulation (meshing problems, convergence of calculation, etc.). Therefore, a circular internal crack with a diameter of 1.7 mm is used to simplify the simulation and save time. The SIF values along the circular crack are uniform

⁵due to the rapid fluctuation of SIF values, the average of three adjacent William plans has been taken

and equal to $9.6MPa\sqrt{m}$ in the case of maximum loads (3500N). The order of magnitude is similar to the average of K_I calculated by Williams series.

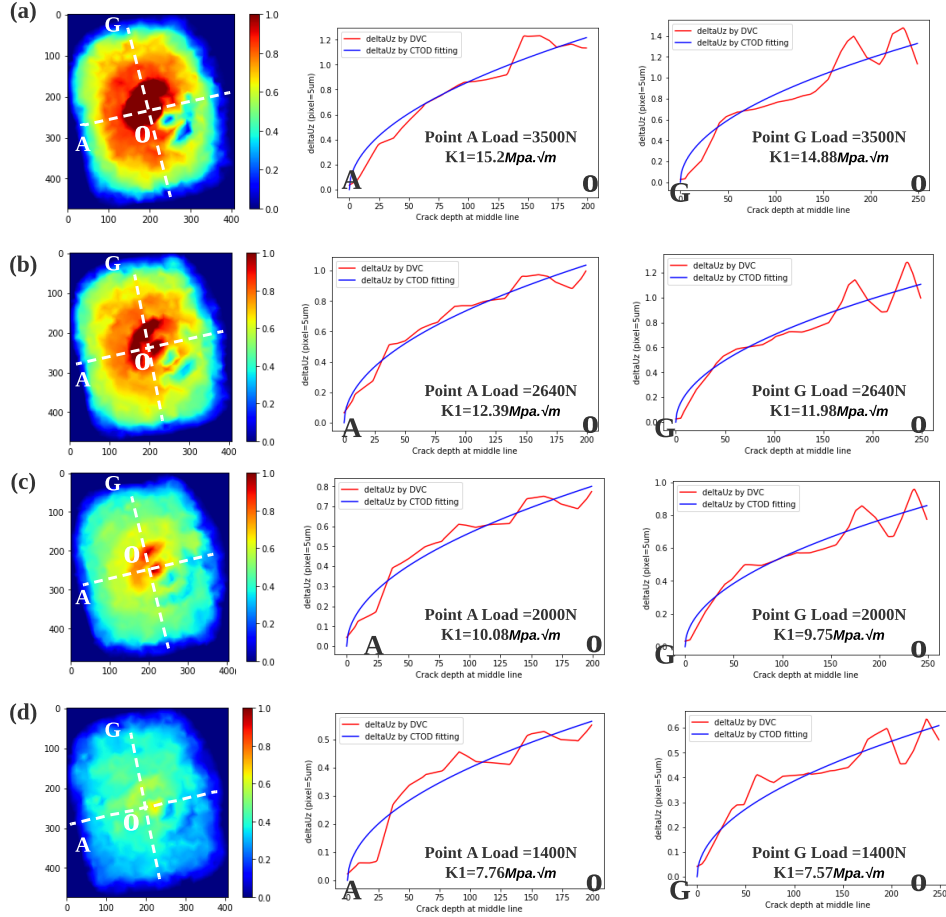


Figure 5.21: (a-d) Left: maps of crack opening displacement (COD) with decreasing loads (3500N/2640N/2000N/1400N), mid: K_I obtained by CTOD fitting along O-A, right: K_I values obtained by CTOD fitting along O-G.

The displacement jumps (ΔU_z) in Mode I have been extracted from the displacement fields (Figure 5.18) for the internal crack. The resulting COD maps for a region of interest containing the crack under different loads have been plotted in Figure 5.21. The profiles ΔU_z from crack center to crack tip were extracted for each loading step along O-A (O is the crack center, A is the midpoint of the left side of the crack) and along O-G (G is the midpoint of the upper side of the crack). K_I values under different loads at point A and G have been calculated by fitting the ΔU_z profiles (Eq 5.3 for plane strain). Their values range between 7.57 and 15.21 $MPa\sqrt{m}$, which is in the range of the values calculated by

the Williams series method.

In summary, the K_I values have been assessed by three different methods. Values obtained by the Williams series and the CTOD method give the same order of magnitude when the analysis is performed using decreasing load steps. The uniform K_I value for the circular crack obtained by a simplified FE simulation is also in reasonable agreement with the average of the K_I values obtained by the Williams series.

Table 5.3: Stress intensity factor values (K_I) at four mid points (A,C,E,G marked in Figure 5.20a) of internal crack front under different loads calculated by three different methods (contour integral in Abaqus software/ Williams series/ CTOD)

Loads	K_I (MPa $\sqrt{m}$)	K_I (MPa $\sqrt{m}$)	K_I (MPa $\sqrt{m}$)
	Contour integral	Williams series	CTOD
	Uniform	A / G	A / G
3500N	9.6	14.9 / 15.4	15.2 / 14.9
2640N	7.2	13.1 / 12.6	12.4 / 12.0
2000N	6.0	11.3 / 10.9	10.1 / 9.8
1400N	4.8	8.2 / 9.1	7.8 / 7.6

Crack closure analysis

The surface-free mesh (introduced in Figure 5.9c) without crack enrichment has been used in the DVC calculation of the intra-cycle tomography images of *Sample – internal – 1* to obtain COD maps which have not an *a priori* defined cracked area. The resulting COD maps are shown in Figure 5.22 for decreasing load levels. Following the procedure used for Figure 5.16, values of ΔU_z larger than three times the standard uncertainty (0.27 voxel) are considered to 'real' crack opening. Dark blue areas in Figure 5.22 indicate a closed crack area. At 1400N (Figure 5.22c), the closed areas can be observed almost throughout all of the crack front, and the corresponding K_I values range between 3-11 $MPa\sqrt{m}$. Therefore, an estimated value of opening SIF (K_{op}) of such internal crack can be given around 10 $MPa\sqrt{m}$ (plotted as dashed red line in Figure 5.16) to match the fact of the majority of the crack front is closed at 1400N. At 2000N (Figure 5.22c), closed areas can be observed at the corners of the crack (e.g. point B and D) where the K_I values are around 5 $MPa\sqrt{m}$; it is quite difficult to determine if the parts of the crack front at point A and point B are open or closed from the COD map. At 2640N (Figure 5.22b), the crack opens at point A and G where the maximum SIF values (K_I) of 12.5 $MPa\sqrt{m}$ are computed; the closed region can be observed at points B and D (i.e. at the corners of the internal crack) with K_I values around 5 $MPa\sqrt{m}$. At 3500N (Figure 5.22a), the crack opens at points A and G where the maximum SIF values (K_I) of 15 $MPa\sqrt{m}$ is given; the closed region can be clearly observed at points B and D with K_I values around 6 $MPa\sqrt{m}$.

In summary, a value of K_{op} closed to 10 $MPa\sqrt{m}$ can be estimated for the internal crack. This value is slightly larger than the value deduced for the surface crack (8 $MPa\sqrt{m}$). In the study of Nadot *et al.* [NAD 97b], the K_{op} values of the same cast iron have been assessed in vacuum and in air respectively giving similar values (5 $MPa\sqrt{m}$ for air and 6 $MPa\sqrt{m}$ for vacuum when $K_{max} = 15 MPa\sqrt{m}$).

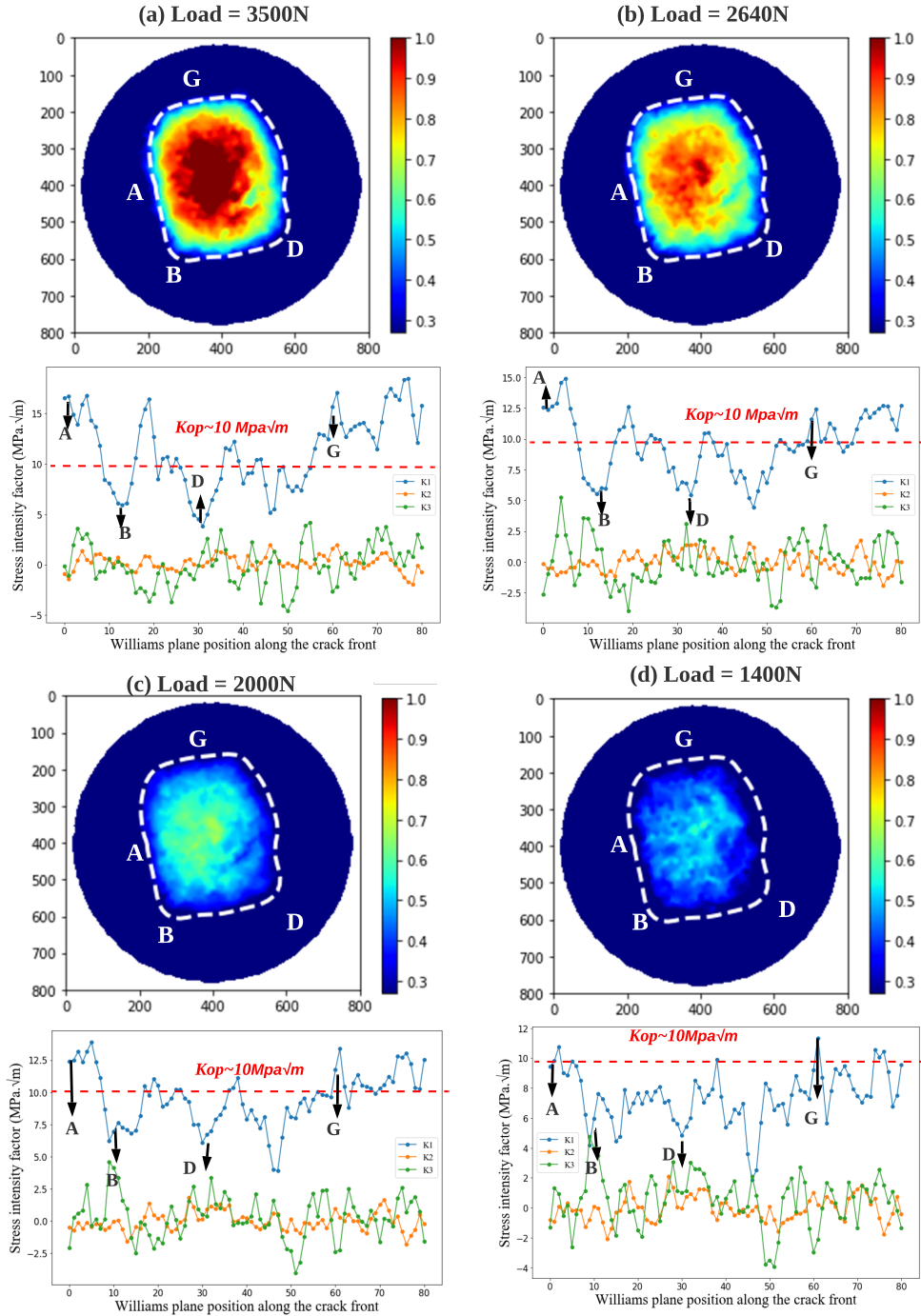


Figure 5.22: (a-d) Upper row: maps of crack opening displacement (COD) computed from surface-free mesh (Figure 5.9c) with decreasing loads (3500N/2640N/2000N/1400N), lower row: SIF values calculated by Williams series method. The crack front is thresholded directly from the projected view of the crack at maximum load (Figure 5.17a) and drawn in dashed white line.

5.3.2 Crack propagation

An ex-situ fatigue test has been performed for *Sample – surface – 1* with $\sigma_{max} = 300\text{MPa}$, tomographic scans under the maximum load of the fatigue test (3800N) have been performed after different number of cycles. The crack growth length at different number of cycles can be measured directly from the 2D vertical slices (containing the rotation axis). The results are shown in Figure 5.23; at the center of the crack front (point: A), the crack propagation length is of the order of 50-60 μm (1-2 nodule distances) after 2000 fatigue cycles passed; at point B, there is no visible crack propagation and at point C, the crack propagates of about 100-120 μm .

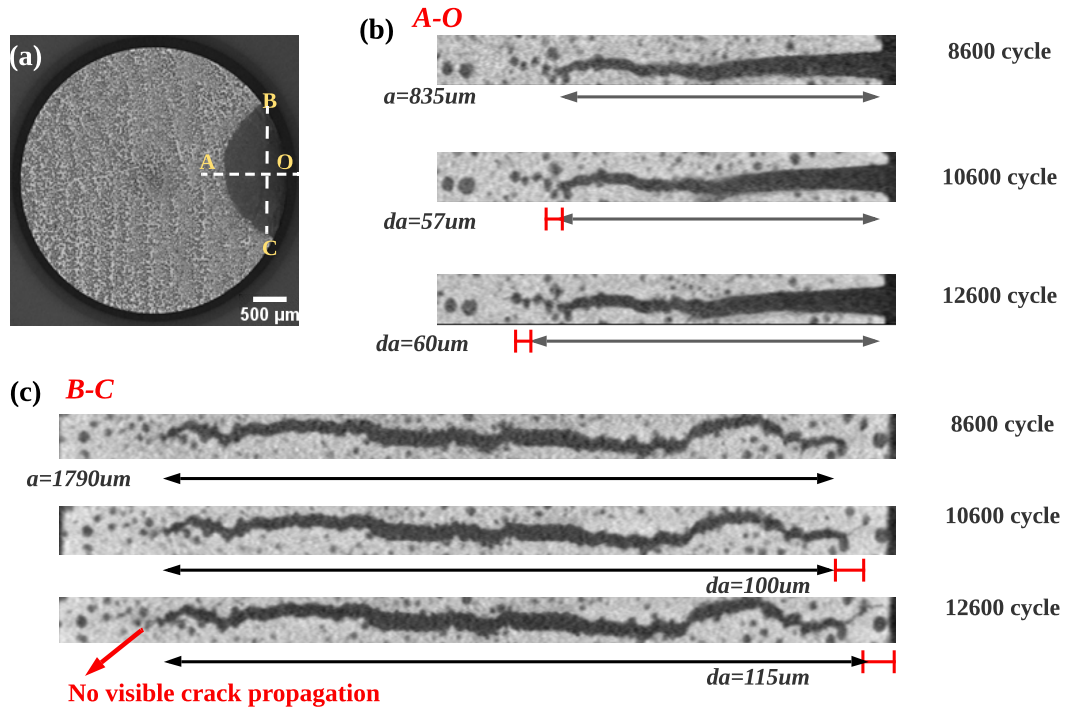


Figure 5.23: Laboratory tomography results of *Sample – surface – 1* after 8600/10600/12,600 cycles of fatigue testing under maximum loads (imaging conditions can be found in section 5.2.3.2). (a) Projected view of the crack after 12600 fatigue cycles; (b) Vertical slices (containing the rotation axis) through the dashed white lines (A-O) marked in (a) for different numbers of cycle; (c) Vertical slices (containing the rotation axis) through the dashed white lines (B-C) marked in (a) for different numbers of cycle.

To characterise the surface crack propagation behaviour, $da/dN - \Delta K_I$ curves are plotted in Figure 5.25.a. No CT scans acquired at minimum load for 8,600 cycles and 10,600 cycles with decreasing load were available (see Table 5.1), thus, the ΔK_I values

on Figure 5.25.a (at three different locations of crack front) are calculated by Williams series for 12,600 cycles. The crack growth behaviour (in air) of the same cast iron has been measured by Nadot [NAD 99] as follows:

$$da/dN = 6.3 \times 10^{-13} \Delta K_I^{4.3} \text{ m/cycle} \quad (5.4)$$

The experimental results of point A and C are in reasonable agreement with the literature data. The crack did not propagate at point B, which may be related to the roughness of the crack.

Ex-situ fatigue tests have also been performed for *Sample – internal – 1* with $\sigma_{max} = 280 \text{ MPa}$ to characterize internal crack propagation. The results can be found in Figure 5.24, on projected images of internal crack, crack propagation can be clearly observed after 30,100 cycles. The lengths of crack growth have been measured from vertical slices (containing the rotation axis) along A-E and C-G (marked in Figure 5.20). The internal crack has similar propagation rates at points A, E, C and G propagating of about 1-2 nodular lengths (30-60 μm) per 10k cycles.

The $da/dN - \Delta K_I$ curves of internal crack are plotted in Figure 5.25.b, like in the case of the surface crack, the ΔK_I values on the figure are calculated by Williams series for 50,100 cycles. At the same level of ΔK_I , internal cracks propagate 5-10 times slower than surface cracks. The crack growth behaviour in vacuum of the same cast iron measured by Nadot [NAD 99] (Eq 5.4) has been plotted to be compared with the measured internal crack propagation behaviour. The measured points are distributed around the vacuum data.

$$da/dN = 8 \times 10^{-15} \Delta K_I^5 \text{ m/ cycle} \quad (5.5)$$

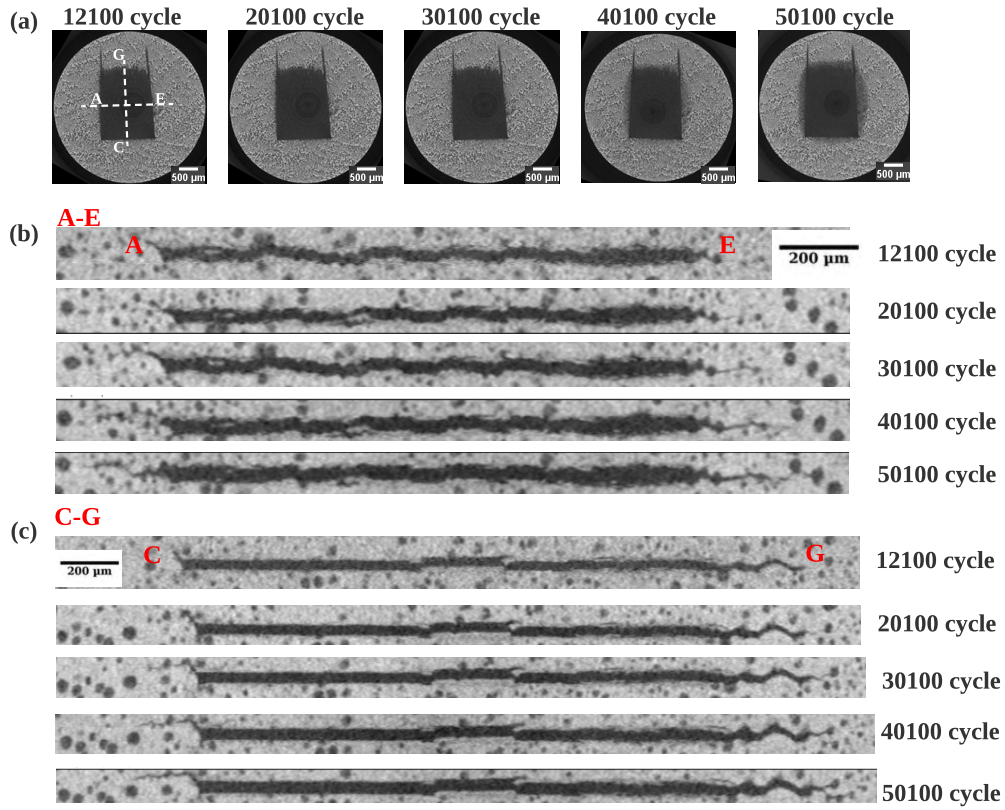


Figure 5.24: Laboratory tomography results of *Sample – internal – 1* after 12100/20100/30100/40100/50100 cycles of fatigue testing under maximum loads (imaging conditions can be found in section 5.2.3.2). (a) Projected view of the crack after 12600/20100/30100/40100/50100 fatigue cycles; (b) Vertical slices (parallel to the rotation axis) through the dashed white lines (A-E same marks with Figure 5.20) marked in (a) for different numbers of cycle; (c) Vertical slices (parallel to the rotation axis) through the dashed white lines (C-G) marked in (a) for different numbers of cycle.

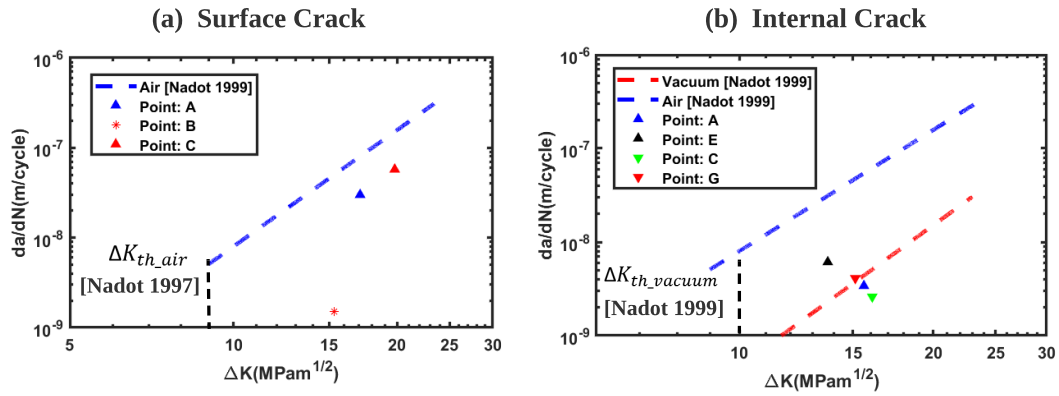


Figure 5.25: $da/dN - \Delta K_1$ curves: measured points and literature data (Nadot 1999 [NAD 99]) of (a) surface crack (*Sample - surface - 1*) and (b) internal crack (*Sample - internal - 1*). The vertical dashed line in (a) show the threshold of SIF for crack propagation in air (ΔK_{th_air}) determined by Nadot [NAD 97a]; in (b) show the threshold of SIF for crack propagation in vacuum (ΔK_{th_vacuum}) [NAD 99].

5.4 Discussion and Future work

As mentioned in the results section, crack closure has been studied in the case of decreasing loads which can eliminate plastic component in the displacement field. But meanwhile, the case of increasing loads has also been tested for both surface crack and internal crack. As shown in Figure 5.26, the opening changes of the surface crack (after 8600 cycles) can clearly be observed in the reconstructed tomography images with increasing loads. When the load is lower than 2330N, the surface crack is barely visible and its opening increases significantly when the load increases from 2330N to 3800N.

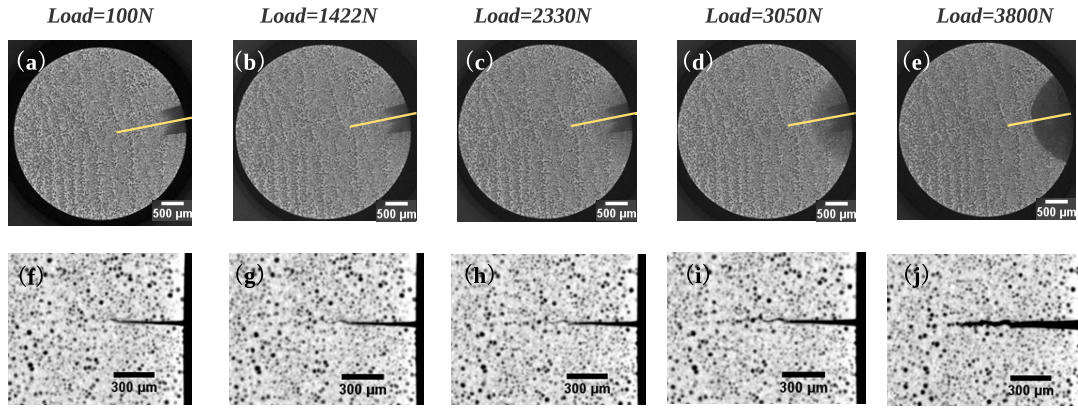


Figure 5.26: Laboratory tomography results of *Sample – surface – 1* after 8,600 cycles of fatigue testing under increasing loads (imaging conditions can be found in section 5.2.3.2). (a)-(e) Projected images of the minimum value of 60 horizontal slices (perpendicular to rotation axis) centered on the crack of *Sample – surface – 1* under 100N/1422N/2330N/3050N/3800N loading; (f)-(j) Vertical slices (parallel to the rotation axis) through the yellow lines marked in (a)-(e).

After 8600 fatigue cycles, *Sample – surface – 1* was removed from the fatigue machine and observed using an optical microscope before undergoing the CT scans. As shown in Figure 5.27a, a crack with much smaller openings ($2 \sim 3 \mu\text{m}$) than the defect were observed on the sample surface. The crack length (on surface) measured from this microscope image is about 1.2 mm, consistent with those measured in the CT images at maximum load (Figure 5.26e). This illustrates the existence of crack in the sample after 8600 fatigue cycles, but no visible crack can be observed in lab CT images until a larger load of 3050N has been employed which shows the limitation of lab CT to observe crack with small opening (close to the voxel size).

The 3D displacement fields measured in the case of increasing loads (Figure 5.26) have been calculated by the DVC method, and the corresponding COD maps are shown in

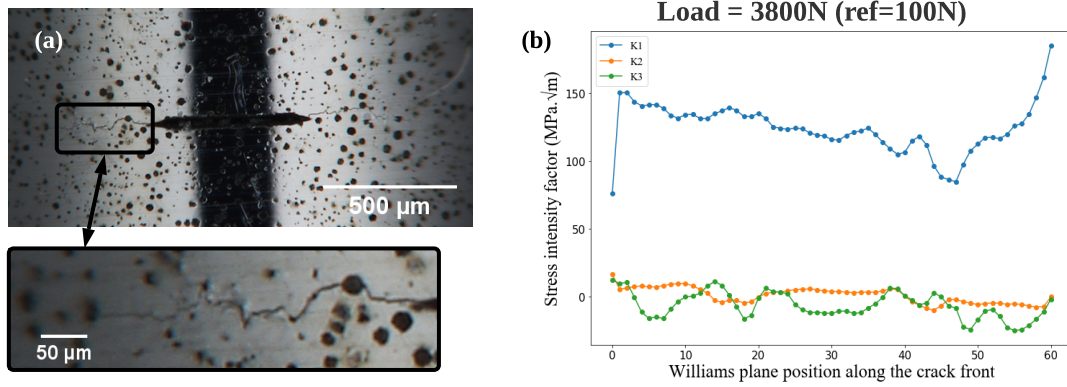


Figure 5.27: (a) Optical microscopy image of *Sample – surface – 1* after 8,600 cycles of fatigue testing; (b) Stress intensity factor values along the crack front corresponding to the maximum load (3800N-100N) computed by Williams series with increasing loads.

Figure 5.28. The crack COD changes increases when the load increases (Figure 5.28e), with a sudden jump at the last step, where the COD increases from 2 pixels (10 μm) to 7 pixels (35 μm). This is quite different from the crack closure phenomenon in the case of decreasing loads (Figure 5.14). From Eq 5.3, it can be inferred that a large crack COD value leads to a large SIF value (K_I). As shown in Figure 5.28d, when the load reaches 3800N, the calculated value of K_I at mid crack front equals $74.26 \text{ MPa}\sqrt{\text{m}}$ which is considerably larger than the value obtained from elastic FE simulation ($11.5 \text{ MPa}\sqrt{\text{m}}$) and than the value obtained during unloading ($18.9 \text{ MPa}\sqrt{\text{m}}$). For smaller loads (1400N and 2330N), the difference between the calculated and simulated SIF value becomes smaller (green curve in Figure 5.28a and b).

SIF values (K_I) corresponding to increasing load steps have also been computed by the Williams series method. The K_I value corresponding to the maximum load (3800N) along the crack front is displayed in Figure 5.27b, ranges between 80 to $180 \text{ MPa}\sqrt{\text{m}}$ which is about 10 times larger than the values obtained with decreasing loads and obtained by FE simulation. SIF values for other increasing loads can be found in Figure 5.32 (Appendix 5.32). The differences in SIF value may be due to the presence of a plastic zone. Strain fields within *Sample – surface – 1* after 8,600 fatigue cycles obtained by DVC are shown in Figure 5.29; highly deformed zones with typical butterfly shape corresponding to zones where ε_{zz} is larger than 0.02 can be observed around the crack front for the larger loads (3050N and 3800N). A similar phenomena has been observed for the internal crack in

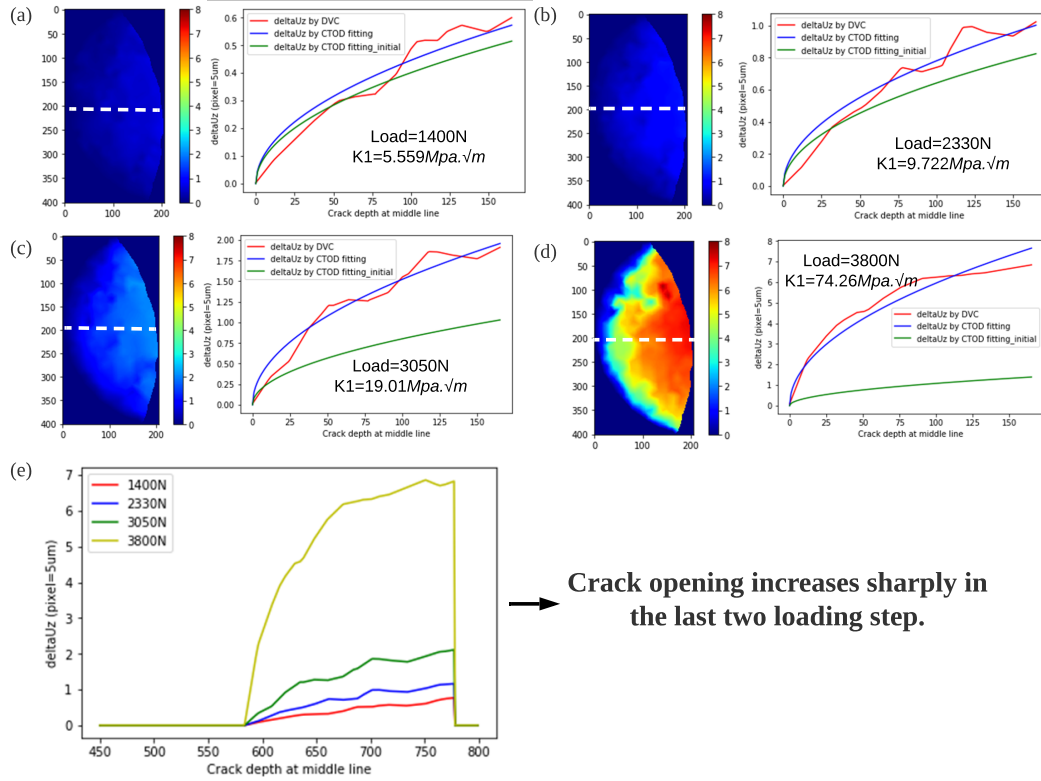


Figure 5.28: (a-d) Left: maps of crack opening displacement (COD) with increasing loads, right: SIF (K_I) values obtained by CTOD fitting (introduced in section 5.2.4), the red curve corresponds to the COD profile along the dashed white line, the green curve corresponds to simulated results in *Abaqus*, the blue curve corresponds to the fitted curve; (e) Profile of crack opening displacement along the crack depth (at mid crack front as indicated by the dashed white line) with increasing loads. The same results but for decreasing load steps are shown in Figure 5.14.

Sample – internal – 1 after 4100 fatigue cycles⁶ with increasing loads. DVC results as well as measurement of SIF values at different increasing loads can be found in Appendix 5.7.

As mentioned in the method section (Figure 5.3), the uni-axial tensile behaviour of the treated material has been measured. A large area ($r \approx 0.5mm$) of plasticity is observed at maximum load, these areas exhibit strain in the tensile direction larger than 2%. The tensile behaviour of the material is shown in Figure 5.30. It can be observed that between 3050N and 3800N corresponding to stress between 240 and 300 MPa, the stress-strain

⁶no propagated crack were observed, but thin artificial notch can be regarded as a crack

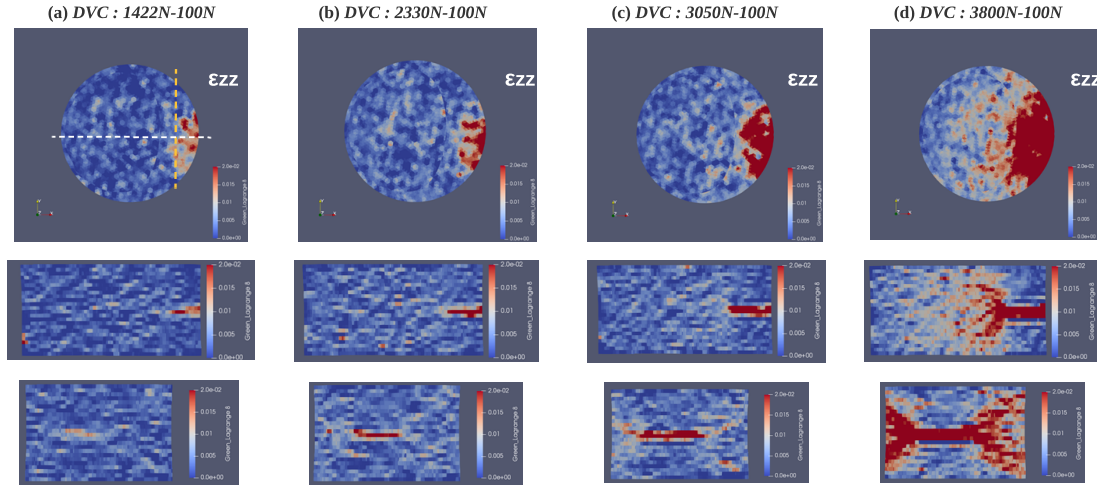


Figure 5.29: ε_{zz} strain fields (z corresponding to the tensile direction) calculated by the DVC method from 5 intra-cycle CT images (increasing loads) (shown in Figure 5.26), the 3D image at minimum load has been used as reference. (a)-(d) correspond to the four increasing loads: 1422N/2330N/3050N/3800N, in each group of images: the top image shows the strain field in the x-y plane (perpendicular to the rotation axis), at the center of the sample; the middle image shows the strain field in the x-z plane (parallel to the rotation axis), along the dashed white line; the bottom image shows the strain field in the y-z plane (parallel to the rotation axis), along the dashed yellow line.

curve is clearly in the plastic region. When calculating K_I using the CTOD method or the Williams series method, an elastic behaviour is assumed, which results in extremely large calculated K_I values. By contrast, the unloading phase (B-D) is completely linear so that K_I values can be correctly measured during unloading.

However, a remaining question is why the actual measured plastic region ($r \sim 0.5mm$) is much larger than the one obtained by the finite element simulation ($r \sim 0.27mm$ in Figure 5.4). One possible explanation is that when loading was applied during the lab CT scan, some bending may have been produced because the heads of specimen were held in place by long threaded rods (Figure 5.7). Due to the bending load, the crack opening increases, so the stress intensity factor (K_I) at the crack tip increases and the extent of the plastic zone increases. This effect has been shown by Langlois *et al.* who performed a systematic analysis of the effect of tensile boundary conditions on the calculation of crack stress intensity factor (K_I) [LAN 20b]. In this study, two different loading conditions have been tested using finite element simulation. The first one is a uniform vertical displacement applied on the upper and lower surfaces of the studied sample (called type 1) which might correspond to the case of the ex-situ fatigue test (Figure 5.6) in our work. The second one is a uniform pressure applied on the upper and lower surfaces (called type 2) which

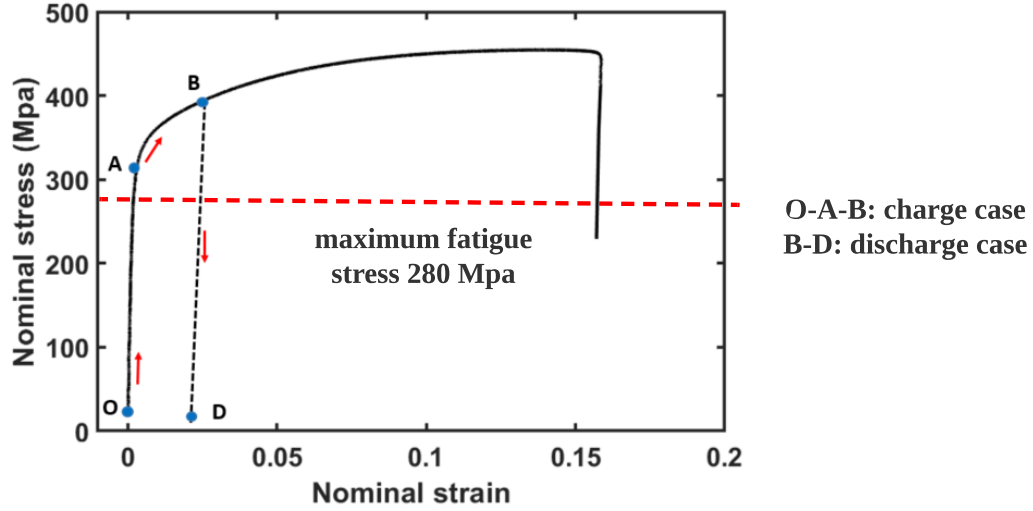


Figure 5.30: Uni-axial tensile behaviour of the studied material after the SPS cycle. O-A-B corresponds to the increasing loading steps in the tomograph, B-D corresponds to discharge case. The dashed red line indicates the maximum fatigue stress 280MPa .

might correspond to the case of the loading during lab CT (Figure 5.7) in our work. From the simulation results in [LAN 20b], type 1 produces lower SIF values compared to type 2. This is due to the fact that for type 1 the overall bending of the specimen is prevented thus leading to lower crack opening values and subsequently lower SIF values than for type 2 for which the two end sections are free to rotate. Observation of the bending of specimen under the load during lab CT should be carried out using DVC in the future. However, an obvious difficulty is that for detecting a potential bending of the samples, a much larger ROI will be needed. Increasing the voxel size may be a solution, but this might lead to less accurate results from DVC.

When unloading and removing the specimen from the fatigue machine. The risk of applying a compressive load cannot be excluded; this would lead to a reduction in crack opening in the reconstructed image of the first few loading steps in the increasing load case.

In short, the present ex-situ experimental procedure might bring some uncertainties of the results in the case of increasing loads ⁷, and a improved in-situ experimental solution may be more preferable in the future. As shown in Figure 5.5b, internal defect with a

⁷in case of decreasing loads, the plastic components in the displacement field have been eliminated

size of $1\text{mm} * 1\text{mm}$ have been successfully produced. It was found in the experiment (Table 5.1) that under the maximum fatigue stress of 300 MPa, an internal crack within *sample – internal – 2* has initiated and propagated after 16800 cycles. The existing *in-situ* fatigue machine adapted for Vtomex has a maximum tension of 2000N. Thus, the in-situ experiment might be possible in future work by reducing the specimen diameter to 2.5 mm.

5.5 Conclusion

Internal cracks were manufactured by diffusion bonding plates containing a laser machined sharp notch (same method as in [JUN 19]). By comparing hardness, grain size, nodules size and tensile properties of post-bonded material and initial material, it was concluded that the bonding procedure used in this work does not change the micro-structure nor the mechanical properties.

Ex-situ fatigue tests have been performed in this work: the fatigue tests have been carried out at room temperature using a servo-hydraulic fatigue testing machine; after a given number of cycles, the cracked samples were removed from this machine and installed inside a tensile machine in the tomograph to be scanned under different loads. The laboratory tomography used in MATEIS has a voxel size limited to $2.5\text{ }\mu\text{m}$ by our specimen diameter which impedes to measure the crack opening displacement directly from the gray-scale image. The Digital Volume Correlation (DVC) technique developed by J.Lachambre *et al.* [LAC 14] has been used in this work to characterize fatigue cracks with sub-voxel opening.

First, in order to validate our method, **a surface crack** was studied and compared to the work of N.Limodin *et al.* on the same type of material. Five different (decreasing) loads (3800N/3050N/2330N/1422N/100N) were used for the scans of *Sample – surface – 1* after 12,600 cycles. SIF values along the surface crack front have been extracted using Williams series, an elastic FE simulation and CTOD measurements. The three different methods give a consistent value for the different (decreasing) loads. COD maps (ΔU_z) have been computed using the DVC calculation with surface-free mesh. By comparing the part of the cracks which are open under load (ΔU_z larger than three times the standard uncertainty) with the crack front thresholded from the projected gray-scale image at maximum load, an estimated value of K_{op} around $8\text{ MPa}\sqrt{m}$ is obtained.

Secondly, **an internal crack** has been studied using the same method. The K_I values obtained by the Williams series and the CTOD method are in the same range. The uniform K_I value for the circular crack with same diameter obtained by simplified FE simulation is similar to the average of the K_I values obtained by Williams series. By comparing

the part of the cracks which are open under load with the crack front thresholded from the projected gray-scale image at maximum load, an estimated value of K_{op} around $10 \text{ MPa}\sqrt{\text{m}}$ is obtained.

Crack propagation was characterised for the surface and the internal crack. $da/dN - \Delta K_I$ curves of surface crack and internal crack are plotted in Figure 5.25. It was found that, at the same level of K_I , internal cracks propagate 5-10 times slower than surface cracks. The points obtained for the surface crack are close to the literature data [NAD 99] for propagation in 'air' for the same cast iron while the points measured for the internal crack are close to the literature data for propagation in 'vacuum'. Internal cracks propagate more slowly than surface cracks possibly due to the effect of the vacuum environment.

In the discussion, the DVC results obtained with increasing loads have been shown for both surface crack and internal crack. Unrealistic large SIF values were computed for both types of cracks. This is likely to be caused by plasticity. A plastic zone with a radius of about 0.5 mm was observed by DVC close to both surface and internal crack. The sizes of the actual measured plastic zones are larger than those predicted in the FE simulation. This may be due to the bending of the specimen during loading in lab CT [LAN 20b] or accidental compression when the specimen was removed from the fatigue machine.

5.6 Appendix: SIF values calculated by Williams series along the crack front for the different loading step

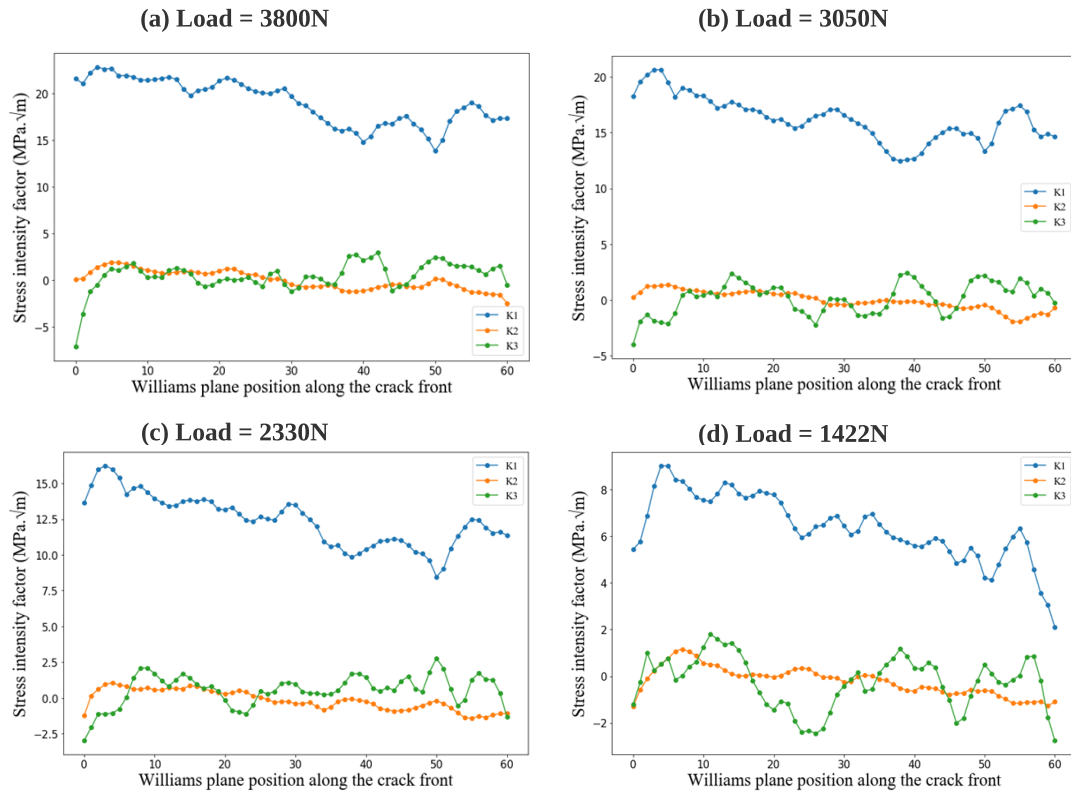


Figure 5.31: Stress intensity factor values along the surface crack front (*Sample – surface – 1* after 12,600 cycles) computed by Williams series for decreasing loading steps (discharge case): (a) load = 3800N; (b) load = 3050N; (c) load = 2330N ; (d) load =1422N.

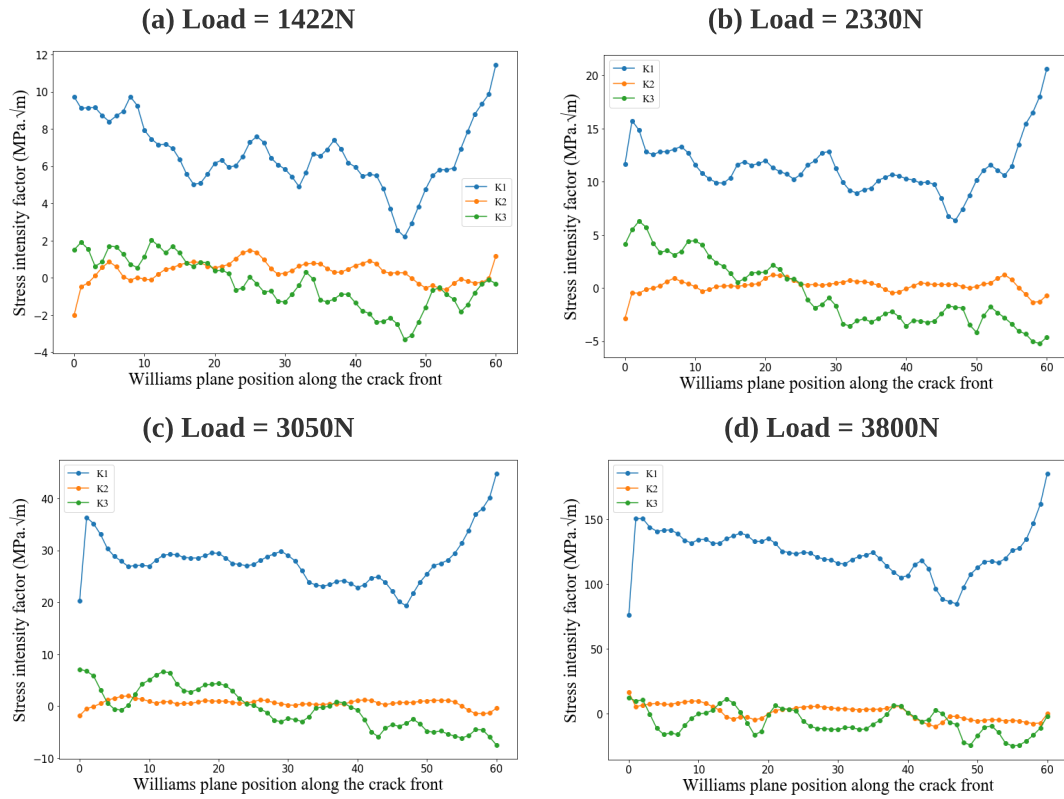


Figure 5.32: Stress intensity factor values along the surface crack front (*Sample – surface – 1* after 8,600 cycles) computed by Williams series for increasing loading steps (charge case): (a) load = 1422N; (b) load = 2330N; (c) load = 3050N ; (d) load = 3800N.

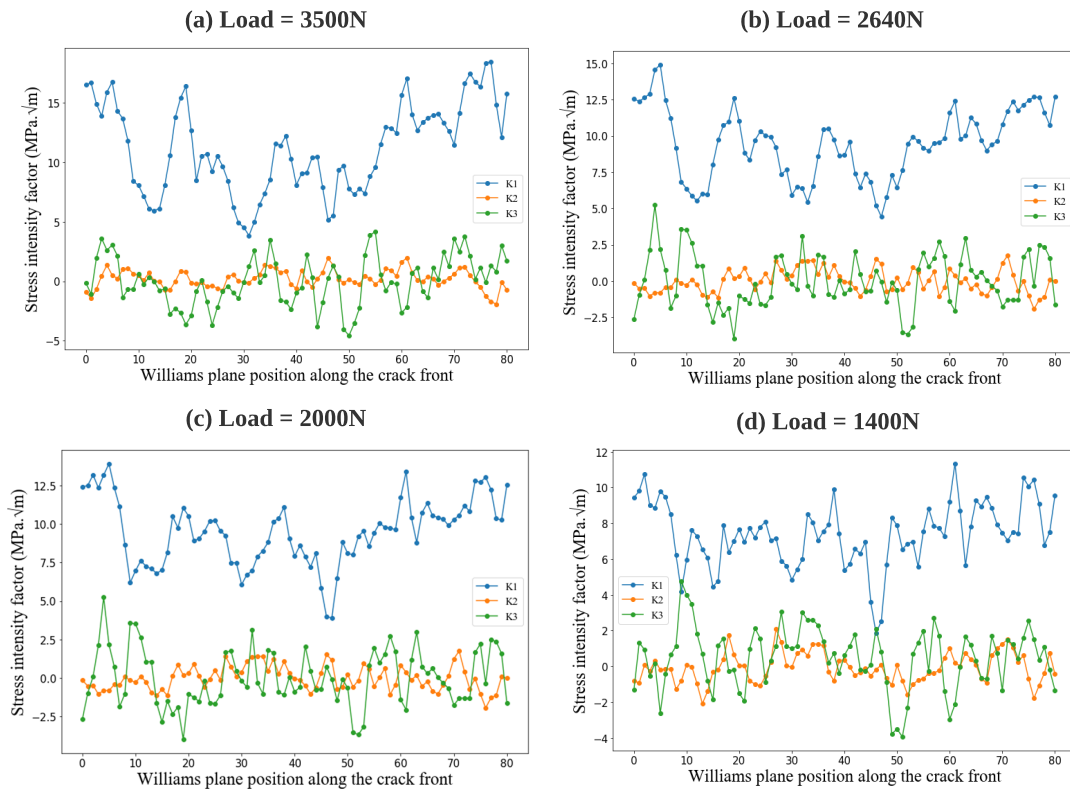


Figure 5.33: Stress intensity factor values along the internal crack front (*Sample – internal – 1* after 50,100 cycles) computed by Williams series for decreasing loading steps: (a) load = 3500N; (b) load = 2640N; (c) load = 2000N; (d) load = 1400N . The corresponding positions of crack front is shown in Figure 5.20.

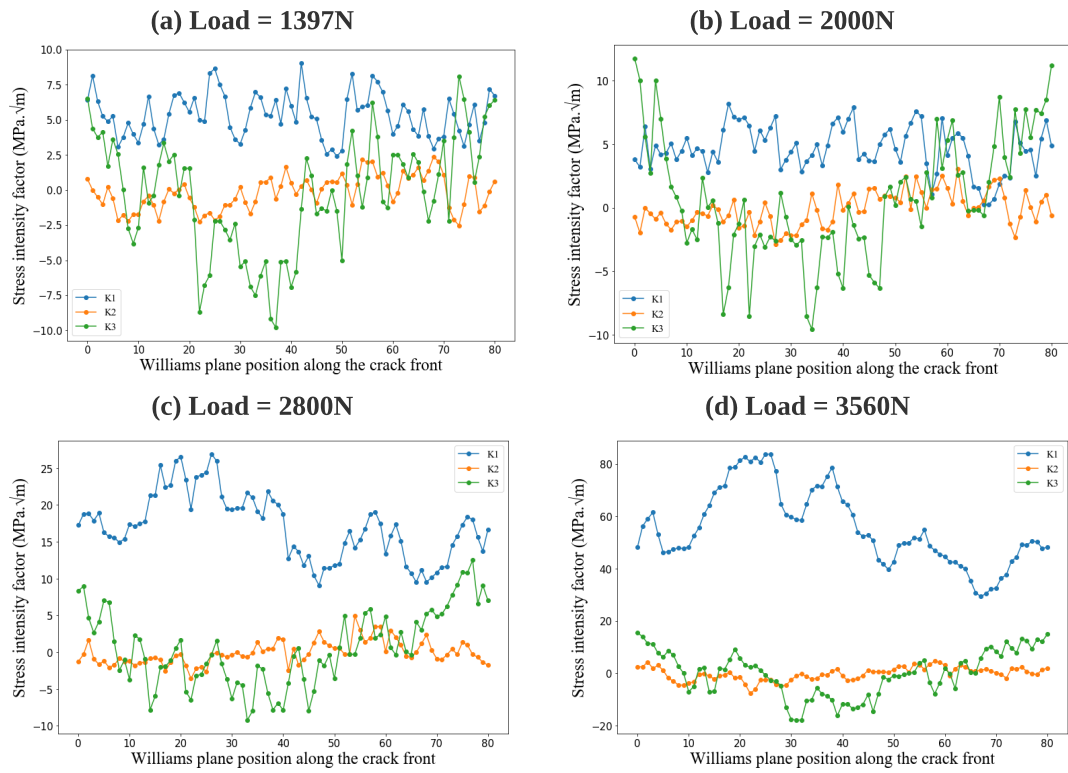


Figure 5.34: Stress intensity factor values along the internal crack front (*Sample – internal – 1* after 4100 cycles) computed by Williams series for increasing loading steps: (a) load = 1397N; (b) load = 2000N; (c) load = 2800N ; (d) load = 3560N. The corresponding positions of crack front is shown in Figure 5.36.

5.7 Appendix: DVC results of internal crack with increasing loads

This section shows the laboratory tomography DVC results of *Sample – internal – 1* after 4100 cycles (no cracks is observed) with increasing loads. As shown in Figure 5.35, although no crack is observed, the defect opening increases significantly with increasing loading during the lab CT, especially in the last two loading steps. The thin and flat defect is regarded as a crack in this case.

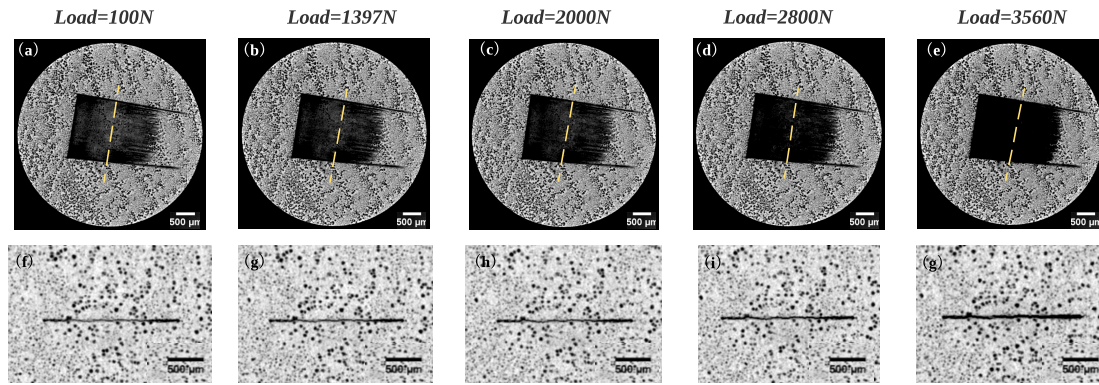


Figure 5.35: Laboratory tomography results of *Sample – internal – 1* after 4,100 cycles of fatigue testing under increasing loads (imaging conditions can be found in section 5.2.3.2). (a)-(e) Projected images of the minimum value of 60 horizontal slices (perpendicular to rotation axis) centered on the crack of *Sample – internal – 1* under 100N/1397N/2000N/2800N/3560N loading; (f)-(j) Vertical slices (parallel to the rotation axis) through the yellow lines marked in above Min-z-projects in (a)-(e).

The SIF values along the front of the internal crack in the increasing loading case have been calculated using Williams series. The K_I corresponding to the maximum load (3560N) along the crack front has been plotted in Figure 5.36b. It varies between 30 and 80 $MPa\sqrt{m}$ which is about 5 times larger than the values obtained with decreasing load steps. SIF values obtained for other increasing load can be found in Figure 5.34.

K_I values of the internal crack have also been calculated by the CTOD method for increasing loads. As shown in Figure 5.37c, at 3560N, the calculated values of K_I at middle points of both sides of crack front are about 30 $MPa\sqrt{m}$ which is 3 times larger than the simulated value (9.6 $MPa\sqrt{m}$). For smaller loads (2800N and 1397N), the difference between the calculated and simulated values becomes much smaller (Figure 5.37a and b).

The strain fields of the internal crack with increased loads have been plotted in Figure 5.38. A plastic zone with a size of 0.5 mm (read area indicates regions where ε_{zz} is larger than 0.02) can be observed around the crack front for the largest load (3560N).

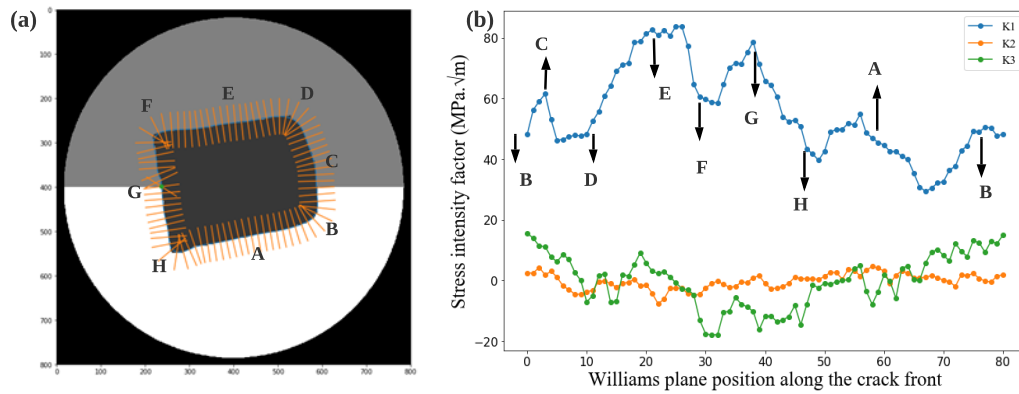


Figure 5.36: Stress intensity factor values computed at maximum load (3500N) at increasing load steps along the internal crack front have been computed by Williams series. (a) 80 planes (radius 60pixel) normal to the crack front are defined (Williams planes). The 4 corners of the notch are labelled as B,D,F,H and 4 midpoint of the 4 sides are labelled as A,C,E,G; (b) Stress intensity factor values along the crack front.

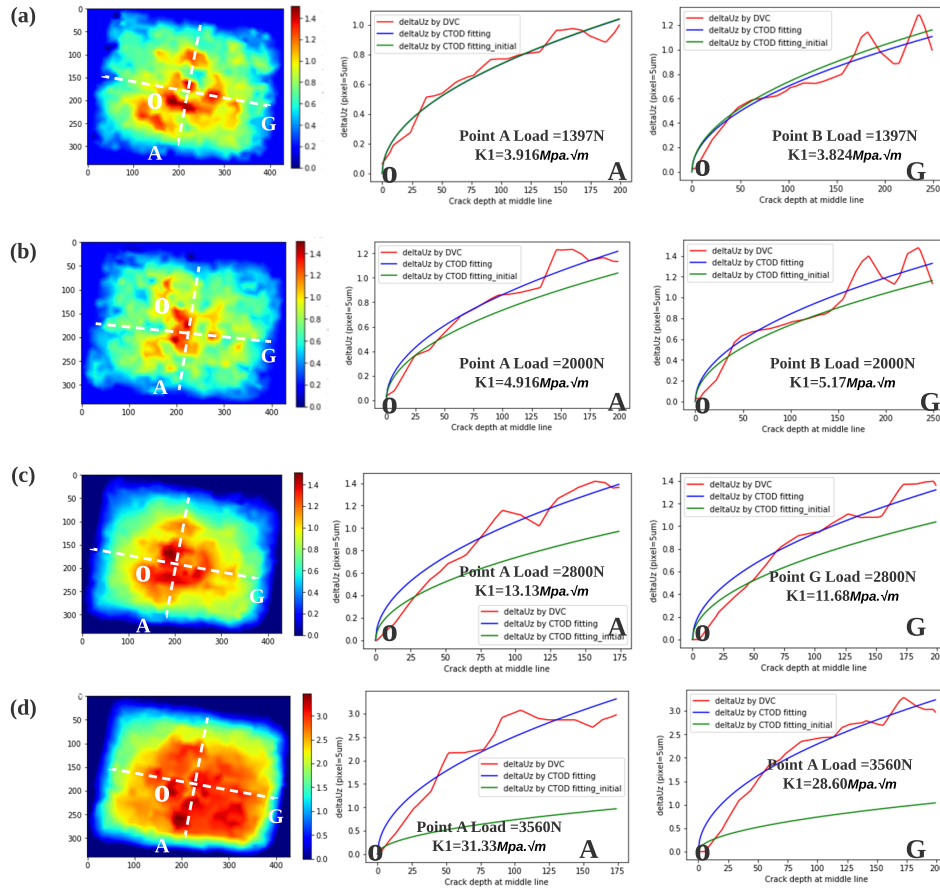


Figure 5.37: (a-d) Left: maps of crack opening displacement (COD) with increasing loads (1397N/2000N/2800N/3560N), mid: K_I SIF fitting by CTOD method along short side (O-A), right: K_I SIF fitting by CTOD method along long side (O-G).

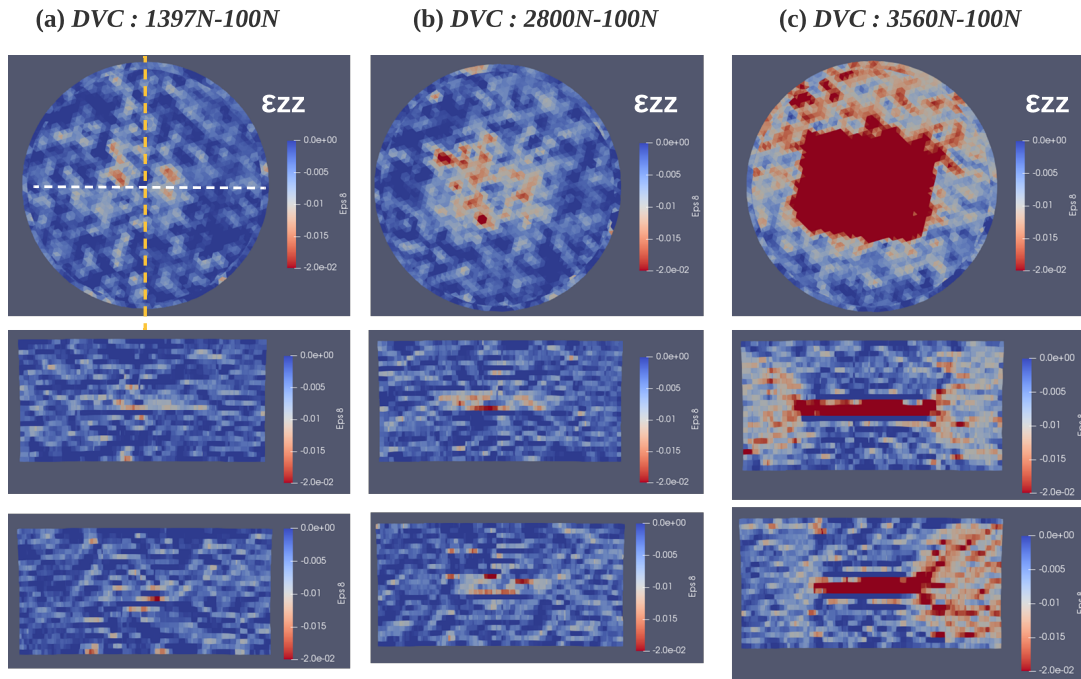


Figure 5.38: ε_{zz} strain fields (z corresponds to the tensile direction) calculated by the DVC method from 4 intra-cycle CT images (increasing load steps) (shown in Figure 5.35), the 3D image at minimum load has been used as reference. (a)-(c) correspond to the four increasing loads: 1397N/2800N/3560N, in each group of images: the top image shows the strain field in the x-y plane (perpendicular to the rotation axis), at the center of the sample; the middle image shows the strain field in the x-z plane (parallel to the rotation axis), along the dashed white line; the bottom image shows the strain field in the y-z plane (parallel to the rotation axis), along the dashed yellow line.

5.8 Appendix: Supplementary images

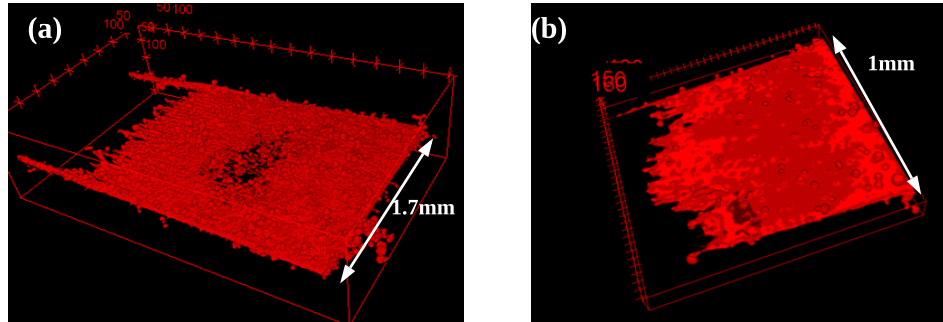


Figure 5.39: 3D rendering of the notch machined by Laser with: (a) a size of 1.7mm, (b) a size of 1mm.

Conclusion and Perspectives

In this PhD thesis we have investigated the application of x-ray tomography for the 3D characterization of fatigue cracks within metals. The study was mainly divided into three parts: 1) developing adapted crack segmentation methods for laboratory tomography images and synchrotron tomography images respectively to obtain more complete and continuous 3D crack images; 2) investigating the sources of two specific artifacts (streak artifacts and wrinkled artifacts) in phase contrast synchrotron images, and understanding the variation of gray-level of pixels belonging to cracks with crack size through phase contrast tomography simulations and experiments; 3) characterizing the closure of internal fatigue cracks in cast iron by DVC on laboratory tomography images.

Developed methods to segment complete 3D fatigue crack images from laboratory tomography and synchrotron tomography images

In a reconstructed 3D image, fatigue cracks can be quite difficult to threshold when their opening is low, particularly in the case of laboratory tomography. Several approaches developed for bones [LAR 11] or concrete [CHA 18] have been merged for thresholding fatigue cracks in lab CT. As a result, a Hessian matrix approach coupled with a series of bilinear filters are used to detect flat cracks which appear in low-contrast in the lab CT images.

In the case of synchrotron tomography, the thresholding process is made more complex by the coherence of the X-ray beam which produces diffraction effects and artifact at the crack edges. We have proposed a deep learning method which uses a U-net network to replace human intervention during thresholding. By manually segmenting a limited amount of images (less than 2%) the software can be efficiently trained to detect cracks from synchrotron tomography images as judged by human mind. The probability map obtained from the neural network is further thresholded using the algorithm developed for laboratory CT images. Finally, without supplementary training, 3D images of the propagation of a crack acquired during an in situ fatigue test have been successfully thresholded,

showing the possibility to automatize the process.

Characterization of internal fatigue cracks and streak artifacts in Al alloy in synchrotron tomography images

In Al alloys (e.g. $AlSi_7$), internal fatigue cracks grow along crystallographic planes; their surfaces form very planar facets with dimensions of the order of several 100 micrometers [SER 16]. In phase contrast 3D images of those cracks, some streak artifacts similar to the flat crack appear because of the diffraction effects of the coherent X-ray beam. Simulations of phase contrast tomography based on a Fresnel propagator have been performed in Gate software [LAN 20a] to better identify and characterize internal fatigue cracks and artifacts. Through the simulation results, it was found that the streak artifacts always appear on both ends of the flat crack segments even when the crack is invisible. Further, in changing the size of the cracks in the simulation it has been found that the length/opening of the crack has little effect on the streak artifact and determines the grey-value of the crack in the reconstructed image. The contrast in gray value of the crack increases with the increase of opening, and decreases with the increase of the crack length. The sources of streak artifacts might be Fresnel diffraction [BRO 02] on the detector. The experimental images were reanalyzed using the results obtained from the simulation. The cracks in horizontal slices (perpendicular to rotation axis) appear as dark or with low contrast to the point of invisibility, and the strong contrast bright parts that appear at their ends are all artifacts. It is worth emphasizing that the artifacts can help to locate the invisible cracks segments. In vertical slices (parallel to rotation axis), the streak artifacts no longer appear at the ends of the flat crack segments; instead, they appear in the same position in the adjacent slices before and after, and take on the same shape as the crack; meanwhile, invisible cracks cannot be observed in a single vertical slice. Using the above information, the U-net deep learning method [XIA 21a] has been used to successfully threshold the invisible cracks using the artifacts at its both ends.

Investigation of wrinkled artifact in phase contrast synchrotron tomography images

Images reconstructed with the classical Filtered Back Projection (FBP) algorithm show interference fringes whenever a phase discontinuity appears in the studied sample allowing for example to detect cracks with small (sub-voxel) opening [CLO 99]. In practice, however, the presence of noise-like irregular diffraction fringes (called wrinkled artifact in this work) can somewhat complicate the quantitative analysis of the 3D images. To investigate the source of the wrinkled artifact and find some ways to reduce them, phase contrast to-

mography simulations (based on a Fresnel propagator and implemented in Gate software [LAN 20a]) have been performed and experiments have been carried out at ESRF to validate the results obtained.

Firstly, through simulations of simple geometry cracks (flat crack, triangle crack, step-like crack), wrinkled artifacts were identified in the reconstructed images of the simulations. Simulations with image based cracks have been performed for varying scan conditions. It was observed that reducing the detector-object distance and increasing the X-ray energy and avoiding incident beam parallel to the crack surface by inclining the specimen are effective ways of reducing the wrinkled artifacts. Finally, experimental phase contrast tomography of cracked specimens in Al alloys (Al-Cu-Li) and Ti alloys (Ti-6Al-V) have been performed at ESRF ID11 under different detector-object distances and orientations which validate the simulation results.

Closure of internal fatigue cracks in cast iron

Digital Volume Correlation (DVC) was used to measure displacement fields in a cracked metallic sample at the sub-pixel scale. From the measured displacement field, the stress intensity factor values along the crack front can be calculated by a CTOD method (used in [LIM 09]) and a Williams series method (used in [LAC 14]). Internal cracks were obtained from controlled internal defect manufactured using the same method as that used in Ti alloys in [JUN 19]. By diffusion bonding plates with laser machined sharp notches, internal defects can be successfully fabricated without changing the micro-structure and mechanical properties of cast iron.

First, a specimen (*sample – surface – 1*) with a surface crack has been characterised during an ex-situ fatigue test. SIF values along the surface crack have been extracted using Williams series, elastic FE simulation and CTOD method. The three different methods give a consistent value in the middle of the crack front. By comparing the parts of the cracks which are open with the crack front thresholded from the projected gray-scale image at maximum load, an estimated value of K_{op} is given around $8 \text{ MPa}\sqrt{m}$.

Secondly, an internal crack has been studied using the same method. The SIF values obtained by Williams series and CTOD method are in the same range. By comparing the part of the crack which remains open under load with the crack front thresholded from the projected gray-scale image, at maximum load an estimated value of K_{op} for internal cracks is given around $10 \text{ MPa}\sqrt{m}$.

In addition, the internal and surface cracks were scanned after different number of fatigue cycles to characterize crack propagation. At the same level of K_I , internal cracks were found to propagate 5 to 10 times slower than surface cracks.

Perspectives

3D U-net and RNN

A deep learning method (U-net) has been used in this PhD work to segment 3D crack images from synchrotron tomography images. The trained model successfully identifies cracks in slices consistent with human judgment, however, it is worth noting that this is a 2D-slice based segmentation which does not capitalize on 3D information. Therefore, in the future, 3D U-net [CIC 16] (three-dimensional convolution) should be attempted for segmenting the 3D crack images to get more accurate 3D segmentation results. Of course, the difficulties of applying 3D U-net are obvious. Among them one can mention the creation of 3D labeled images, the possible need of several different fatigue tests as training data, the increased computation time and whether the training can converge with a limited number of training periods. Moreover, in the proposed approach, each segmented 3D image of a crack is independent of the previous or the next 3D image in the series, although a clear continuity exist between them. Some deep learning algorithms (Recurrent Neural Network - RNN or Long Short Term Memory-LSTM) have been suggested for taking into account the continuity between different data-sets in the field of 3D biomedical imaging [CHE 16] or in the prediction of gradual ocular disease [JIA 18]. This type of algorithms might be used in the future to ensure a better compatibility between the different 3D images in the temporal sequence and produce more reliable results on crack growth.

Improved in-situ fatigue test to study crack closure in cast iron

The type of loading (uniform displacement/uniform stress) has been shown to induce a significant change in the stress intensity factor at crack tip [LAN 20b]. The way the specimens are held in Lab CT using long screws (equivalent to uniform stress) may lead to bending of the specimens. At the same time, there are some risks of compressing the specimen during removal and reinstallation of the specimen from the fatigue machine. Thus, the ex-situ approach may affect the accuracy and reliability of the DVC results. In future work, specimens with a smaller size (section $2.5mm \times 2.5mm$) with 1 mm internal defects should be tested in a improved *in-situ* experience to obtain more reliable results.

Acknowledgement

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References

- [AGU 05] AGUET F., JACOB M., UNSER M.
Three-dimensional feature detection using optimal steerable filters. *IEEE International Conference on Image Processing 2005*, vol. 2, 2005, p. II–1158. ISSN: 1522-4880, 2381-8549.
- [AMI 07] AMIRI M., TAVASSOLY M.
Fresnel diffraction from 1D and 2D phase steps in reflection and transmission modes. *Optics Communications*, vol. 272, n° 2, 2007, p. 349–361.
- [BAB 14] BABOUT L., JOPEK L., PREUSS M.
3D characterization of trans- and inter-lamellar fatigue crack in (a+b) Ti alloy. *Materials Characterization*, vol. 98, 2014, p. 130–139.
- [BAL 15] BALERNA A.
Introduction to Synchrotron Radiation. MOBILIO S., BOSCHERINI F., MENEGHINI C., Eds., *Synchrotron Radiation: Basics, Methods and Applications*, p. 3–28 Springer, Berlin, Heidelberg, 2015.
- [BEL 99] BELYTSCHKO T., BLACK T.
Elastic crack growth in finite elements with minimal remeshing. *International Journal for Numerical Methods in Engineering*, vol. 45, n° 5, 1999, p. 601–620.
- [BHO 14] BHOWMIK U. K., MANDALA D., HUDYMA N. W., KREIDL O. P., HARRIS A.
Segmentation of cracks in X-ray CT images of tested macroporous plaster specimens. *IEEE SOUTHEASTCON 2014*, 2014, p. 1–8. ISSN: 1558-058X, 1091-0050.
- [BIL 04] BILLAUDEAU T., NADOT Y.
Support for an environmental effect on fatigue mechanisms in the long life regime. *International Journal of Fatigue*, vol. 26, n° 8, 2004, p. 839–847.
- [BIR 09] BIROSCA S., BUFFIERE J. Y., GARCIA-PASTOR F. A., KARADGE M., BABOUT L., PREUSS M.
Three-dimensional characterization of fatigue cracks in Ti-6246 using X-ray tomography

- and electron backscatter diffraction. *Acta Materialia*, vol. 57, n° 19, 2009, p. 5834–5847.
- [BIR 11] BIROSCA S., BUFFIERE J. Y., KARADGE M., PREUSS M.
3-D observations of short fatigue crack interaction with lamellar and duplex microstructures in a two-phase titanium alloy. *Acta Materialia*, vol. 59, n° 4, 2011, p. 1510–1522.
- [BLA 18] BLAUM D. R.
August Wöhler. MATSCHOSS C., Ed., *Beiträge zur Geschichte der Technik und Industrie: Jahrbuch des Vereines Deutscher Ingenieure. Achter Band*, p. 35–55 Springer, Berlin, Heidelberg, 1918.
- [BRO 02] BRONNIKOV A.
Theory of quantitative phase-contrast computed tomography. *Journal of the Optical Society of America. A, Optics, image science, and vision*, vol. 19, 2002, p. 472–80.
- [BUF 06] BUFFIERE J. Y., FERRIE E., PROUDHON H., LUDWIG W.
Three-dimensional visualisation of fatigue cracks in metals using high resolution synchrotron X-ray micro-tomography. *Materials Science and Technology*, vol. 22, n° 9, 2006, p. 1019–1024.
- [BUF 08] BUFFIÈRE J. Y., CLOETENS P., LUDWIG W., MAIRE E., SALVO L.
In Situ X-Ray Tomography Studies of Microstructural Evolution Combined with 3D Modeling. *MRS Bulletin*, vol. 33, n° 6, 2008, p. 611–619.
- [BUF 10] BUFFIERE J. Y., MAIRE E., ADRIEN J., MASSE J. P., BOLLER E.
In Situ Experiments with X ray Tomography: an Attractive Tool for Experimental Mechanics. *Experimental Mechanics*, vol. 50, n° 3, 2010, p. 289–305.
- [BUF 17] BUFFIERE J.-Y.
Fatigue Crack Initiation And Propagation From Defects In Metals: Is 3D Characterization Important? *Procedia Structural Integrity*, vol. 7, 2017, p. 27–32.
- [CAR 18] CARTER S. T., ROTELLA J., AGYEI R. F., XIAO X., SANGID M. D.
Measuring fatigue crack deflections via cracking of constituent particles in AA7050 via in situ x-ray synchrotron-based micro-tomography. *International Journal of Fatigue*, vol. 116, 2018, p. 490–504.
- [CEC 14] CECILIA A., JARY V., NIKL M., MIHOKOVA E., HÄNSCHKE D., HAMANN E., DOUISSARD P. A., RACK A., MARTIN T., KRAUSE B., GRIGORIEVC D., BAUMBACH T., FIEDERLE M.
Investigation of the luminescence, crystallographic and spatial resolution properties of LSO:Tb scintillating layers used for X-ray imaging applications. *Radiation Measurements*, vol. 62, 2014, p. 28–34.
- [CHA 15] CHAPMAN T. P., KAREH K. M., KNOP M., CONNOLLEY T., LEE P. D.,

- AZEEM M. A., RUGG D., LINDLEY T. C., DYE D.
Characterisation of short fatigue cracks in titanium alloy IMI 834 using X-ray microtomography. *Acta Materialia*, vol. 99, 2015.
- [CHA 18] CHATEAU C., NGUYEN T. T., BORNERT M., YVONNET J.
DVC-based image subtraction to detect microcracking in lightweight concrete. *Strain*, vol. 54, n° 5, 2018, Page e12276.
- [CHE 16] CHEN J., YANG L., ZHANG Y., ALBER M., CHEN D. Z.
Combining Fully Convolutional and Recurrent Neural Networks for 3D Biomedical Image Segmentation. *arXiv:1609.01006 [cs]*, , 2016. arXiv: 1609.01006.
- [CHO 12] CHO H., LISSENDEN C. J.
Structural health monitoring of fatigue crack growth in plate structures with ultrasonic guided waves. *Structural Health Monitoring*, vol. 11, n° 4, 2012, p. 393–404.
- [CHU 85] CHU T. C., RANSON W. F., SUTTON M. A.
Applications of digital-image-correlation techniques to experimental mechanics. *Experimental Mechanics*, vol. 25, n° 3, 1985, p. 232–244.
- [CIC 16] CICEK O., ABDULKADIR A., LIENKAMP S. S., BROX T., RONNEBERGER O.
3D U-Net: Learning Dense Volumetric Segmentation from Sparse Annotation. OURSELIN S., JOSKOWICZ L., SABUNCU M. R., UNAL G., WELLS W., Eds., *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2016*, Cham, 2016 Springer International Publishing, p. 424–432.
- [CLE 84] CLEMENT P., ANGELI J. P., PINEAU A.
Short crack behaviour in nodular cast iron. *Fatigue & Fracture of Engineering Materials & Structures*, vol. 7, n° 4, 1984, p. 251–265.
- [CLO 97] CLOETENS P., PATEYRON-SALOMÉ M., BUFFIÈRE J. Y., PEIX G., BARUCHEL J., PEYRIN F., SCHLENKER M.
Observation of microstructure and damage in materials by phase sensitive radiography and tomography. *Journal of Applied Physics*, vol. 81, n° 9, 1997, Page 5878.
- [CLO 99] CLOETENS P., LUDWIG W., BARUCHEL J., GUIGAY J.-P., PERNOT-REJMANKOVA P., SALOME-PATEYRON M., SCHLENKER M., BUFFIERE J.-Y., MAIRE E., PEIX G.
Hard x-ray phase imaging using simple propagation of a coherent synchrotron radiation beam. *Journal of Physics D: Applied Physics*, vol. 32, n° 10A, 1999, p. A145–A151.
- [CRO 18] CROTON L. C. P., MORGAN K. S., PAGANIN D. M., KERR L. T., WALLACE M. J., CROSSLEY K. J., MILLER S. L., YAGI N., UESUGI K., HOOPER S. B., KITCHEN M. J.
In situ phase contrast X-ray brain CT. *Scientific Reports*, vol. 8, n° 1, 2018, p. 1–12.

- [DAN 19] DANIELSEN H. K., CARRASCO A. J., FÆSTER S., DAHL K. V., GUZMÁN F. G., SAUVAGE P., JACOBS G.
3D X-ray computerized tomography of White Etching Cracks (WEC). *Materials Characterization*, vol. 150, 2019, p. 78–87.
- [DOL 00] DOLBOW J., MOËS N., BELYTSCHKO T.
Discontinuous enrichment in finite elements with a partition of unity method. *Finite Elements in Analysis and Design*, vol. 36, n° 3, 2000, p. 235–260.
- [EDE 94] EDELSBRUNNER H., MÜCKE E. P.
Three-dimensional alpha shapes. *ACM Transactions on Graphics*, vol. 13, n° 1, 1994, p. 43–72.
- [FUJ 11] FUJITA Y., HAMAMOTO Y.
A robust automatic crack detection method from noisy concrete surfaces. *Machine Vision and Applications*, vol. 22, n° 2, 2011, p. 245–254.
- [Fæ 19] FÆSTER S., DANIELSEN H. K.
X-ray tomography data of White Etching Cracks (WEC). *Data in Brief*, vol. 27, 2019, Page 104531.
- [GHO 20] GHOORCHI-BEYGI M., DASHTDAR M.
Single-shot measurements by Fresnel diffraction of divergent waves from a phase plate. *Applied Optics*, vol. 59, n° 7, 2020, p. 1968–1973.
- [GOO 05] GOODMAN J. W.
Introduction to Fourier Optics. Roberts and Company Publishers, 2005. Google-Books-ID: ow5xs_Rtt9AC.
- [HEI 18] HEINE L.-M., BEZOLD A., BROECKMANN C.
Long crack growth and crack closure in high strength nodular cast iron. *Engineering Fracture Mechanics*, vol. 192, 2018, p. 24–53.
- [IRV 14] IRVINE S., MOKSO R., MODREGGER P., WANG Z., MARONE F., STAMPANONI M.
Simple merging technique for improving resolution in qualitative single image phase contrast tomography. *Optics Express*, vol. 22, n° 22, 2014, p. 27257–27269.
- [JIA 18] JIANG J., LIU X., LIU L., WANG S., LONG E., YANG H., YUAN F., YU D., ZHANG K., WANG L., LIU Z., WANG D., CHANGZUN X., LIN Z., WU X., CUI J., ZHU M., LIN H.
Predicting the progression of ophthalmic disease based on slit-lamp images using a deep temporal sequence network. *PLOS ONE*, vol. 13, 2018, Page e0201142.
- [JOS 81] JOSEPH P. M., SPITAL R. D.

- The exponential edge-gradient effect in X-ray computed tomography. *Physics in Medicine and Biology*, vol. 26, n° 3, 1981, p. 473–487.
- [JUN 19] JUNET A., MESSEGER A., BOULNAT X., WECK A., BOLLER E., HELFEN L., BUFFIERE J.-Y.
Fabrication of artificial defects to study internal fatigue crack propagation in metals. *Scripta Materialia*, vol. 171, 2019, p. 87–91.
- [JUN 21] JUNET A.
Étude tridimensionnelle de la propagation en fatigue de fissures internes dans les matériaux métalliques. These de doctorat, Lyon, 2021.
- [KAK 01] KAK A. C., SLANEY M.
Principles of computerized tomographic imaging. N° 33 Classics in applied mathematics Society for Industrial and Applied Mathematics, Philadelphia, 2001.
- [KHO 06] KHOR K. H., BUFFIÈRE J. Y., LUDWIG W., SINCLAIR I.
High resolution X-ray tomography of micromechanisms of fatigue crack closure. *Scripta Materialia*, vol. 55, n° 1, 2006, p. 47–50.
- [KIN 11] KING A., LUDWIG W., HERBIG M., BUFFIÈRE J. Y., KHAN A. A., STEVENS N., MARROW T. J.
Three-dimensional in situ observations of short fatigue crack growth in magnesium. *Acta Materialia*, vol. 59, n° 17, 2011, p. 6761–6771.
- [KIR 20] KIRKLAND E. J.
Advanced Computing in Electron Microscopy. Springer International Publishing, 2020.
- [KRU 07] KRUPP U.
Fatigue Crack Propagation in Metals and Alloys: Microstructural Aspects and Modelling Concepts. John Wiley, 2007.
- [LAC 14] LACHAMBRE J.
Développement d’une méthode de caractérisation 3D des fissures de fatigue à l’aide de la corrélation d’images numériques obtenues par tomographie X. Thèse de doctorat, 2014.
- [LAC 15] LACHAMBRE J., RÉTHORÉ J., WECK A., BUFFIERE J.-Y.
Extraction of stress intensity factors for 3D small fatigue cracks using digital volume correlation and X-ray tomography. *International Journal of Fatigue*, vol. 71, 2015, p. 3–10.
- [LAN 20a] LANGER M., CEN Z., RIT S., LÉTANG J. M.
Towards Monte Carlo simulation of X-ray phase contrast using GATE. *Optics Express*, vol. 28, n° 10, 2020, p. 14522–14535.
- [LAN 20b] LANGLOIS R., CUSSET R., HOSDEZ J., BONNAND V., BLAYSAT B., MENUT-

- TOURNADRE L., NEGGERS J., CORET M., HENRY J., DOQUET V., GRÉDIAC M., CHIARUTTINI V., PONCELET M., PROUDHON H., LIMODIN N., RÉTHORÉ J.
Multi-partner benchmark experiment of fatigue crack growth measurements. *Engineering Fracture Mechanics*, vol. 235, 2020, Page 107157.
- [LAR 11] LARRUE A., RATTNER A., PETER Z.-A., OLIVIER C., LAROCHE N., VICO L., PEYRIN F.
Synchrotron Radiation Micro-CT at the Micrometer Scale for the Analysis of the Three-Dimensional Morphology of Microcracks in Human Trabecular Bone. *PLOS ONE*, vol. 6, n° 7, 2011, Page e21297.
- [LI 11] LI T., ALMOND D. P., REES D. A. S.
Crack imaging by scanning pulsed laser spot thermography. *NDT & E International*, vol. 44, n° 2, 2011, p. 216–225.
- [LIM 09] LIMODIN N., RÉTHORÉ J., BUFFIÈRE J.-Y., GRAVOUIL A., HILD F., ROUX S.
Crack closure and stress intensity factor measurements in nodular graphite cast iron using three-dimensional correlation of laboratory X-ray microtomography images. *Acta Materialia*, vol. 57, n° 14, 2009.
- [LOU 13] LOU S., JIANG X., SCOTT P. J.
Application of the morphological alpha shape method to the extraction of topographical features from engineering surfaces. *Measurement*, vol. 46, n° 2, 2013, p. 1002–1008.
- [LUD 03] LUDWIG W., BUFFIÈRE J.-Y., SAVELLI S., CLOETENS P.
Study of the interaction of a short fatigue crack with grain boundaries in a cast Al alloy using X-ray microtomography. *Acta Materialia*, vol. 51, n° 3, 2003, p. 585–598.
- [MAD 13] MADONNA C., QUINTAL B., FREHNER M., ALMQVIST B. S. G., TISATO N., PISTONE M., MARONE F., SAENGER E. H.
Synchrotron-based X-ray tomographic microscopy for rock physics investigationsSynchrotron-based rock images. *Geophysics*, vol. 78, n° 1, 2013, p. D53–D64.
- [MAI 01] MAIRE E., BUFFIÈRE J. Y., SALVO L., BLANDIN J. J., LUDWIG W., LÉTANG J. M.
On the Application of X-ray Microtomography in the Field of Materials Science. *Advanced Engineering Materials*, vol. 3, n° 8, 2001, p. 539–546.
- [MAI 08] MAIRE E., BOUAZIZ O., DI MICHIEL M., VERDU C.
Initiation and growth of damage in a dual-phase steel observed by X-ray microtomography. *Acta Materialia*, vol. 56, n° 18, 2008, p. 4954–4964.
- [MAI 14] MAIRE E., WITHERS P. J.

- Quantitative X-ray tomography. *International Materials Reviews*, vol. 59, n° 1, 2014, p. 1–43.
- [MAR 04] MARROW T. J., BUFFIERE J. Y., WITHERS P. J., JOHNSON G., ENGELBERG D.
High resolution X-ray tomography of short fatigue crack nucleation in austempered ductile cast iron. *International Journal of Fatigue*, vol. 26, n° 7, 2004, p. 717–725.
- [MAU 20] MAUREL V., CHIARUTTINI V., ABECASSIS M., KOSTER A., DEZECOT S.
Influence of a 3D realistic crack path in the driving forces for fatigue crack growth under mode I+II loading. *Theoretical and Applied Fracture Mechanics*, vol. 108, 2020, Page 102570.
- [MES 20a] MESSENGER A.
Étude de l’amorçage et de la propagation de fissures de fatigue internes courtes en régime gigacyclique dans un alliage d’aluminium de fonderie. These de doctorat, Paris, HESAM, 2020.
- [MES 20b] MESSENGER A., JUNET A., PALIN-LUC T., BUFFIERE J.-Y., SAINTIER N., RANC N., MAY M. E., GAILLARD Y., KING A., BONNIN A., NADOT Y.
In situ synchrotron ultrasonic fatigue testing device for 3D characterisation of internal crack initiation and growth. *Fatigue & Fracture of Engineering Materials & Structures*, vol. 43, n° 3, 2020, p. 558–567.
- [MOO 13] MOOSMANN J., ALTAPOVA V., HELFEN L., HÄNSCHKE D., HOFMANN R., BAUMBACH T.
High-resolution X-ray phase-contrast tomography from single-distance radiographs applied to developmental stages of *Xenopus laevis*. *Journal of Physics: Conference Series*, vol. 425, n° 19, 2013, Page 192003.
- [NAD 97a] NADOT Y., RANGANATHAN N., MENDEZ J., BÉRANGER A. S.
A study of natural cracks initiated on casting defects by crack front marking. *Scripta Materialia*, vol. 37, n° 5, 1997, p. 549–553.
- [NAD 97b] NADOT Y.
Influence des défauts de fonderie sur la résistance à la fatigue d’une fonte GS. These de doctorat, Poitiers, 1997.
- [NAD 99] NADOT Y., MENDEZ, RANGANATHAN M., BERANGER
Fatigue life assessment of nodular cast iron containing casting defect. *Fatigue & Fracture of Engineering Materials & Structures*, vol. 22, 1999, p. 289–300.
- [NAD 04] NADOT Y., MENDEZ J., RANGANATHAN N.
Influence of casting defects on the fatigue limit of nodular cast iron. *International Journal of Fatigue*, vol. 26, n° 3, 2004, p. 311–319.

- [NIZ 15] NIZERY E.
Amorçage et propagation des fissures de fatigue dans les alliages d'aluminium 2050-T8 et 7050-T7451. These de doctorat, Lyon, INSA, 2015.
- [OLI 14] OLIVEIRA H., CORREIA P. L.
CrackIT — An image processing toolbox for crack detection and characterization. *2014 IEEE International Conference on Image Processing (ICIP)*, 2014, p. 798–802. ISSN: 1522-4880, 2381-8549.
- [PAC 13] PACUREANU A., LARRUE A., LANGER M., OLIVIER C., MULLER C., LAFAGE-PROUST M. H., PEYRIN F.
Adaptive filtering for enhancement of the osteocyte cell network in 3D microtomography images. *IRBM*, vol. 34, n° 1, 2013, p. 48–52.
- [PAG 02] PAGANIN D., MAYO S. C., GUREYEV T. E., MILLER P. R., WILKINS S. W.
Simultaneous phase and amplitude extraction from a single defocused image of a homogeneous object. *Journal of Microscopy*, vol. 206, n° 1, 2002, p. 33–40.
- [PAR 63] PARIS P.
A Critical Analysis of Crack Propagation Laws. *Journal of Basic Engineering*, vol. 85, n° 4, 1963, p. 528–533.
- [PRO 06] PROUDHON H., BUFFIÈRE J. Y., FOUVRY S.
Characterisation of fretting fatigue damage using synchrotron X-ray micro-tomography. *Tribology International*, vol. 39, n° 10, 2006, p. 1106–1113.
- [RAN 10] RANNOU J., LIMODIN N., RÉTHORÉ J., GRAVOUIL A., LUDWIG W., BAÏETTO-DUBOURG M.-C., BUFFIÈRE J.-Y., COMBESURE A., HILD F., ROUX S.
Three dimensional experimental and numerical multiscale analysis of a fatigue crack. *Computer Methods in Applied Mechanics and Engineering*, vol. 199, n° 21, 2010, p. 1307–1325.
- [RAV 21] RAVI P., NARAGANI D., KENESEI P., PARK J.-S., SANGID M. D.
Direct observations and characterization of crack closure during microstructurally small fatigue crack growth via in-situ high-energy X-ray characterization. *Acta Materialia*, vol. 205, 2021, Page 116564.
- [RON 15] RONNEBERGER O., FISCHER P., BROX T.
U-Net: Convolutional Networks for Biomedical Image Segmentation. NAVAB N., HORNEGGER J., WELLS W. M., FRANGI A. F., Eds., *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015*, Computer Science, Lecture Notes, Cham, 2015 Springer International Publishing, p. 234–241.
- [SAL 03] SALVO L., CLOETENS P., MAIRE E., ZABLER S., BLANDIN J. J., BUFFIÈRE J. Y., LUDWIG W., BOLLER E., BELLET D., JOSSEROND C.

- X-ray micro-tomography an attractive characterisation technique in materials science. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 200, 2003, p. 273–286.
- [SAL 17] SALVDARI H., TAVASSOLY M. T., HOSSEINI S. R.
Fresnel diffraction from a step in the general case. *JOSA A*, vol. 34, n° 4, 2017, p. 674–680.
- [SAR 14] SARRUT D., BARDIÈS M., BOUSSION N., FREUD N., JAN S., LÉTANG J. M., LOUDOS G., MAIGNE L., MARCATILI S., MAUXION T., PAPADIMITROULAS P., PERROT Y., PIETRZYK U., ROBERT C., SCHAAART D. R., VISVIKIS D., BUVAT I.
A review of the use and potential of the GATE Monte Carlo simulation code for radiation therapy and dosimetry applications. *Medical Physics*, vol. 41, n° 6, 2014, Page 064301, American Association of Physicists in Medicine.
- [SCH 09] SCHIJVE J.
Fatigue of Structures and Materials, Texte d'origine. Springer Netherlands, 2 édition, 2009.
- [SER 16] SERRANO-MUNOZ I., BUFFIERE J. Y., VERDU C., GAILLARD Y., MU P., NADOT Y.
Influence of surface and internal casting defects on the fatigue behaviour of A357-T6 cast aluminium alloy. *International Journal of Fatigue*, vol. 82, 2016, p. 361–370.
- [SER 17] SERRANO-MUNOZ I., BUFFIERE J.-Y., MOKSO R., VERDU C., NADOT Y.
Location, location & size: defects close to surfaces dominate fatigue crack initiation. *Scientific Reports*, vol. 7, n° 1, 2017.
- [SHA 09] SHAO J., DU D., ZHU X., WANG L.
Weld Slim Line Defects Extraction Based on Adaptive Local Threshold and Modified Hough Transform. *2009 2nd International Congress on Image and Signal Processing*, 2009, p. 1–5.
- [SHI 16] SHI Y., CUI L., QI Z., MENG F., CHEN Z.
Automatic Road Crack Detection Using Random Structured Forests. *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, n° 12, 2016, p. 3434–3445.
- [STO 19] STOCK S. R.
MicroComputed Tomography: Methodology and Applications, Second Edition. CRC Press, 2019. Google-Books-ID: 1GPBDwAAQBAJ.
- [STR 19] STROHMANN T., BUGELNIG K., BREITBARTH E., WILDE F., STEFFENS T., GERMANN H., REQUENA G.
Semantic segmentation of synchrotron tomography of multiphase Al-Si alloys using a

- convolutional neural network with a pixel-wise weighted loss function. *Scientific Reports*, vol. 9, n° 1, 2019, p. 1–9.
- [SYP 03] SYPEK M AN DPROKOPOWICZ C., GÓRECKI M.
Image multiplying and high-frequency oscillations effects in the Fresnel region light propagation simulation. *Optical Engineering*, vol. 42, n° 11, 2003, Page 3158, SPIE-Intl Soc Optical Eng.
- [TAN 09] TANKYEVYCH O., TALBOT H., DOKLADÁL P., PASSAT N.
Spatially-Variant Morpho-Hessian Filter: Efficient Implementation and Application. WILKINSON M. H. F., ROERDINK J. B. T. M., Eds., *Mathematical Morphology and Its Application to Signal and Image Processing*, Computer Science, Lecture Notes, Berlin, Heidelberg, 2009 Springer, p. 137–148.
- [TAV 10] TAVASSOLY M. T., SABER A.
Optical refractometry based on Fresnel diffraction from a phase wedge. *Optics Letters*, vol. 35, n° 21, 2010, p. 3679–3681.
- [THO 96] THOMSON J. J.
The Röntgen Rays. *Nature*, vol. 53, n° 1374, 1896, p. 391–392.
- [TOD 03] TODA H., SINCLAIR I., BUFFIÈRE J.-Y., MAIRE E., CONNOLLEY T., JOYCE M., KHOR K. H., GREGSON P.
Assessment of the fatigue crack closure phenomenon in damage-tolerant aluminium alloy by in-situ high-resolution synchrotron X-ray microtomography. *Philosophical Magazine*, vol. 83, n° 21, 2003, p. 2429–2448.
- [TOM 98] TOMASI C., MANDUCHI R.
Bilateral filtering for gray and color images. *Sixth International Conference on Computer Vision (IEEE Cat. No.98CH36271)*, Bombay, India, 1998 Narosa Publishing House, p. 839–846.
- [TOM 18] TOMOHIRO IKEDA T. U., OGI K.
Influence of Internal Shrinkage Cavities on High Cycle Fatigue Strength of Spheroidal Graphite Cast Iron. *Casting Engineering J-STAGE*, vol. 171, 2018, p. 52–52.
- [TUB 21] TUBEI V., TODA H., HASSANIPOUR M., HIRAYAMA K., TAKAKUWA O., TAKEUCHI A., UESUGI M.
3D short fatigue crack closure behavior in Ti-6Al-4V alloy investigated using in-situ high resolution synchrotron X-ray tomography. *Engineering Fracture Mechanics*, vol. 249, 2021, Page 107755.
- [VAS 94] VASUDEVEN A. K., SADANANDA K., LOUAT N.
A review of crack closure, fatigue crack threshold and related phenomena. *Materials Science and Engineering: A*, vol. 188, n° 1, 1994, p. 1–22.

- [VID 05] VIDAL F. P., LÉTANG J. M., PEIX G., CLOETENS P.
Investigation of artefact sources in synchrotron microtomography via virtual X-ray imaging. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 234, n° 3, 2005, p. 333–348.
- [VOO 13] VOORN M., EXNER U., RATH A.
Multiscale Hessian fracture filtering for the enhancement and segmentation of narrow fractures in 3D image data. *Computers & Geosciences*, vol. 57, 2013, p. 44–53.
- [WEB 16] WEBER L.
Iterative tomographic X-Ray phase reconstruction. These de doctorat, Lyon, 2016.
- [WEC 07] WECK A., CRAWFORD T., BOROWIEC A., WILKINSON D., PRESTON J.
Femtosecond laser-based fabrication of a new model material to study fracture. *Applied Physics A*, vol. 86, n° 1, 2007, p. 55–61.
- [WIL 13] WILLIAMS J. J., YAZZIE K. E., PADILLA E., CHAWLA N., XIAO X., DE CARLO F.
Understanding fatigue crack growth in aluminum alloys by in situ X-ray synchrotron tomography. *International Journal of Fatigue*, vol. 57, 2013, p. 79–85.
- [WIL 21] WILLIAMS M. L.
On the Stress Distribution at the Base of a Stationary Crack. *Journal of Applied Mechanics*, vol. 24, n° 1, 2021, p. 109–114.
- [WOL 16] WOLFRAM U., SCHWIEDRZIK J., MIRZAALI M., BÜRKI A., VARGA P., OLIVIER C., PEYRIN F., ZYSSET P.
Characterizing microcrack orientation distribution functions in osteonal bone samples. *Journal of Microscopy*, vol. 264, n° 3, 2016, p. 268–281.
- [WU 17] WU S. C., XIAO T. Q., WITHERS P. J.
The imaging of failure in structural materials by synchrotron radiation X-ray microtomography. *Engineering Fracture Mechanics*, vol. 182, 2017, p. 127–156.
- [XIA 21a] XIAO C., BUFFIERE J.-Y.
Neural network segmentation methods for fatigue crack images obtained with X-ray tomography. *Engineering Fracture Mechanics*, vol. 252, 2021, Page 107823.
- [XIA 21b] XIAO C., LETANG J.-M., BUFFIERE J.-Y.
Characterization of Internal Fatigue Cracks in Aluminum Alloys by Simulation of Phase Contrast Tomography. 2021.
- [YAN 89] YANOWITZ S. D., BRUCKSTEIN A. M.
A new method for image segmentation. *Computer Vision, Graphics, and Image Processing*, vol. 46, n° 1, 1989, p. 82–95.
- [YOS 16] YOSHINAKA F., NAKAMURA T., NAKAYAMA S., SHIOZAWA D., NAKAI Y.,

UESUGI K.

Non-destructive observation of internal fatigue crack growth in Ti-6Al-4V by using synchrotron radiation uCT imaging. *International Journal of Fatigue*, vol. 93, 2016, p. 397–405.

FOLIO ADMINISTRATIF

THESE DE L'UNIVERSITE DE LYON OPEREE AU SEIN DE L'INSA LYON

NOM : Xiao

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Prénoms : Ce

TITRE : Dislocations and nanomechanics in Alumina using atomistic simulations

NATURE : Doctorat

Numéro d'ordre : 2022LYSEI032

École doctorale : ED 34 Matériaux de Lyon

Spécialité : Science des Matériaux

RÉSUMÉ : La tomographie à rayons X est la méthode expérimentale la plus couramment utilisée et la plus efficace pour la caractérisation en 3D des fissures dans les métaux, notamment dans le cadre des essais de fatigue in-situ. La forme et la taille des fissures peuvent être observées et caractérisées avec une résolution variant entre 10 et 1 μm selon le type de source de rayons X utilisé, qu'il s'agisse de sources de laboratoire ou de sources synchrotron. Dans certains cas, l'analyse des images de tomographie de fissures présente un certain nombre de problèmes. Pour les images de tomographie de laboratoire, l'énergie limitée des rayons X et le rapport signal/bruit donnent des images en niveaux de gris à faible contraste et bruitées, ce qui rend difficile l'extraction automatique et précise de la forme des fissures. Ainsi, une méthode de segmentation d'images basée sur les matrices Hessienne a été utilisée pour une image de tomographie de laboratoire contenant une fissure faiblement contrastée. La corrélation d'images volumiques, une autre méthode efficace d'analyse quantitative, a été également utilisée pour caractériser des fissures avec le même type d'images. La fermeture de fissures de fatigue internes dans une fonte à graphite sphéroïdal a ainsi pu être mesurée pour la première fois à partir d'images de tomographie de laboratoire. Dans les images de tomographie synchrotron, le contraste de phase aide à détecter des fissures dont l'ouverture est inférieure à la taille du voxel, mais il complique également le contraste des fissures dans l'image et génère certains artefacts spécifiques (streak artefact et wrinkled artefact notamment) lorsque l'algorithme de reconstruction classique par rétro-projection filtrée est utilisé. Une méthode de segmentation basée sur un réseau neuronal a été développée pour extraire automatiquement des fissures de fatigue 3D d'une série d'images de tomographie synchrotron in-situ. Afin de mieux comprendre le contraste des fissures dans les images 3Dreconstruites, d'étudier la source des artefacts mentionnés précédemment et de trouver des moyens de réduire ces artefacts, des simulations de la tomographie par contraste de phase ont été réalisées et les résultats en bon accord avec les images expérimentales ont permis une meilleure analyse de ces dernières.

MOTS-CLÉS : Synchrotron tomographie, fissure, contraste de phase, corrélation d'images volumiques

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