Research on Defect Depth Measurement Algorithm In Digital Radiography Testing

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Abstract. The defect depth had always been difficult to measure in the regular Radiographic Testing in the past, but can be accurately measured in Digital Radiographic image grayscale by the digital image processing technology. In the paper, the corresponding relation between the digital image grayscale value of the welding defect and the X-ray strength, was analyzed by means of Beer Theorem, and an algorithm for accurate weld defect depth was put forward. The algorithm was verified by comparing with the experimental data by means of the experimental platform and the simulation software. The result shows that the algorithm error range does not exceed ± 5% of the measured value.

1. Introduction

In conventional industrial production, the workpiece can be formed subtle flaws due to prolonged of loss, it is difficult to avoid in daily production, and depth of the defects will have a huge impact to performance of the workpiece[1]. Defect detection is one of the important part quality assurance techniques, it plays a positive role to reduce or avoid accidents due to defects. Currently, Digital Radiography technology becomes one of the main methods of non-destructive testing and the continuous development of techniques provide a more scientific and objective basis for defect detection and in the detection of defects compared with other methods are intuitive and accurate[2-4].

DR image defect detection purpose to locate the workpiece defect from an image and obtain information about the defect of geometric parameters and so on. The main task of defect detection is segmentation and measurement of a defective area, and the measurement accuracy will affect the final results of the experiment directly. Therefore, top priority is how to find a more accurate defect measurement algorithms to improve defect detection accuracy based on high-precision image segmentation technology foundation.

In this paper, the research aimed at a single material for the workpiece, on the basis of the defect has been achieved over the image segmentation, through the research of existing literature on Beer theorem, and derived the new algorithm defect depth measurement according to the relationship between the X-ray image grayscale value (hereinafter referred to as grayscale value) and intensity of X-ray incidence. The algorithm eliminate the main factors affecting the calculation of defect depth by Beer theorem through research and transformation, and by comparing the method of standard test blocks, the intensity of the X-rays can be represented by the grayscale value, make further improve the accuracy. Through the establishment of experimental environment, a large number of experimental
data verification to prove that the new measuring algorithm error range does not exceed ±5% of the measured value.

2. Research on new algorithm of defect measurement

2.1 The relationship between image grayscale values and incident intensity

Digital Radiography is displayed in grayscale values, in this process we need change X-ray intensity into a digital signal (image grayscale values). First, the incident X-ray photons must to be changed to charge[5-6], the number of X-ray photons irradiated on the pixel element converts and the number of charges was approximately linear relationship, according to formula (1).

\[ U_0 = IR \]  

Wherein, \( I \) represents the intensity of the incident X-rays, \( R \) represents photoelectric conversion coefficients. Analog to digital converter (A / D) will give a voltage into a digital signal to form digital images[7]. The resolution \( Q \) of analog to digital converter equal to voltage of LSB.

\[ Q = \frac{E_{FSR}}{2^D} \]  

Under normal circumstances, the voltage number of intervals is \( N=2^D \), where, \( D \) is the number of bits accuracy of ADC module with bits as a unit. In the above process, it can be directly used quantized voltage values (ie, information bits) already as the grayscale value image, Binding of formula (1), (2) can be derived variation of the grayscale value image, as shown in formula (3):

\[ G = f(R_0, E_0, D_0)I \]  

Where, \( f(R_0, E_0, D_0) \) as a function of \( R_0, E_0, D_0 \) parameters, which \( R_0 \) represents photoelectric conversion coefficient, \( E_0 \) represents the conversion coefficient A/D, \( D_0 \) represents the number of bits for grayscale value, \( G \) denotes an image grayscale value. The value of the function \( f(R_0, E_0, D_0) \) is related to the internal structure of the X-ray machine and the receiving plate, In the detection system for a fixed environment, the function \( f(R_0, E_0, D_0) \) should be a constant, reduced to a constant coefficient \( K \). Therefore, formula (3) can be transformed into formula (4), i.e., the image grayscale value relationship between the intensity of the incident is as follows:

\[ G = KI \]  

2.2 Derivation for defect measurement algorithm

For a single material substance to be detected, the attenuation coefficient of rays pass through the material are related to material density and radiation energy, general ray detection attenuation theory is based on the Beer law[2]. In the current study, we are given international standards data sheets of a variety of interaction cross section parameters, attenuation coefficient, the absorption coefficient of photons and material[8-10], these data validate samely, in an ideal situation monochromatic source, through the attenuation of the object in line meets the formula (5), that Beer's law:

\[ I = I_0 e^{-\mu r} \]
$T$ represents the thickness of the object, $I$ express ray intensity after attenuation, $I_0$ represents the incident light intensity. $u$ is the rays pass through the attenuation coefficient per unit thickness of substance, it depends on the density of materials and X-ray wavelengths\cite{11-12}. When a single material is detected on the surface of the workpiece, as shown in Figure 1, assume that defect depth is $D$, the total thickness of the workpiece is $T_0$, defects of the workpiece thickness is $T_1$, the relationship between the three satisfied formula (6):

$$D = T_0 - T_1 \quad (6)$$

![Figure 1](image)

Figure 1. Sketch map of workpiece with defect detection

As shown in Figure 1, the incident light intensity of X-ray is assumed that $I_0$. When the rays penetrate the workpiece of detected, provided the non-defect ray intensity after attenuation is $I_1$, defect-ray intensity after attenuation is $I_2$. According to Beer Theorem formula (5) we can be drawn the transmission case from defects and non-defects, as shown in formula (7) and (8).

$$I_1 = I_0 e^{-uT_0} \quad (7)$$
$$I_2 = I_0 e^{-uT_1} \quad (8)$$

Deform the formula (7) and the formula (8), take the logarithm to both sides in the same time, we can get the formula (9) and the formula (10), as shown below:

$$\ln \frac{I_1}{I_0} = -uT_0 \quad (9)$$
$$\ln \frac{I_2}{I_0} = -uT_1 \quad (10)$$

As can be seen from formula (9) and formula (10), calculating the thickness defect detected at the workpiece, not only with radiation incident intensity and attenuated intensity, but also related to the attenuation coefficient of the detected workpiece. Among them, by research data shows that aspects related to the attenuation coefficient, attenuation coefficient values significantly affect the accuracy of the results. In order to eliminate the influence of factors that can be divided the formula (9) with formula (10), to eliminate variable $u$ can be obtained by formula (11).

$$\frac{T_0}{T_1} = \frac{\ln I_1 - \ln I_0}{\ln I_2 - \ln I_0} \quad (11)$$

Combining formula (11) and formula (6) can be obtained about the defect depth of formula (12).

$$\frac{T_0}{T_0 - D} = \frac{\ln I_1 - \ln I_0}{\ln I_2 - \ln I_0} \quad (12)$$

For formula (12) further simplification can be obtained formulas on defect depth $D$ (13).

$$D = \left(\frac{\ln I_2 - \ln I_1}{\ln I_0 - \ln I_2}\right) T_0 \quad (13)$$
As can be seen from the formula (13), Under the premise of the known thickness of the workpiece, the new defect measurement algorithms can be obtained by defect depth values ray intensity of the incident radiation intensity and attenuated, the exact value of defect depth and intensity of X-ray are related, regardless of the attenuation coefficient of the material, to eliminate the effect of the attenuation coefficient[13-15].

Analysis to the formula (13) further more, the new defect measurement algorithms need to know the thickness D of workpiece, the initial incident intensity \( I_0 \) of X-rays, and the ray intensity attenuation \( I_2 \) and \( I_1 \) through the defect and non-defect respectively. Since the X-ray intensity after attenuation will be converted by the ray receiver, forming DR image digital information, by the formula (4) we can know that there is a certain proportional relationship, it can be used instead of grayscale value images. But the initial incident intensity rays \( I_0 \) is not be measured. The solution is placed standard test block next to the detected workpiece, calculating the X-ray initial incident intensity \( I_0 \) by thickness of the standard test block and radiation after attenuation indirectly.

Suppose the thickness of the standard test block is \( T_2 \), radiation after attenuation is \( I_3 \), according to the formula (9), the workpiece satisfied formula (14).

\[
\ln \frac{I_2}{I_0} = -uT_2
\]  (14)

Dividing the formula (14) and the formula (9), we will get the formula (15) from the elimination of the attenuation coefficient \( u \).

\[
\frac{T_0}{T_2} = \frac{\ln I_1 - \ln I_0}{\ln I_3 - \ln I_0}
\]  (15)

Put further variation of formula, we can get solving formula (16) about \( I_0 \).

\[
\ln I_0 = \frac{T_0 \ln I_3 - T_2 \ln I_1}{T_0 - T_2}
\]  (16)

Combining formula (16) and formula (13) in combination, to eliminate the factors of initial X-ray irradiation intensity \( I_0 \), i.e., formula (17).

\[
D = \left( \frac{T_0 \ln I_3 - T_2 \ln I_1}{T_0 - T_2} \right) T_0
\]  (17)

Put the formula (17) and the formula (4) further integration, we can get new defect depth measurement formula, expressed as the formula (18).

\[
D = \left( \frac{\ln G_2 - \ln G_1}{T_0 \ln T_3 - T_2 \ln G_1 - \ln G_2} \right) T_0
\]  (18)

Among them, \( G_1 \) is the grayscale value at non defect image, \( G_2 \) is the grayscale value at defect image, \( G_3 \) is the image grayscale value at standard test block. As can be seen from formula (18), in the same irradiation environment, the exact value of defect depth is related to thickness and image grayscale values of the workpiece and standard test blocks.

3. The experimental verification and results analysis

3.1 Experimental verification of defect measurement formula

In order to verify the accuracy of the new defect measurement algorithms, CMOET 225KV X-ray machine and Israeli vidisco amorphous silicon digital detectors (pixels 127μm) is used to build X-ray inspection system platform, wherein the tube voltage is chosen to suit different thicknesses[13-15], the tube current is 5mA and the focal length is 700mm. Choose different thickness steel plate (7mm, 10mm, 12mm) as experimental test block, the size of test block is 210mm * 150mm, each specimen contain different specifications defect depth(1mm, 2mm,
3mm), the standard test block were selected for the thickness of 6mm, 7mm, 8mm of steel test block. Finally, average image grayscale value extracted by detecting software under different areas, and put it into the formula (18) to calculate. The main factors include the tube voltage instability and hardening phenomenon, the experimental data and calculation results are shown in Table 1.

<table>
<thead>
<tr>
<th>Tube voltage (kV)</th>
<th>Defect grayscale value</th>
<th>Non-defect grayscale value</th>
<th>Test block grayscale value</th>
<th>Workpiece thickness (mm)</th>
<th>Standard test block thickness (mm)</th>
<th>Depth measuremt (mm)</th>
<th>Depth calculated value (mm)</th>
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<td>12909</td>
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Table 1. The validation results of defect depth formula under different thickness of the workpiece

3.2 The experimental results

As can be seen from table 1, in different tube voltage detection environment, by measuring the thickness of different defects to verify formula (18), the error of results solving the theoretical and experimental values is between ± 5%. Its margin of error does not uncertain, the only factor affecting the error can not be determined, the main reason for this phenomenon is as follows:

1. Digital image grayscale value directly related to the digital-ray inspection system, the response of different digital detector is different, even the same digital detectors will change accordingly over the time, and will cause the digital image grayscale value changed.

2. X-ray machine is a continuous-ray source, the X-ray tube voltage machine is not stable and fluctuating within in a range, for accurate calculation of defect depth will have a greater impact.

3. For each test piece thickness, the depth of the defect measurement errors due to human also impact affects results.

4. In the course of the grayscale values extracted DR images, the grayscale value of defect area and non-defective area is calculated using the average, also will have a greater impact on the results of the experiment.

4. Conclusions

This paper mainly launches for defect detection in the measurement part of the study, based on ray attenuation theory, by analyzing the relationship between the image grayscale values between ray intensity, and the introduction of a standard methodology of test block, designed to eliminate influencing factors in the defect depth calculation process, ultimately the new algorithm is derived defect depth measurements and experimental platform to be verified. Analysis calculated by a plurality of sets of data obtained from the experiments show that: a certain thickness of the workpiece, the depth of the defect measured error value within a range of ± 5%. In the actual detection of defect depth, with respect to the defect depth of ± 5% margin of error is negligible, so the new defect depth measurement algorithm is more accurate. The new measuring algorithm has high accuracy, easy to obtain data, etc., Not only
improve the defect detection accuracy, but also for DR image automated defect detection provides a new method of calculation.

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References