

Specific depth step wedge to estimate weld's quality in radiographic inspection: validation & performances evaluation.

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Abstract :

The aim of this study consists in the validation of a welding quantitative non destructive evaluation in industrial radiology.

The welding objects presented in this paper are composed of high density metal rings. Perfect knowledge of the weld geometry and flaws characteristics is an important step to appreciate the weld quality.

The apparatus is composed of a 450kV X-ray generator associated with numerical data acquisition systems (conventional films digitizer / flat panel / image plates).

This article presents the validation of the whole radiographic experimental device. A specific depth step wedge, made in the same metal than the inspected object, is placed above the rings for every X-ray acquisition inspection. Its stairs allow the determination of material thickness as a function of grey levels on the image. A dedicated image processing is then performed to determine characteristics of the welding joints and the flaws.

Little holes, sized with the help of X-ray simulation, in the standard depth step wedge determine the flaw detection performance on each image. Another contribution of modelling in image processing development is to test and validate algorithms very easily because of the perfect knowledge of the virtual object.

Keywords : radiographic inspection, welded rings, standard depth step wedge, calibrated holes, validation, performance evaluation.

I. Introduction

First of all, radiographic inspection needs a continuous effort of validation and performance evaluation [1]. Furthermore, image analysis is more and more used with the numeric radiography development. The systematic use of dedicated algorithms enables a fast radiograms analysis and ensures the reproductibility of the results.

This paper deals with the development and validation process of a radiographic inspection chain. It takes the example of two metals rings weld's inspection.

In section II, the details concerning the objects and apparatus are given.

The section III presents the different tools and methods that are used to develop, evaluate and validate the X-ray inspection process.

The section IV of this paper deals with the validation results obtained in this study. Therefore, the capability of this Non Destructive Technique (NDT) is discussed and the different validation tools validate the others.

II. Inspection description

The welded objects are inspected with X-ray apparatus and the resulting images are analysed thanks to dedicated software.

II.1 Inspected objects

In this study, the welding objects are made of high density metal rings. The weld quality of two Tantalum rings has to be appreciated in order to determine its geometry and in particular flaws characteristics. Due to the manufacturing process, this Tantalum inner cylinder is placed inside an other bigger cylinder made in a lower density metal.

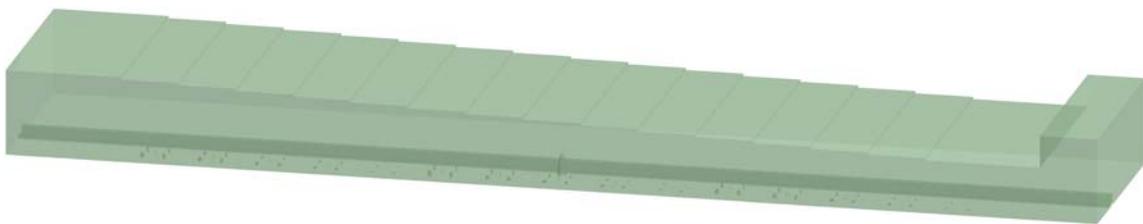


Figure 1. Depth step wedge for grey level calibration.

A specific depth step wedge, made in the same material as the inspected welded object (i.e. Tantalum in this case), is placed above the rings for every X-ray acquisition inspection. The radiography of this standard depth step wedge allows the determination of material thickness as a function of grey levels on the image after digitization. Characteristic values of the weld are then calculated: number and size of porosities, width and thinning of the weld ... This standard depth step wedge is enclosed in a box with a thickness and material similar to the outer cylinder.

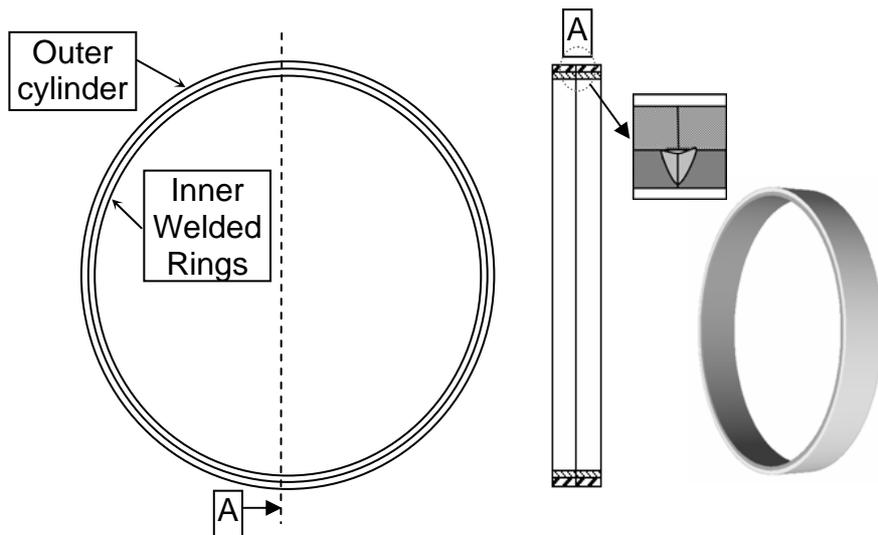


Figure 2. Inner welded rings and outer cylinder.

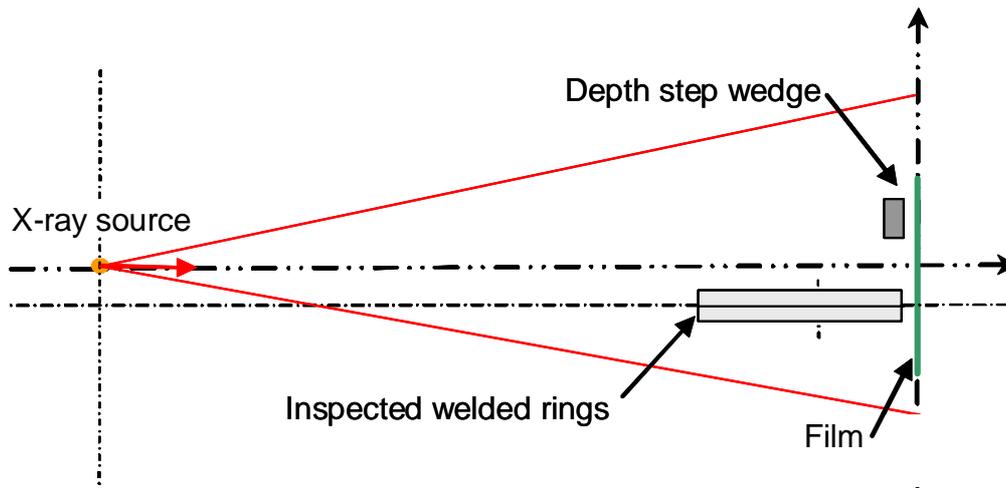


Figure 3. X-ray inspection bench configuration

II.2 X-ray Generators and detectors

The apparatus is composed of a 450kV X-ray generator because of the high density and thickness of materials inspected in this work.

Different kinds of detectors have been tested for this application: conventional films digitizer, image plates or flat panel.

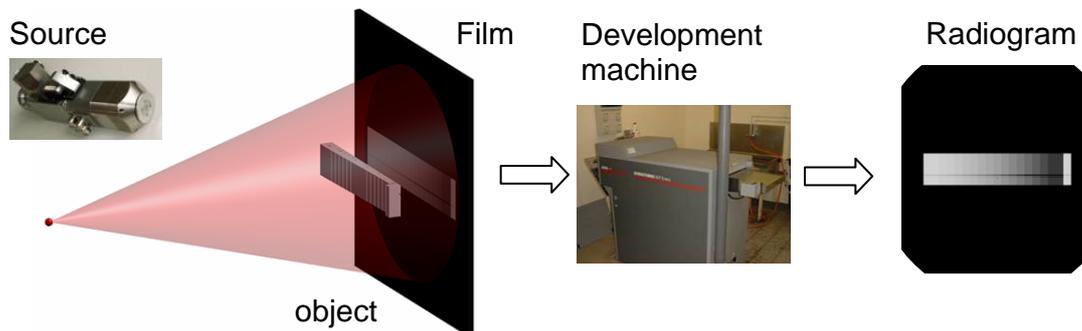


Figure 4. X-ray bench.

The present work deals with the digitization of conventional radiographic films obtained with the AGFA FS50HD system (Figure 5 and Figure 6) providing images pixel size of $50\ \mu\text{m} \times 50\ \mu\text{m}$ and 12 bits grey level.



Figure 5. Digitization and image analysis system.



Figure 6. Digitized radiogram of the welded rings.

II.3 Software for defaults detection

The weld's digitized images are exploited for measurements in the image plan and in the grey levels dimension. The dedicated image processing software developed in our laboratory gives results characterizing the welding joints and its flaws features. This software is called VISU_CND [2][3] and has been developed with Matlab [4][5] since 1999. Flaws' edges [3][6][7] are detected with this software and their characteristics are then calculated (Figure 7).

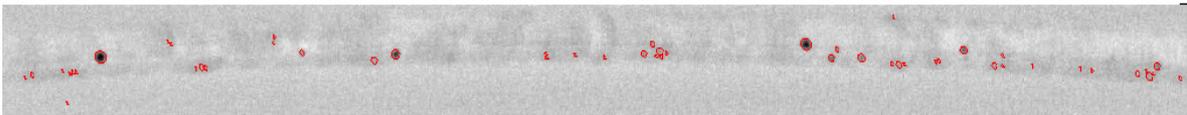


Figure 7. Flaws edges detection with VISU_CND [3].

III. Methods of validation

Different methods are used in order to validate the reliability and the sharpness of image processing on simulated images or on real experimental devices.

III.1 Photomacrographs and lessons learned

An X-ray inspection system is usually validated with the help of a destructive or dimensional inspection method. For example, weld's photomacrographs enable the qualification of the results given with an X-ray apparatus. Thus, it is possible to validate the non destructive evaluation in a direct way with the real characteristics of the weld (thinning, lack of penetration ...) or of its flaws (volume, depth ...).

Unfortunately, flaws are sometimes so small that the limits of the validation methods are reached. For example, the flaws detected with X-ray are so small that it is difficult to find them on photomacrographs. Indeed, it is hard to find and preserve the flaws during the sample preparation steps: cut out, chemical attack and burnishing phase.

The last but not the least drawback of such methods concerns the cost, both in money (the samples objects) and time (for the analysis).

An other way to ensure the coherence of an inspection system is the experimental feedbacks on the previous apparatus. It is possible to compare the results given by the change of an element of the chain: the generator, the sensor or the analysis of the data.

In our case we validate each traced change on calibrated or reference objects and we verify the coherence of the results. In a production chain it ensures that the new inspection system does not introduce changes in the statistical distribution of the flaws. This verification is justified by the constant improvement of inspection benches. For example, the use of a smaller X-ray generator source or a better detector sensibility enables to detect smaller flaws ... but the inspected welding is not worst at all.

III.2 Calibrated Holes

Small artificial holes, machined very sharply in the standard depth step wedge, are used to estimate the detection threshold on each image. Indeed, the threshold could be determined by calculation or simulation but this calibrated object (characterized by optical method) enables us to give a realistic value on each radiogram because of its simultaneous inspection with the welded rings.

Holes are sized cylindrical and their radius and depth range from 50 to 250 μm . They are placed on 5 identical depth holes group on each step of the standard. For example (Figure 8), 5 holes of 150 μm depth and diameter values of 100, 200, 300, 400 and 500 μm are placed on the central step. On the others steps of the standard depth step wedge are the same radius holes with the others depth values (Figure 8).

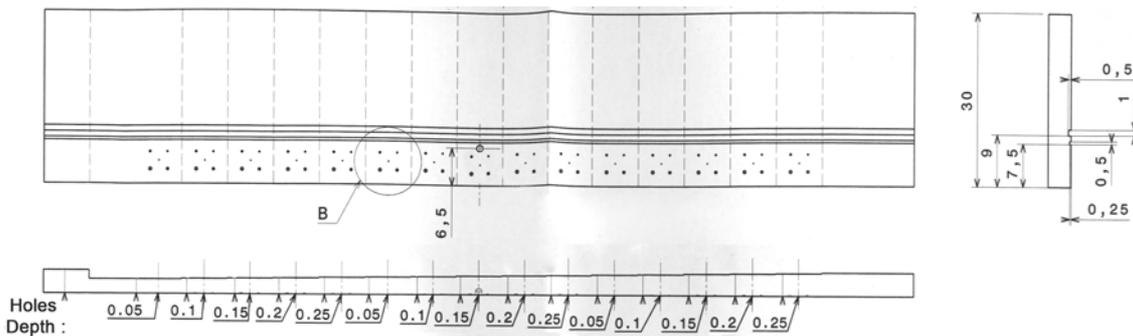


Figure 8. Conception of the depth step wedge and simulated image of X-ray inspection.

III.3 Simulation: SindBad and VXI

Radiographic simulation allows us to have a perfect control on each parameter of the whole radiographic system [8][9][10], especially the knowledge of characteristics of Computer-Aided Design (CAD) object. Radiographic simulation is based on the modelling of each component of the system. Two specific softwares are used for radiographic simulations in our laboratory: Sindbad [11] and VXI.

III.3.1 Sindbad

Very complete software including different models for each component of the radiographic bench and an extent control of shoot parameters. Developed by CEA Leti, one of the interests of this software is the possibility to simulate the scattered radiation [8] and the noise response of the system. Nevertheless, computation of a Sindbad simulation needs a good knowledge of models and compromises between image quality and run-time of simulation.

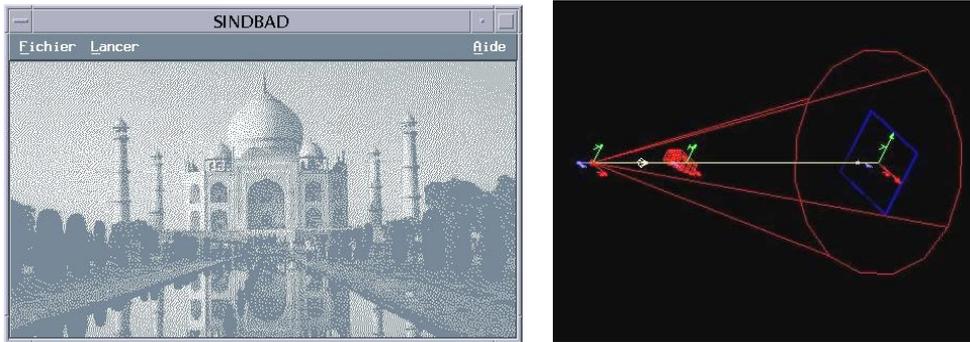


Figure 9. Simulation scene with Sindbad.

III.3.2 VXI

Easy to use, this software is developed by INSA and we have developed a graphical interface dedicated to our needs [12]. The main characteristic of VXI is the defects detectability mapping and multi-image radiography with moving sources. However this software does not allow to simulate directly a detector (film, flat panel...). First version of VXI made analytical simulation with use of Beer-Lambert law and doesn't take into account scattered radiation.

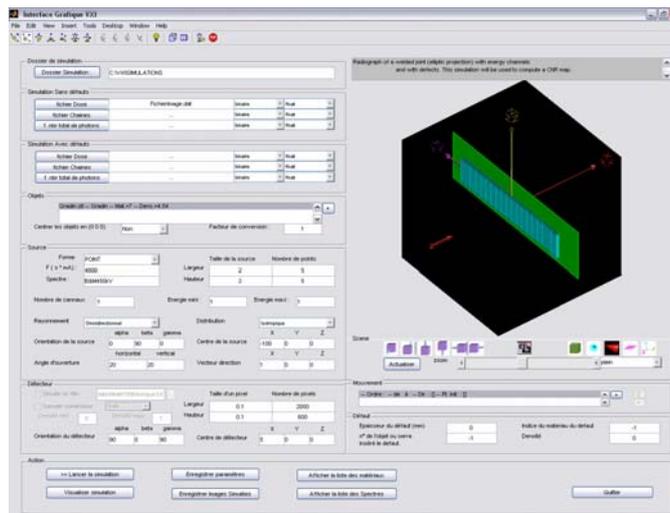


Figure 10. Graphical interface dedicated to our needs with VXI [12].

IV. Results with validation tools

This section presents some results of our cycle of validation. The tools described in section III are used and compared.

IV.1 Constitution of standard object

The sizes of the holes described in III.2 were determined with the help of X-ray modelling (Figure 11). We voluntary chose some holes that are known small enough,

with the simulation prediction, so that our inspection system is not able to detect them [12].

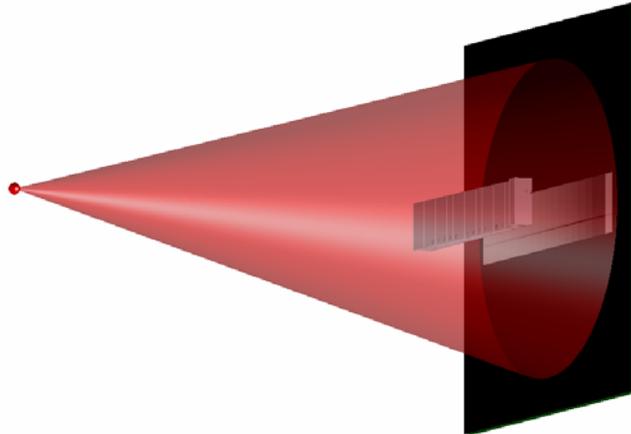


Figure 11. Simulated scene of the standard depth step wedge with holes.

The standard depth step wedge and its holes are calibrated with an optical method. Then it is inspected with X-ray and compared with the simulated image (Figure 12). We observe visually that the prediction of the simulation is confirmed: some holes aren't visible on the radiogram.

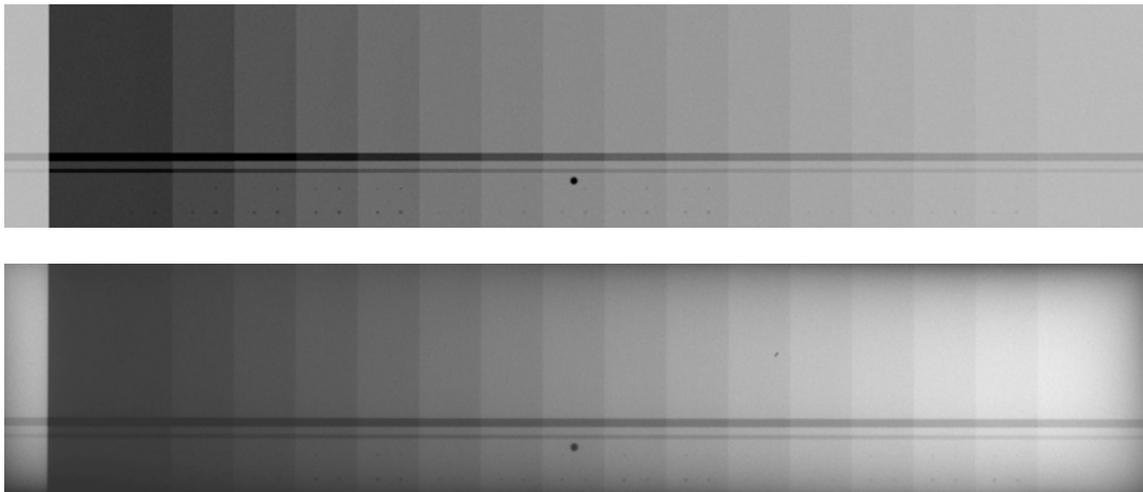


Figure 12. Simulated image [12] (top) and digitized image of the radiogram (down).

The detection threshold is determined with the help of the calibrated holes. At this step a visual criteria is used with the help of an optical gnarl. The thresholds of the radius and depth are estimated by this way. A table (example in Figure 13) summarizes the results combining these two dimensions: holes range from clearly visible (green) to difficult (in orange) and not visible (in red).

It is noticeable that the thickness of the steps where the holes are placed is very important for the threshold. Indeed, the holes are more easily visible on its thinnest steps where they are more contrasted. For this reason, we chose 5 steps which central one has the same thickness as the inspected welded rings.

Dertection threshold		Holes radius (μm)				
		50	100	150	200	250
Holes depth (μm)	50					
	100					
	150					
	200					
	250					

Figure 13. Thresholds of detection with visual inspection.

IV.2 Validation of defaults detection algorithm

We dispose of a standard depth step wedge with calibrated holes which are characterized (radius and depth) by the way of an optical method. Thus, the whole apparatus performances are tested: the X-ray bench, the digitizing process and in particular the analysis software. For that purpose, the algorithm presented in section II.3 is applied on this image. The results are the diameter (surface for non circular flaws) and depth (volume for non spherical flaws) of each hole. Then, these results are compared with the calibrated holes characteristics. We consider that it is a good way to estimate the errors generated by our experimental inspection system.

For example, the results are compared on the holes with 100 μm aimed depth. The optical calibration shows that the depths and diameters after the manufacturing process are very close to the aimed values (Figure 14 and Figure 15). The difference between the X-ray results and optical calibration gives an experimental evaluation of the characterization errors.

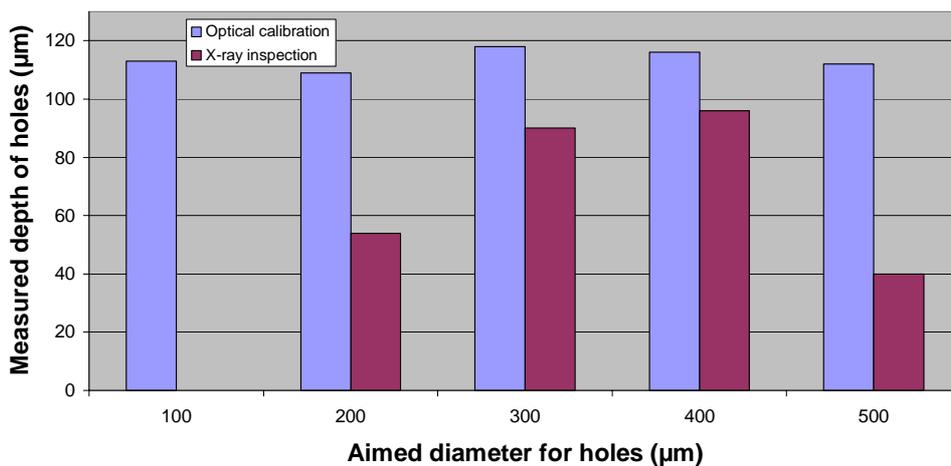


Figure 14. Optical calibration and X-ray determination of holes depth.

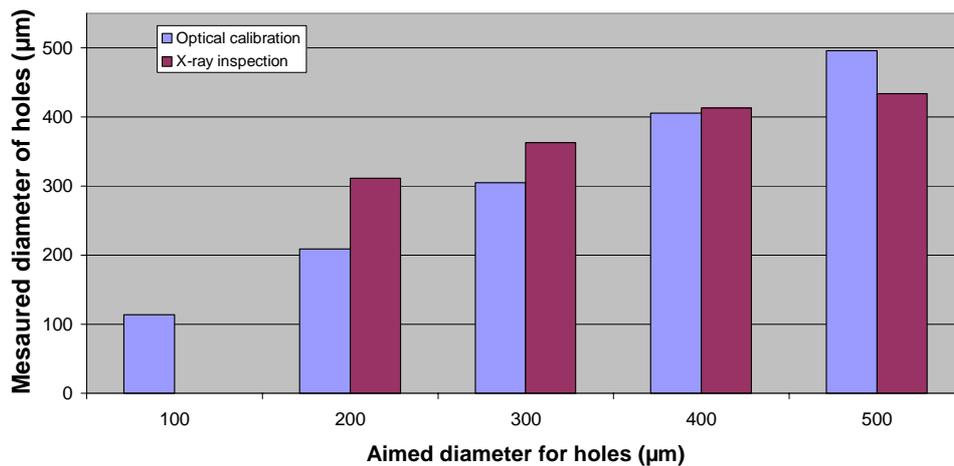


Figure 15. Optical calibration and X-ray determination of holes diameter.

IV.3 Image Quality Indicator on each radiogram

The perfect knowledge of the calibrated depth step wedge and holes is a good Image Quality Indicator (IQI). This is a good reason to inspect it systematically and simultaneously with all our studied specimens. Indeed, the experimental parameters may vary. For example, we use several X-ray generators and environment conditions. Furthermore, the influence of the detectors is obvious: a conventional film development, because of chemical products or intrinsic film constitution, can vary in the time. Another example is the fact that the calibration of a flat panel, for direct digital radiography case, is very important for the inspection results quality.

Then, after the digitization of the radiogram, the analysis of the depth step wedge enables us to estimate the image quality and the threshold of each inspection. Indeed, the knowledge of the standard depth step wedge enables us to detect and find each step for the grey level calibration. In the same way, all the holes are found and characterized very easily and quickly. This allows us to determine the threshold (Figure 13) and errors (Figure 15) tables of each radiogram.

IV.4 Realistic distribution of flaws for simulation

A simulation software aims to be as realistic as possible. For that purpose, X-ray phenomena are sometimes very sophisticated with the help of physical models and mathematical algorithms. Thus, the modelling of the X-ray source and the radiations propagation, the detector's response and the digitization process are the subject of huge improvement efforts. The last element, but not the least, of an X-ray simulation scene is the virtual object. Indeed, a computed object tends to be quite perfect because of its mathematical nature. However, the conception of the most realistic object is a key point for succeeding in making images that look like the experimental radiograms. This is the reason why we make a special effort on our virtual object. In that mind, the statistical distribution (Figure 16) of the flaws characteristics found on previous X-ray inspections is exploited. Then, the resulting mathematical objects (Figure 17) and simulated images (Figure 18) enable us to validate the inspection process.

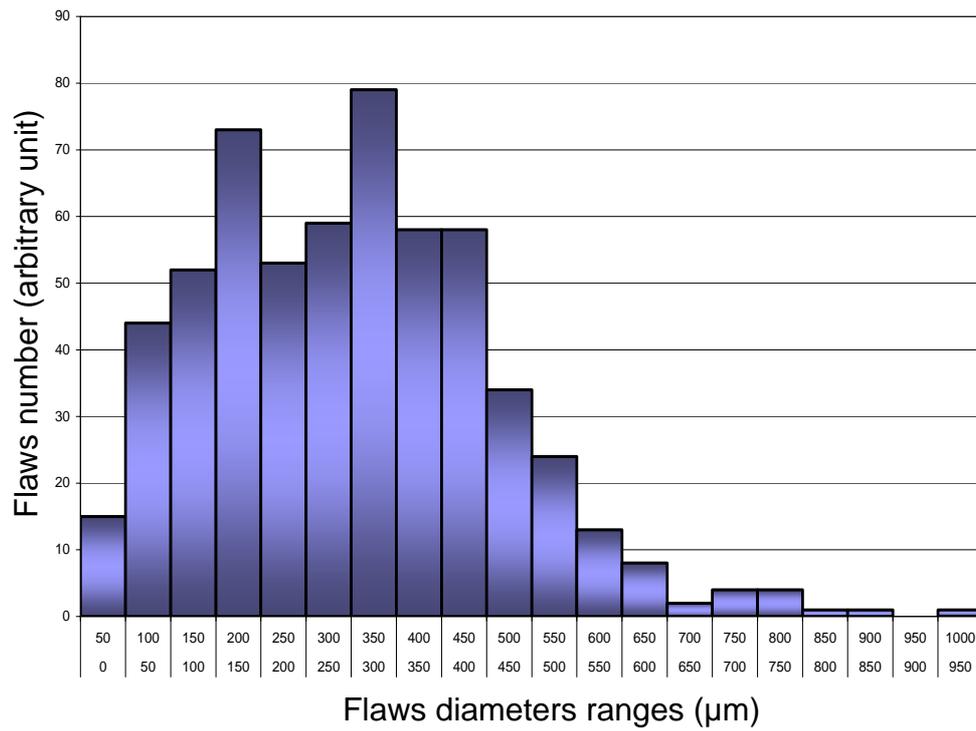


Figure 16. Real flaws statistical distribution.

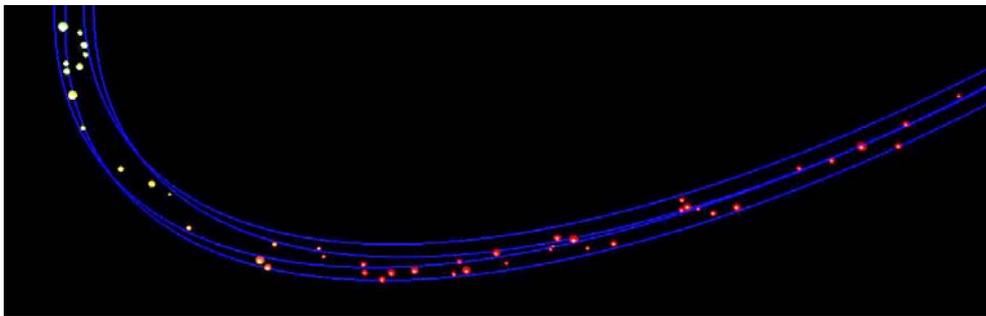


Figure 17. Realistic simulated welded rings [12].

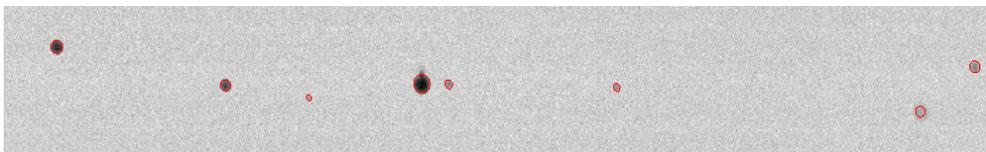


Figure 18. Simulated flaws and their edges detected with VISU_CND [3][2].

IV.5 Development and validation of new image analysis algorithms

With the previous results, we tend to validate and qualify as much as possible our different tools each others (Figure 19). Then, we dispose of a coherent system for X-ray inspection and development.

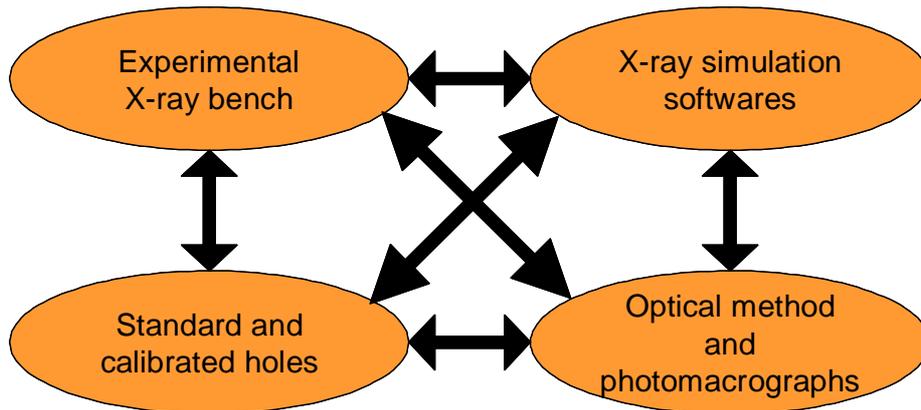


Figure 19. Ideal validation links between different elements of X-ray system.

The calibrated holes (IV.2) and simulated images (IV.4) allow the development of new experimental benches or new analysis algorithms. For example, the improvements on the flaws characterization software are tested and qualified by this low cost way. Test objects and their photomacrograph's analysis is the last step of the development qualification.

The most noticeable work on the flaws detection analysis was realized in 2005 with the LE2I of Dijon's University. Indeed, they developed a powerful algorithm based on the non linear oscillators network principle [13][14]. The application to our X-ray images leads to simultaneous noise removal and contrast amplification.

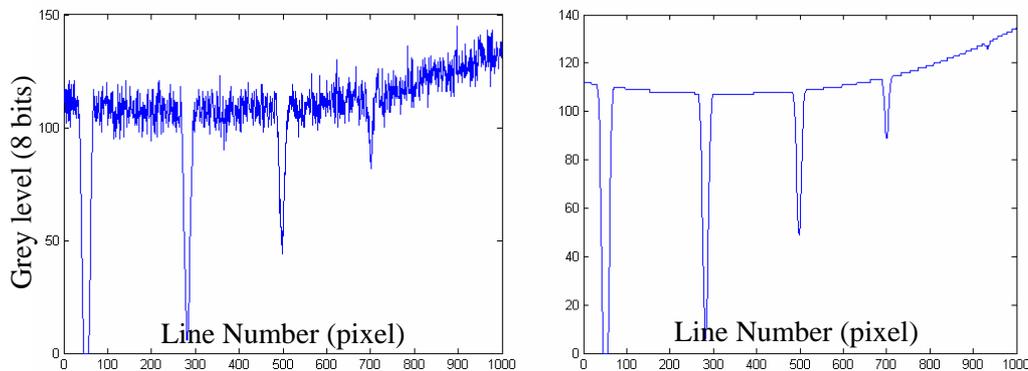


Figure 20. Simulated images profiles of holes with and without noise [15].

At the beginning of this study, the standard depth step wedge with calibrated holes was not machined yet. Then, the adjustment work of this promising algorithm was realized with simulated images [15]. The most interesting point in using simulation software is the fact that it is possible to get images that take into account, or not, the noise sources. It seems to be the ideal tool to test a noise removal algorithm. Indeed, we dispose of a mathematical object, which is perfectly known, and its X-ray simulated images with and without noise. Then, the image without noise is compared with the noisily image after applying a noise removing algorithm (Figure 20 and Figure 21).

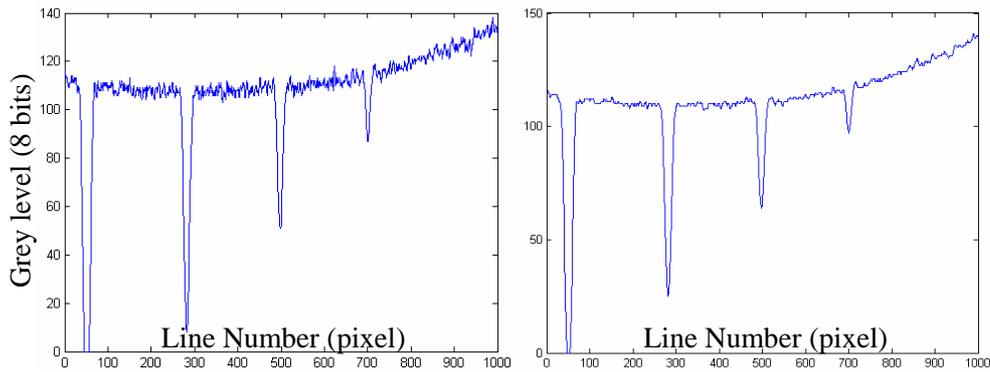


Figure 21. Comparison of Wiener filter (left) and the non linear filter (right) [15].

In order to test the algorithm's performances, the signal on noise ratio is calculated as follows [15]:

$$\frac{S}{N} = \frac{\sum_1^n \text{Noiseless image}(i, j)}{\sum_1^n |\text{Noisily image}(i, j) - \text{Noiseless image}(i, j)|} \quad (1)$$

The signal on noise ratio value in this example is 207 with the Wiener filter included in Matlab and 49318 with the present non linear algorithm. The profit is interesting enough to justify the use of such a sophisticated algorithm, although it is a bit more time consuming.

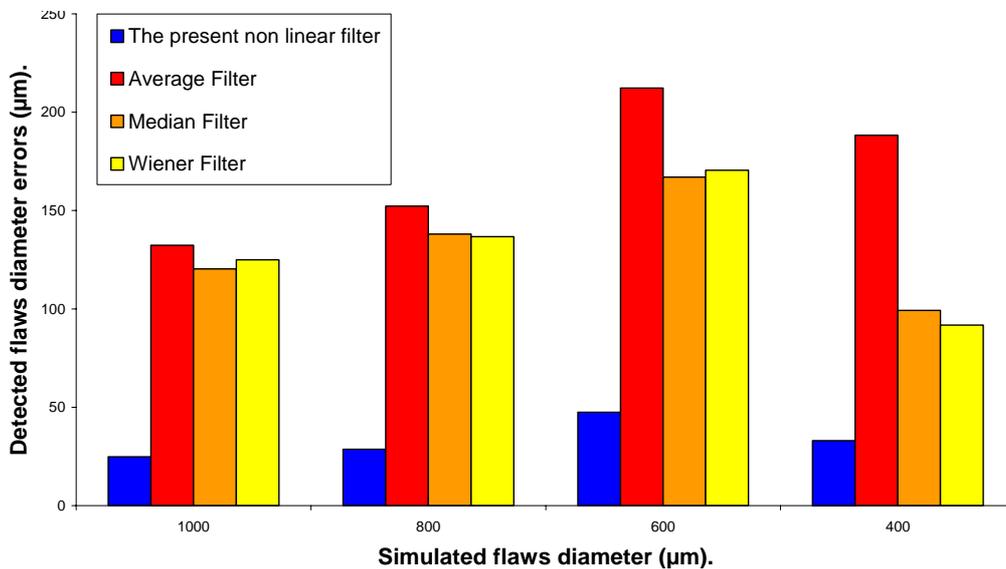


Figure 22. Errors due to the characterization algorithm with different filters and flaws diameter families [15].

Furthermore, the knowledge of the mathematical object allows us to calculate the errors of the flaws characterization algorithm with different filters and flaws diameters (Figure 22). Once more, the non linear algorithm leads to the best results, given with by our validation process.

V. Conclusions

The present work is dedicated to the qualification of an X-ray inspection chain. Every tool is used for that purpose: photomicrographs and optical method, simulation software, calibrated standards and experimental feedbacks. We try to make them validate each other in order to dispose of a coherent X-ray inspection method. Furthermore, after its qualification with calibrated and real objects, the simulation is also a low-cost and easy way to develop and adjust new analysis software or to establish the feasibility of a new inspection.

Now, these tools contribute to qualify new apparatus like the new detectors (flat panel and image plates) ensuring the continuity of the inspection results.

The next image analysis development, planned for this summer, is the full test of the image interpolation contribution [17]. The purpose is to quantify such algorithms improvements on analysis results and to conclude to the sub pixel capabilities.

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