Preliminary Study of Digital Laminography Parameters on Carbon Steel Plate

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Abstract. Laminography is a technique used to determine the depth of a defect in Radiographic Testing (RT). It enables RT operators to accurately locate the defect from the object’s surface especially for welded components. The technique will ensure the quality of weld components meets the standard requirement for reliability and safety purposes. This paper intends to study the exposure parameters of laminography technique on carbon steel plate by using Radiographic Testing – Digital. (RT-D). The important exposure parameters that are considered in this preliminary study are voltage, current, and frame time. The radiography images with achievable level of contrast sensitivity and image quality are analyzed according to the ISO 17636-2. Discussion on correlation between the normalized Signal to Noise ratio (SNRN) and the exposure parameters are done based on the plotting graphs. The results show the exposure parameters has significantly influenced the value of SNR N. Further experimental works are performed using triangulation technique on welded sample. The deviation between the calculated depth of defects and actual results is less than 1.0mm.

1. Introduction

Identification of welding defects is important to determine the integrity and fit for purpose of a welded component in steel structures. Cracks, cavities, solid inclusion, lack of fusion/penetration, and imperfect dimension, are examples of defects which are not homogenous to the parent metal due to welding activities and may lead to failure during in-service condition [1].

Carbon steels are the most widely recognized and used in steel structures. Low carbon, medium carbon, and high carbon steel materials are highly demanded for large and heavy components because of the lower cost [1]. Structures made of carbon steel are typically welded to form a strong and sturdy build up.

Welding is a joining process involving melting and solidification for homogenous metallurgical composition. An understanding on welding metallurgy of carbon steels is required for excellent mechanical properties, chemical composition, and weldability as well as to ensure the welded components are free from any defects [2].

Characterization of welding defects by various Non-Destructive Testing (NDT) techniques is a critical part in welding inspection of steel structures. A primary, simplest, easy to apply, fast, and relatively inexpensive technique in inspection is by visual examination [3]. However this technique has a limitation to evaluate the sub-surface defects. It requires one or more of the other NDT techniques.
such as Radiographic Testing (RT), Ultrasonic Testing (UT), Penetrant Testing (PT), or Magnetic Testing (MT) for a better quality of welded steel structure that meets the requirements for safety and reliability [4].

Radiographic Testing (RT) is a sophisticated NDT technique that is commonly used to evaluate almost all carbon steels surface and sub-surface defects. RT employs X-rays or gamma rays to penetrate an object and indicate any defects on viewing medium; i.e. photographic film or electronic detector [1]. Over the years, RT is based on film radiography systems [5]. It is traditionally demand for an experienced operator to interpret the film radiography (RT-F) image. Manual interpretation is time consuming and sometimes due to lack experience of interpreter, the results will be inconsistent even when high resolution radiography images is provided [4]. Hence, a development of Radiographic Testing – Digital (RT-D) should be taking place as new digital technologies to overcome this issues [6].

RT-D with Digital Detector Array (DDA) system offered a lot of benefit compared to RT-F [7]. RT-D with calibrated DDA is completely tends to eliminate the noise sources arise in radiography. Essential parameters of RT-D such as basic spatial resolution of the image ($SR_{b_{image}}$) and normalized Signal-to-Noise Ratio ($SNR_N$) are the key measurements for high contrast, sensitivity, and image quality for visibilities of defects [8]. Hence, the optimum exposure parameters of X-ray source and DDA, i.e voltage, current, source to object distance (SOD), and frame time are required in determining achievable value of $SR_{b_{image}}$ and $SNR_N$.

The evaluation of contrast sensitivity of radiography image used a single wire Image Quality Indicator (IQI) which contains a series of straight wires (with different diameters) and similar material with object to evaluate [9]. Following standard ISO 19232-5, a standardized duplex wire IQI which consists of 13 wires pairs of platinum with different diameters is used to determine the $SR_{b_{image}}$ for requirement of image unsharpness [10]. Then, the value of $SNR_N$ can be measured from $SR_{b_{image}}$ value as stated in (1).

In this research paper, ISO 17636-2 is followed as standard practice in determining minimum requirement for image quality values of IQI and $SNR_N$ for application of DDAs for weld inspection [11][12].

$$SNR_{N} = SNR_{measured} \frac{88.6 \mu m}{SR_{b}}$$

(1)

For determination on minimum source to object distance (SOD), $f_{min}$ as exposure parameter, the following equation is followed [12]:

$$\frac{f_{min}}{d} \geq 7.5 b^{2}$$

(2)

Where $b$ is the object to detector distance while $d$ is the focal spot size.

Early development of RT-D in carbon steel structures, it is used as a high image quality forming for visibility of defects. Evaluation depth of defects is impossible by this technology without experienced in projection techniques [13]. Laminography technique is one of the projection techniques that enables the operator to accurately evaluate the depth of a defect. In figure 1(a), the principle of laminography is referred to the relative motion of the X-ray source, the detector and the object. The image produced by this approach will be projected at the same location onto the detector due to correlated motion of X-ray source and detector which moved synchronously in opposite directions [13][14]. This technique was used for detecting the defects size with restriction of irradiation from all directions. As required projection angle up to 200°, this technique allows to examine application of flat and large components, lack of access, limited angle accessibility, time consuming, and thick insulation or concrete coatings that normally cannot be examined with conventional projection radiography [14][15].
In present study, triangulation technique is performed as a simplest projection techniques in determining the depth of defects. This technique is practically required two image radiographs at two different positions of X-ray source or sample at projection angle 10° to 45°. ‘Lead Marker Method’ is the most method used in this technique. The schematic diagram of this method is illustrated in figure 1 (b).

Measurement for depth of defects (d), can be expressed as follow:

\[ d = T \frac{S2 - S1}{S3 - S1} \] (3)

Where S1, S2, and S3 are the distance of shift image and lead markers while T is the thickness of the object.

In this study, two essential parameters, i.e: \(SR_{\text{image}}\) and \(SNR_N\) for digital laminography are studied for achievable contrast sensitivity and visibilities of defects in welded samples. Hence, regarding to these essential parameters on digital laminography technique, the preliminary experimental study and analysis were done on welded sample by triangulation technique in obtaining the high image quality the depth of defects. This study focused on cone beam configuration of X-ray system since this configuration is widely used in NDT industry [16].

2. Experimental procedure

A known defect weld test sample (SAMPLE 1) of carbon steel plate is used in this research. Welded plate with parent metal (PM) thickness 10.07mm, weld metal (WM) thickness 2.33mm, and 144 mm x 74mm in dimension. The chemical composition of the welded sample is shown in table 1. All the experimental works are conducted at Malaysian Nuclear Agency, Bangi.

Table 1. Chemical composition of low carbon steel plate.

|   | C    | Si   | Mn   | P    | S    | Cr  | Ni   | Fe        |
|---|------|------|------|------|------|-----|------|-----------|
|   | 0.160| 0.216| 0.698| 0.024| 0.040| 0.110| 0.082| Balance   |

Study on exposure parameters of digital laminography are performed by using an YXLON X-ray tube EUO 225D model with focal spot size of 3.0mm according to EN12543. A Digital Detector Array (DDA) PerkinElmer XRD 1611 is used to acquire the image. This device has a 100 μm pixel size and...
sensitivity of amorphous silicon photodiodes which resulting basic spatial resolution (SR_b) of 100μm without binning. ADC resolution of DDA is 16 bits per pixel with total pixel number of 4096x4096. The Isee! Professional software from Vision in X is used for radiography image acquisition and DDA calibration. The experimental setup for digital radiography is shown in figure 2.

![Experimental setup](image)

**Figure 2.** Experimental setup: (a) X-ray source, (b) welded sample, c) DDA.

A total of 25 experimental works are performed to study the exposure parameters by varying the current at specific voltage and acquired number of frame. The exposure details of experiment are presented in table 2.

| X-ray voltage (kV) | X-ray current (mA) | Focal spot (mm) | SDD (mm) | ODD (mm) | f_min (mm) | No. of frame | Frame time (sec) |
|-------------------|--------------------|-----------------|----------|----------|------------|--------------|-----------------|
| 180 kV            | 0.5, 1.0, 2.0, 4.0, 6.0 | 3.0             | 700      | 40       | 263.2      | 1            | 15, 30, 60, 90  |

Then, geometric magnification is calculated using formula below:

\[
M = \frac{SDD}{SOD} = \frac{700}{660} = 1.17
\]

(4)

The analysis on the Grey Values (GV) and normalized Signal-to-Noise Ratio (SNR_N) at weld metal area are measured at Region of Interest (ROI) of 20 by 50 pixels [12]. The size of the ROI is used to measure the mean intensity for reliable SNR measurements [17]. The minimum requirement for IQI and SNR_N values at weld metal (WM) are presented in table 3 [12].

| Single Wire | Duplex Wire | SNR_N (WM) |
|-------------|-------------|------------|
| W12         | D8          | 70         |
A triangulation technique is performed in the preliminary study on laminography, whereas two lead markers are placed, one on the source side (L1) of the sample and the other on the DDA side (L2). These steps must be done carefully in order to avoid the images of the defects and markers do not coincide or get mixed. The detail diagram as shown above in Figure 3. The acquired radiography images are analyzed by Isee! Professional and ImageJ software in determining the distance of S1, S2, and S3. Then, the value of depth of defect, d is measured. As confirmation of this technique, another a known defects carbon steel sample (SAMPLE 2) with PM thickness of 8.00mm and WM thickness of 1.15mm is tested by using this approach.

3. Result and discussion

3.1. Evaluation of acquired radiography images

Figure 3 shows the raw and filtered acquired radiography images are captured by RT-D. The SAMPLE 1 consists of sub-surface crack approximately 30mm in length. The values of SNR_N are determined by SR_b where directly measured from the SNR_measured as stated in (1).

![Figure 3. The acquired radiography image; raw image (a) and filtered image (b).](image)

The analysis on GV and SNR_N on all acquired radiography images are carried out with achievable contrast sensitivity and minimum image quality value. The result of single and duplex IQI wires are illustrated in figure 4.

![Figure 4. Minimum detectable single and duplex IQI wires.](image)
The measurement of GV and SNR$_N$ are plotted with the respective square root of exposure at specific frame time as shown in figure 5 (a), (b), (c), and (d).

Figure 5. SNR$_N$ and GV over the sqrt exposure of (a) frame time = 15 seconds; (b) frame time = 30 seconds; (c) frame time = 60 seconds; (d) frame time = 90 seconds.

Based on figure 5 (a), (b), (c), and (d), the GV and SNR$_N$ increase with increasing on the square root of exposure. Increasing the radiation dose will increase radiation intensity as larger number of photons are absorbed [10]. Hence, it will produced the greater number of the SNR values with the less noise of the radiography image [18].

3.2. Depth of defect location in digital industrial radiography

According to equation 3, the relationship of the image shift and the markers are proportional to S1, S2, and S3 distance based on triangle approach. By analyzing on acquired images at two different positions, the distance of S1, S2, and S3 are measured as well as determine the depth of defect values. The determination of depth of defects (d) are mostly depends on the quality of acquired radiography image. Table 4 displays the result of the experimental work. For comparison, figure 6 shows the corresponding optical macrograph obtained by metallographic method of the SAMPLE 1.
Further experimental work was done on SAMPLE 2 that consist of porosity and slag inclusion. The filtered acquired radiography image as shown in figure 7. The results show a good, consistent ability to determine the depth of defects to within ±1.00 mm of the actual depth. Table 5 shows the results of SAMPLE 2.

| Defects       | PM Thickness | S1     | S2     | S3     | \(d_{\text{calculated}}\) | \(d_{\text{actual}}\) | Error | % Error |
|---------------|--------------|--------|--------|--------|---------------------------|------------------------|-------|---------|
| Porosity      | 8.0mm        | 262.99mm| 264.47mm| 265.62mm| 4.50mm                   | 3.95mm                 | 0.55mm| 13.92%  |
| Slag inclusion| 8.0mm        | 262.99mm| 264.30mm| 265.62mm| 4.00mm                   | 3.95mm                 | 0.05mm| 1.27%   |

**Figure 7.** SAMPLE 2 with porosity (a) and slag inclusion (b).

4. Conclusion
The aim of this preliminary work is study the exposure parameters of laminography technique on carbon steel plate using RT-D. The result of optimum exposure parameters indicate that this technique is able to determine the depth of defects in carbon steel plate. Further research in digital laminography will be conducted on number of projection angle and image reconstruction algorithm technique in producing 3D image. The depth information will be discovered by applying several projection angles up to 200° projections followed by application of various image reconstruction algorithm for developments 3D image with minimum artefact inherent.
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