Combining a Computed Laminography Approach with Tomographic Analysis for a Study of Weld Joints

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Abstract

The quality of a weld joint is subject to several factors, from material characteristics to environmental conditions. Its mechanical behavior is a broad field of study with specific industrial standards. Within a study of a weld joint, we employed a combination of a computed laminography [1] approach with tomographic analysis in order to extract and analyze specimens that were afterwards tested to assess the welding stress-strain and fracture characteristics. The main objective was to study the effect of surface porosity-type flaws. For this purpose, instead of a blind extraction of specimens from a welded block, we proceeded to a pre-identification of large porosity defects and the specimens were then cut and machined such that the flaws would be situated on the surface of test samples. The positions of these flaws were extracted with the laminography approach and it was crosschecked with measurements with an ultrasound testing technique. Computed tomography was employed as a characterization step before the stress-strain and fracture tests.

Keywords: X-ray CT, computed laminography, weld inspection

1 Introduction

A specific type of weld joint was studied on several test blocks, welded with different parameters. A metal inert gas (MIG) welding was employed for test blocks of roughly 80 cm by 30 cm and 4 cm of thickness with a V-type weld geometry, as indicated in Figure 1. The weld volume is therefore sufficient to extract several specimens for fatigue test machines and the corresponding study. By varying the environmental humidity level and the percentage of inert gas during welding, several levels of porosity were obtained. Classical radiographies gave first indications on the different cases, from having a lot of small porosities in the range of tens to hundreds of microns, to a case with few large porosities of the order of few millimeters in diameter.

Figure 1: Weld joint blocks and weld geometry.

The main challenge for the global study was to extract specimens with either open-type porosities on the tested area. Another interesting case was to have internal pores of large diameters in specimens with a pore-free surface. Therefore an accurate localization of pores was needed before machining the test specimens.

The problem was addressed by a three-step method:

#1 Position estimation of large pores with laminography
#2 Verification of pore coordinates after cutting out parallelepiped workpieces with a parallel beam X-ray imaging setup
#3 CT imaging and analysis of pores within machined specimens, before mechanical tests

These steps are detailed individually in the following chapters. In total, more than 50 specimens were machined for the mechanical tests, with the region of interest fully or partially inside the welded area, longitudinal or transversal with respect to the initial block.

The robotized inspection cell at CEA LIST [2] is a highly flexible facility for X-ray imaging in various configurations. The possibility to change the acquisition configuration allowed us to propose the method that combines the two mentioned techniques. This setup consists of a 225 kV micro-focus X-ray generator and a flat panel detector with 1024x1024 pixels of 200 µm. Both
the source and the detector are fixed onto 6-axis anthropomorphic robotic arms as depicted Figure 3. The robots are geometrically coupled and controlled with a master-slave strategy, so that the robot equipped with the detector (slave) always follows the robot equipped with the X-ray source (master) to keep a constant relative position between both devices.

Figure 2: Robotized inspection cell at CEA LIST.

2 Identification and position estimation of large flaws with laminography

In a first phase, our objective was to identify and estimate the position of large pores inside the test blocks. Simple radiography does not provide depth information and tomography is not best suited for such objects because of the size and their form-factor. Therefore we considered the laminography as a better suited technique since it allows scanning flat objects and can provide depth information.

2.1 Experimental setup

The robotized inspection cell was used for this task, in a configuration of laminography-type scanning. The X-ray generator and the detector are positioned at a fixed distance and moved through a number of acquisition points in a plane parallel with the major axis of the weld plate as indicated in Figure 1Figure 3. The scan area and the sampling were set in order to cover the entire sample and for this case 375 images were acquired (15 points horizontally and 25 vertically). On the illustration in Figure 3 b), each blue point corresponds to a position of the X-ray source spot, while the detector keeps a constant relative position with respect to each source point all along the trajectory.

Figure 3 : Computed laminography setup: a) photography of the experimental setup and b) visualization of the scan points.

The scan parameters were chosen to minimize the geometric blur and in order to obtain a good contrast, no additional filtering was employed (see Table 1).

<table>
<thead>
<tr>
<th>Parameter</th>
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<td>Number of points horizontally</td>
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</tr>
<tr>
<td>Number of points vertically</td>
<td>25</td>
</tr>
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</table>

Table 1: Acquisition parameters for laminography scans
2.2 Method

The reconstruction algorithm combines the multiple 2D images acquired along the trajectory to create a large size image at a chosen depth ‘z’. This depth value ‘z’ defines the relative shift applied to the radiographic images during the combination step. Therefore, a unique set of 2D images allows the reconstruction of several combined images corresponding to different depth focalization. The drawing in Figure 4 illustrates the principle of the combination step and how it allows the localization in depth of a flaw (red ellipse) detected on two radiographic images acquired before and after a translation of the source-detector couple. On the first image, acquired with the X-ray source at position S1 and the detector at position D1, the flaw projects in I_{D1}. On the second image, where the source and detector are respectively moved to S2 and D2, the same flaw projects in I_{D2}. By back-projecting these two images on an image plane aligned with the real depth of the flaw (Pf), the signals I_{D1} and I_{D2} are superimposed. On the contrary, if the reconstructed image plane is positioned before or after this depth, signals are shifted and the flaw appears blurred or as a double.

![Figure 4: Schematics of flaw plane focusing](image)

2.3 Results and analysis

The projection data was processed with the laminography type algorithm previously described with a focalization on several planes. We reconstructed a number of 45 large size images along the depth of the object with 1 mm spacing. For two samples we have reduced the spacing to 0.5 mm. These images, obtained from the 375 initial images of 1024 x 1024 pixels, have a resolution of 8000 pixels width and 13500 pixels height. Figure 5 presents an example of reconstructed image, which corresponds to the first slice (close to the source point) of one of the test blocks. The darker central area of the image is the weld joint of plate. We consider the top left corner of this zone as the origin of a 3D frame in which we localize the position of each detected flaw. The size of the reconstructed pixels is 100 µm. From the reconstructed planes, we compute the depth position of a flaw by identifying the plane where it appears sharper. For one given porosity, we display in Figure 5 b), c) and d) three images of the region of interest around this porosity at three different depth (respectively 5 mm, 20 mm and 35 mm from the block surface). On images b) and d), the signals of the flaw back-projected from the four projections are not superimposed, which indicates that the reconstructed plane is not aligned with the depth of the flaw. On the contrary, from the sharp and unique signal of the flaw on the image plane c), we can conclude that the actual depth of this flaw with respect to the block surface is 20 mm.

![Figure 5: Laminography results. a) reconstructed radiography of size 8000 x 13500 pixels at the first focal point (at the surface), b) zoom on the reconstructed plane at depth z = 5 mm, c) zoom on the reconstructed plane at depth z = 20 mm and d) zoom on the reconstructed plane at depth z = 35 mm.](image)
3 Digital radiography in a fan-beam configuration

Once the large pores were identified, parallelepipeds were extracted from plates in order to be machined into test specimens. In order to avoid potential errors in the position estimation and during the cutting of the workpiece blocks, an intermediate check was performed with a digital radiography system, depicted in Figure 6. It employs a fan-beam geometry with the displacement perpendicular to the fan-beam. Therefore, in the scan direction the image equivalently to a parallel beam. By avoiding the divergence, we can identify specific points and in this particular case pores by a cross correlation of three scans with the sample rotated orthogonally.

3.1 Acquisition setup

The system is composed of an industrial X-ray generator and a linear detector with a pixel size of 48 µm, in a setup with a magnification close to 1. This choice is also made in order to minimize the geometric blur because the X-ray generator has a macroscopic spot size. In view of the magnification factor of 1.06, the displacement and pixel size along the scan direction is 44.8 µm. The specified accuracy of the linear displacement units is given as being inferior to 12.5 µm.

![Digital radiography setup](image)

Figure 6: Digital radiography setup

The scan parameters used for this series of images are gathered in Table 2.

<table>
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Table 2: Acquisition parameters for digital radiography

3.2 Results and analysis

Several sets of workpieces were images in the same time, each with three orthogonal positions. A corner was taken as origin for each workpiece and the positions of the pores were re-evaluated. Figure 1 presents a photograph with the imaged workpieces end the associated X-ray image.

![Example of imaging of parallelepiped workpieces](image)

Figure 7: Example of imaging of parallelepiped workpieces: a) photograph and b) orthogonal digital X-ray images

For each pore of interest, its position was reevaluated with respect to an origin set as a corner of the parallelepiped. The positions were measured on the orthogonal images on the scan direction. Since the scan step was set to obtain squared pixels, i.e. 44.8 µm, the errors in the measurements are considered inferior to 50 µm.
4 Computed Tomography Analysis

Typical specimens for mechanical testing devices were machined from the workpieces. Their dimension varies in function of the test machine, between 80 and 150 mm in length and between 8 and 12 mm in diameter near the central test region. These specimens were all characterized with X-ray CT, in a classical full rotation configuration.

4.1 Acquisition setup

The same robotized cell was employed as for the first step but in a configuration with the source and the detector fixed as in Figure 8. The specimens were fixed on a turntable and the acquisition consisted of 900 projections mostly around the center of the specimen and for some cases shifted with respect to the center.

For these experiments, in order to reduce the beam hardening effect, a hardware filter in Copper was used. For most of the acquisitions a magnification factor of 5 was used, except few cases for which a magnification of 8 was employed. The acquisition parameters are listed in Table 3.

<table>
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<td>Voxel size in 3D volume</td>
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</table>

Table 3: Acquisition parameters for CT inspection

4.2 Results and analysis

We have used VGStudio MAX [3] for reconstruction and analysis of CT results. The reconstruction algorithm is FDK [4] with a cone-beam geometry. Figure 9 presents two examples of reconstructed volumes. The first presents a relatively high number of small pores, with a larger one situated near the interface of the weld to the support material. The second one presents a specimen having an open pore as requested by the main objective of the study.

Figure 9 : Examples of CT reconstructions of two specimens
The porosity analysis was done with the tools provided by the software. The surface determination was computed with an ISO50 threshold and using the algorithm VGDefXOnly Threshold with a lower limit on the porosity diameter of 100 µm. Porosity maps and distributions were extracted for further analysis.

5 Discussion and conclusions

We presented a method to identify pores inside large test blocks from which specimens for mechanical tests were extracted and characterized with X-ray CT. The proposed method uses a laminography type reconstruction for large metallic plates, a digital imaging without divergence for a validation after cutting workpieces from the weld blocks and finally typical tomography was employed for the characterization of the specimens before the mechanical tests. The robotized inspection facility proved to be a very adapted tool for the study allowing the use of the same equipment in different configurations.

The first step of identifying the large pores inside the weld test blocks was in fact done in parallel with an evaluation through a different technique. Another team of our laboratory specialized in ultrasound testing, inspected the blocks along the weld with a multi-element transducer at a frequency of 5 MHz. A cartography of the pores with their positions was obtained through a scan. A reference test block had to be used for calibration purposes. With this technique, the estimated position uncertainty was lower than 1 mm, with the most accurate results for the depth estimation which is an intrinsic characteristic of the technique. The results were cross-correlated with the ones obtained with laminography, before deciding on the optimal extraction of workpieces that served for machining the test specimens. The results were coherent between the two techniques.

The X-ray imaging didn’t have special difficulties mainly because the test blocks are made of aluminum alloys. For steel alloys the method might have been more problematic because of the limited penetration of the X-ray beam. In that case employing ultrasound techniques might be more adapted.

The results of the mechanical tests indicated that even the largest pores situated on surface did not alter to an unacceptable extent the mechanical characteristics. For the studied type of weld and within the limits of porosity obtained in the available blocks, the main conclusion was that welded parts and structures can still satisfy the specifications in terms of mechanical properties. This conclusion cannot be simply and directly extrapolated to other alloys, new evaluations would have to be performed.

References