Precision Measurement of Small Gap within Closed Components by Industrial Computed Tomography

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Abstract. The signal of small gap less than 0.15mm in closed components, which can be observed clearly on industrial computed tomography (ICT) image, can't be distinguished because of the limitation of resolution. In this paper, zone edge integration and its corresponding mathematic model have been established. The relative expression between the gap width and its specific integration value has been achieved by experimental results. The precise measuring method for small gaps, from 0.01mm to 0.15mm, of Beryllium, Aluminium and Steel has been established and the Beryllium, Aluminium and Steel corresponding measuring results have been given out. When the credibility probability is 95%, the measuring uncertainty is better than ±0.005mm.

Introduction

There are many standard methods to measure the width of regular small gap. But the X-ray tomography is superior for measuring the inner structure, assembly and geometric dimensions of the closed components. The common method for CT measurement is to make out the CT value curve through the measurement direction, to determine the measurement result with the full width at half maximum (FWHM)[1]. Figure 1 shows how to measure the dimension of one round hole of the standard sample. The principle is to determine the eigenedge by the maximum CT grads within a certain region. For bigger gaps, the best measuring uncertainty can be up to half of the pixel size[2].

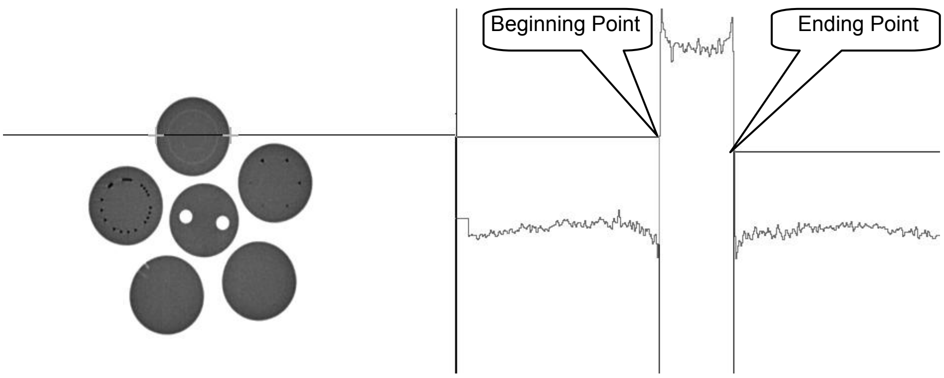


Fig.1 Small Hole Diameter Measurement

The minimum of the industrial computed tomography measurement is determined by the system spacial resolution. When the resolution is 3 lp/mm, the precisely measurable minimum is 0.33mm, according to the definition. In the practical applications, there are many gap dimensions less than 0.1mm. So it's not competent for small gap measurements with the common ICT method, owing to the theoretical confines of measuring scale and uncertainty. Figure 2 gives out the CT tomogram and the measuring curve of the 0.15mm gap, achieved by the layered cross-section scanning method[3]. It shows the diversification eigenvalve of the gap density equals to the noise value, and the precise measurement can't be done. But the features of the gap are visible, even the 0.01mm gap can be easily found in the tomogram. It can be explained by the statistic theory: the CT values of the less features distribute in definite area, and it presents the probability denseness to be discerned. In the paper, a method called zone edge integration has been put forward, based on theoretical inference and experimental confirmation. The method can be used in the accurate measurement for Beryllium, Aluminium and Steel from 0.01mm to 0.15mm.

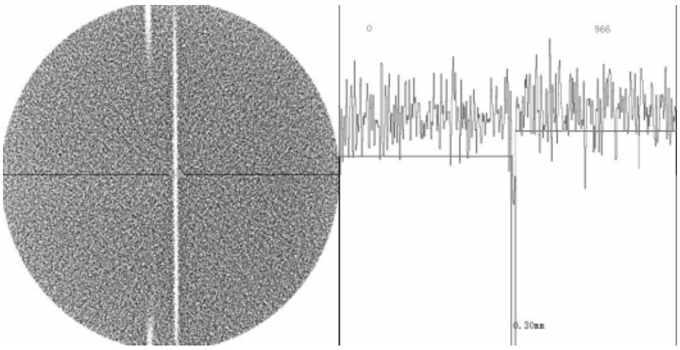


Fig.2 Gap Measurement of Aluminium Component

2 Mathematic Model for Zone Edge Integration

The CT reconstruction submit to the linearity translation invariant theorem. The detectors have definite solid angle, so if the absorb coefficients are uniform and not consider the noise interference, the following expression can be proved:

$$T_i \propto \mu_i S_i \tag{1}$$

Where T_i stands for the CT value of a pixel, μ_i stands for the absorb coefficient of the pixel, S_i stands for the corresponding object area of the pixel.

For the continuous and invariable space, the expression above can be simplified into:

$$T_i \propto S_i \tag{2}$$

For the integral domain determined by gap features, the specific integration value S (non-dimension) and the CT value submit to the following expression:

$$S \propto \iint T(x, y)dxdy \tag{3}$$

If the scanning mode has been determined, the CT value is only related to the gap width. For the average value x within a certain length, there is:

$$x \propto \int_{x_0}^{x_1} \overline{T}_y(x)dx \tag{4}$$

For the discrete circumstances, the proportion constant has been introduced, then the value is:

$$x = A\sum_{i=0}^{n} \overline{T}_{yi} + B \tag{5}$$

In the formula, *A* and *B* are related to the detected material and the scanning mode, which are determined by experiments.

The integrating range can be determined by distinguishing the effective signal from the random noise. In a certain area, there is:

$$\overline{T} = \frac{1}{m}\sum_{i=1}^{m} T_i \tag{6}$$

$$\sigma = \left[\frac{\sum_{i=1}^{m} (T_i - \overline{T})^2}{m-1} \right]^{\frac{1}{2}} \tag{7}$$

Where $\overline{T}/\sigma$ stands for the signal noise ratio (SNR) in a certain area, and 3σ is the determinant value of the integrated edge.

According to above mathematic model, the special software for measuring the small gap has been developed.

3 Experimental Method and Equipment

In the experiment samples are made of Beryllium, Aluminium (LY12) and Steel (00Cr17Ni4Mo2) respectively, and each contains two rings whose gap can be adjusted by the special tools to imitate the inner gap of the component between 0.01mm to 0.15mm.The measured gap value is defined the nominal value. After the gaps scanned by the CT system, and the images got processed by special software, a serial of specific integration value *S* of the gaps can be achieved.

The X-ray tube voltage is continuous and adjustable from 0 keV to 420 keV. The size of the focus is 0.8mm. The CT system has been equipped with five scanning modes, the field are Ø300 mm, Ø200 mm, Ø100 mm, Ø50 mm, Ø25 mm respectively. The best spacial revolution is 3 lp/mm, and the measuring uncertainty is ±0.05mm. In the experiment the voltage is 350 keV, the scan field is Ø25 mm, and the slice thickness is 0.5 mm.

4 Results

4.1 Experimental Data Processing

The linear regression equation about the integration value and the nominal value can be determined by least square fit. The result is:

$$\hat{x} = A \times S + B \tag{8}$$

The values of *A* and *B* can be got by the following formula:

$$A = \frac{\sum S \cdot x - n \cdot \overline{S} \cdot \overline{x}}{\sum S^2 - n \cdot \overline{S}^2} \tag{9}$$

$$B = \overline{x} - A \cdot \overline{S} \tag{10}$$

The linearly dependent coefficient can be got by the following formula:

$$r = \frac{\sum (S - \overline{S})(x - \overline{x})}{\sqrt{\sum (S - \overline{S})^2 \sum (x - \overline{x})^2}} \tag{11}$$

The Table 1 shows the values of A, B, r got by experiments. The regression coefficients of the three materials are all close to 1.0. It indicates the significant linear dependence relation between the specific integration value S and the gap width. It can also testify the established mathematic model is correct.

Table 1. Linear Regressive Parameters of Three Materials

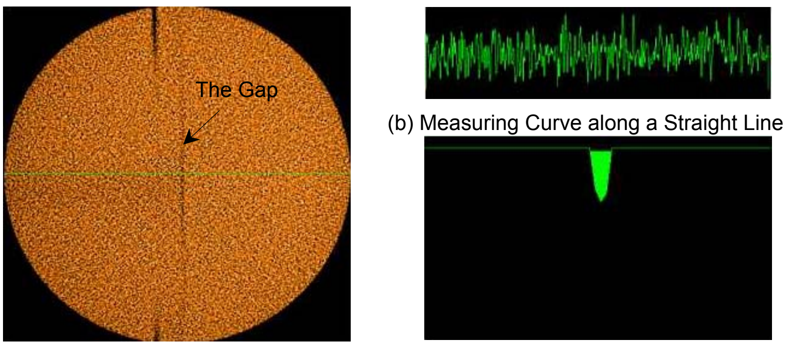
Material	A	B	γ
Aluminium	1.9477×10^{-5}	0.00539	0.9973
Steel	6.9296×10^{-6}	0.00467	0.9977
Beryllium	2.9452×10^{-5}	0.00083	0.9989

The gap width value got by zone edge integration can be determined after putting the values of A, B, S of Beryllium, Aluminium and Steel into the formula (8). Calculate the differences between the gap width values and the nominal values and list the results into Table 2. The maximal differences between the calculated values and nominal values of Beryllium, Aluminium and Steel are 5.3μm 2.4μm 3.9μm respectively. The results satisfy the testing requests of normal components.

Table 2. Differences between Nominal Value and Gap Value Achieved by Zone Edge Integration mm

No.	Aluminium	Steel	Beryllium
1	0.0025	0.0006	0.0005
2	-0.0025	-0.0024	-0.0018
3	-0.0027	0.0021	-0.0005
4	0.0004	-0.0008	-0.0004
5	0.0008	0.0013	0.0017
6	0.0004	-0.0015	0.0031
7	-0.0020	0.0022	0.0034
8	0.0030	-0.0003	-0.0001
9	0.0005	-0.0011	-0.0039
10	0.0053	—	-0.0011

Figure 3 shows the CT image and its measuring result of small gap. Figure 3(a) is the tomogram of Aluminium component with 0.015mm gap. The measuring value is 0.13mm according to FWHM method (Fig.3(b)) and 0.0125mm according to zone edge integration method (Fig.3(c)).



(b) Measuring Curve along a Straight Line

(a) Tomogram of the Gap (c) Measurement of Specific Integration Value(S)

Fig.3 Tomogram and the Measuring Result of Small Gap for Aluminium Component

4.2 The Uncertainties of Repeated Measurements

Make the experimental parameters invariable, and repeat scanning 7 times for the same layer of Beryllium sample. So do the Aluminium and Steel samples. According to the statistic theory, the centre limiting law can't be applied when the number of sampling is small. So it can only apply the t distribution method to estimate the uncertainties of repeated measurements.

If the confidence is 0.95, then $\alpha = 0.05$ $\alpha / 2 = 0.025$. When the number of repeated measurements is 7, the freeness is n-1=6, and $t_{0.025} = 2.447$. So when the fiducial probability is 95%, the expectable uncertainty of measurement is:

$$\Delta x = \pm 2.447 \times \sigma_{n-1}$$

The uncertainties of measurements of small gaps for Beryllium, Aluminium and Steel samples are:

$$\Delta x_{Al} = \pm 2.447 \times 0.0019 = \pm 0.0046 \text{ mm}$$
$$\Delta x_{Be} = \pm 2.447 \times 0.0016 = \pm 0.0039 \text{ mm}$$
$$\Delta x_{Fe} = \pm 2.447 \times 0.0018 = \pm 0.0044 \text{ mm}$$

5 Discussion

Figure 4 shows the regression lines of Beryllium, Aluminium and Steel samples. It shows the slopes of different material regression lines differ much, and the more the density, the smaller the slope value.

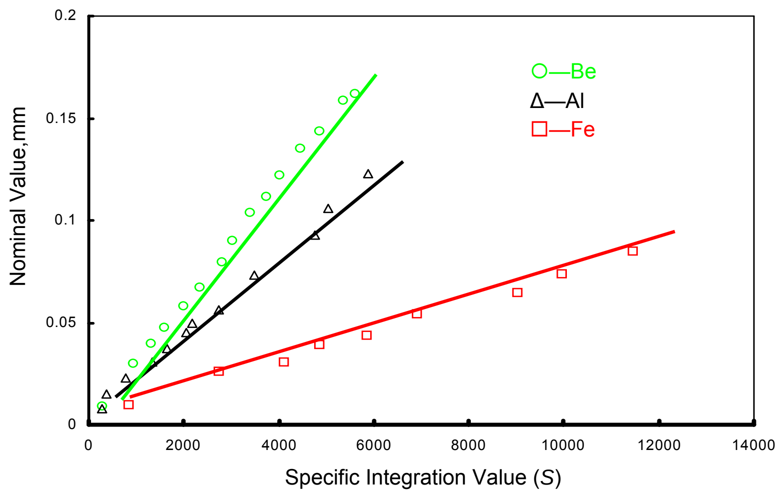


Fig.4 Regression Lines of Nominal Values and Specific Integration Values

There is a interested regulation that the regression coefficient *A* times the density of corresponding material is approximately equal to a constant. The data is showed in Table 3 (the material density ρ not measured on the experiment).

Table 3. Relation between Regression Coefficient A and Material Density

Material	A	ρ (g/cm^3)	A × ρ
Aluminium	1.9477×10^{-5}	2.78	5.41×10^{-5}
Steel	6.9296×10^{-6}	7.8	5.41×10^{-5}
Beryllium	2.9452×10^{-5}	1.84	5.42×10^{-5}

The regulation is important to measure some special materials. The linear coefficient A can be calculated by its density. Just one standard sample be required to determine the coefficient *B* before measuring the small gap by zone edge integration.

To modify the material density on slope value by the rule in the measuring software, and to re-determine the linear modified parameters of Beryllium, Aluminium and Steel (see Table 4), it has been found that there is little difference among the slopes of different materials. The corresponding regressive lines have been showed in figure 5.

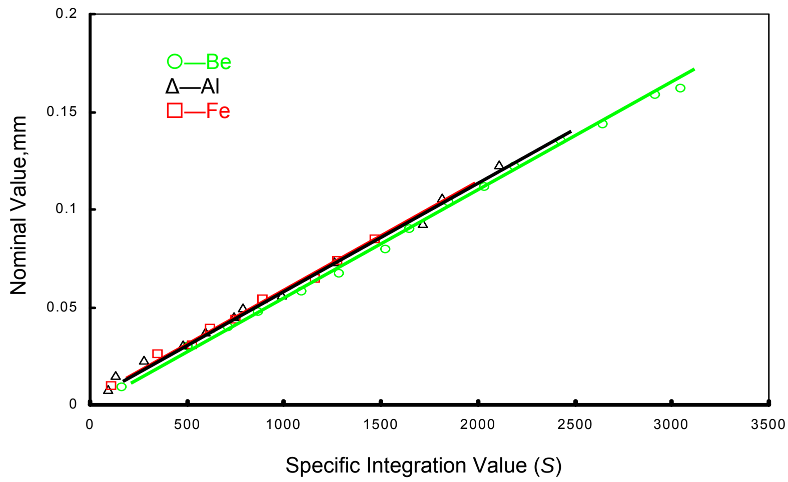


Fig.5 Regression Lines of Beryllium, Aluminium and Steel after Density Modified

6 Conclusion

X-ray computed tomography is a developing technique. Even though the existing hardware conditions can't be bettered, the measurement range and the uncertainty of measurement can be promoted by improving the arithmetic and optimizing programming. The small gap measuring method based on the zone edge integration, can better the measurable sizes of Beryllium, Aluminium and Steel from 0.33mm to 0.01mm and better the uncertainty of measurement from ±0.05mm to ±0.005mm. The result that the regression coefficient of the linear equation times the density of corresponding material is approximately equal to a constant, is significantly meaningful for measuring the small gaps in other materials.

References

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