Measurement of Small Defect Testing Accuracy in Additive Manufacturing Alloy Using Industrial CT Method

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Abstract. This article is based on the application of industrial CT testing in additive manufacturing parts. Based on the existing industrial X-ray CT inspection equipment, it aims to solve the problem of identifying small defects under the uncertainty of test results. Under the premise of removing artifacts, this paper studies the measurement methods of small defects, and analyzes the uncertainty of the test results by designing a comparison test block. This paper combines theoretical analysis and experimental research, and compares the test results with the half-width method to study the accuracy of the test method. In order to improve the accuracy of industrial CT quantitative non-destructive detection of small defects, this paper closely studies the engineering application and combines the practical application of industrial CT to solve the basic problems of key research work.

1. Introduction

With the use of additive manufacturing technology of titanium alloy materials in the domestic aerospace field[1], especially the application of the "heart" of the satellite system—the propulsion system, the performance of additive manufacturing products in a multi-physics coupling environment is reliable[2]. Research on performance evaluation has also been gradually carried out, and a series of technical problems have also been revealed: the size of defects in titanium alloy additive manufacturing products is small, such as pores, inclusions[3], and micro-cracks[4], which are in the order of micrometres, which cannot be detected by conventional non-destructive testing methods; The small defects, fine structure, and high dimensional accuracy requirements in complex thin-walled components make it impossible to judge by conventional testing methods; in the specific use environment of spacecraft, it is difficult to evaluate the performance of additive manufacturing components, and Industrial CT technology is used to test the defect size[5].

In the process of the industrial CT detection, defect can be found is different with the defects can be distinguished or defect size can be measured. For example, VJT Company’s product VJ CT225/450 industrial computed tomography (CT) system in the United States, this system can find single artificial defects with the diameter of 0.05 mm, this paper research on small defect identification technology and test verification of additively manufactured turbocharger housing.

In view of the defect size, how can we apply the traditional measuring method and a half high width to achieve the better test result? In the practical test, many kinds of industrial computed tomography (CT)
were used, for example, 160-225 kV nano-tubes low-power CT, 225-600 kV conventional X-ray industrial computed tomography (CT), and high-energy industrial computed tomography (CT). The work piece size and equivalent steel penetration thickness is different, and the spatial resolution of the equipment also different[6].

Generally, the spatial resolution of nano-tubes CT or micro-focus CT can reach dozens of line pairs per millimetre, but the small focus also product small power, lower radiation dose, and longer sampling time, but defect detection can reach micron grade. Conventional X-ray industrial computed tomography (CT) has a small focus usually around 0.5 mm, tube current is controlled under 2 mA, cooperate with suitable detector, the spatial resolution can reach 5 line pairs per millimetre. Defect detection can detect the defects of decades - a few hundred microns.

The focus size of the high-energy industrial computed tomography (CT) is about 2 mm, because of high radiation energy, the thicker the probe is needed to get effective energy deposition, so the probe channel size is larger, the spatial resolution is usually around 2.5 - 5 line pairs per millimetre. Defects can be checked out the defects of a few hundred microns[7].

Therefore, small defects are not an absolute dimensional constant, according to different industrial CT system, and different detection technology, the size of the small defects is also changing. This paper describes a measurement method based on statistical method, to resolve small size defect size measurement[8].

2. Analysis

Because the difference of actual implementation and principle of hypothesis above, causing the CT image of object is a limited fuzzy representation. According to standard ASTM E 1441[9], in the process of Point Spread Function (PSF) available (Point Spread Function, the PSF) and the effective beam width (BW) of systems described with details of the convolution[10]. Recognize several different types of defects and regional defects, analyse the influence rules of defect types, number, slice position, defect shape and other parameters on the analysis results through experiments, modify the measurement model, and find out from the gray information of the edge area Differences, obtain effective information for defect identification, extract defect structure information based on the morphological characteristics of the defect image, establish structure information, the corresponding relationship between the internal gray value drop/gray distribution of the defect and the defect type, and realize the identification of the defect type. It has important guiding significance.
In this paper, detailed features can be treated as defects. By the above analysis shows, small defects concept is not an absolute value, should be a relative value; According to different equipment, different detection technology, small defects of absolute value is different; the definition of small defects should be associated with BW value. So we can say when the defect size less than BW value can be considered a small defect.

3. Remove artifacts of CT image
The existence of artifacts seriously affects the measurement accuracy of small defects, so the artifacts should be removed before the experiment.

Combining products with complex structures, the effect of artifact removal in this paper is quantitatively analyzed, and high-carbon and high-chromium steel parts are used as the detection object, as shown in the figure. Using the multivariate statistical method, sine projection method, and polar coordinate transformation method in this paper to correct the ring artifacts. And use the signal-to-noise ratio as the image quality evaluation index, and select three local areas inside the workpiece, the background and the middle part to compare the effects. Use image signal-to-noise ratio as a quantitative evaluation index of image quality

$$SNR = 20 \log \left( \frac{\bar{f}(i,j)}{\sigma} \right)$$  \hspace{1cm} (1)

where: $\bar{f}(i,j)$ is the mean CT value and $\sigma$ standard deviation of CT images, and the signal-to-noise ratio in the background area is calculated.

![Figure 2. Test result of the part Test](image_url)

4. Experiment
We designed the following test block, the size of the test block is 70mm*70mm*5mm, and cylindrical through holes with different diameters are set on the test block, the diameters are $\Phi 3mm, \Phi 2mm, \Phi 1mm, \Phi 0.9mm, \Phi 0.8mm, \Phi 0.7mm$ in sequence, $\Phi 0.6mm, \Phi 0.5mm, \Phi 0.4mm, \Phi 0.3mm, \Phi 0.2mm, \Phi 0.1mm$, printed by laser selective melting forming method, CT test on the printed test block, and size of the acquired CT data Measure and verify the sensitivity of printed hole shapes. The test block is shown in Figure 3.

The test block is tested with M300 micro-focus industrial CT. The process parameters are as follows: voltage 250kV, current 200uA, exposure time 1000ms, pixel size 40um, the CT diagram of test block 1 is shown in Figure 3, the measurement results of circular holes with different diameters See Table 1.
This paper adopts a comparatively verified size measurement method, based on the test results of the standard test block, calculates the factors and rules that affect the measurement results, and applies the test rules of the standard test block to the defect test results of the actual additive manufacturing samples.

Table 1. Test result of the reference block

| NO | The designed size (mm) | Test result(mm) |
|----|------------------------|-----------------|
| 1  | 0.1                    | 0.16            |
| 2  | 0.2                    | 0.24            |
| 3  | 0.3                    | 0.36            |
| 4  | 0.4                    | 0.32            |
| 5  | 0.5                    | 0.52            |
| 6  | 0.6                    | 0.58            |
| 7  | 0.7                    | 0.7             |
| 8  | 0.8                    | 0.82            |
| 9  | 0.9                    | 0.92            |
| 10 | 1                      | 1.02            |
| 11 | 2                      | 2.04            |
| 12 | 3                      | 3.06            |

Combining products with complex structures, the effect of artifact removal in this paper is quantitatively analyzed, and additively manufactured parts are used as inspection objects, and the image is corrected for ring artifacts. And use the signal-to-noise ratio (SNR) as the image quality evaluation index, and select three local areas inside the workpiece, the background and the middle part to compare the effects, see Figure 4, the two method we choose were original local graph and multivariate statistical method respectively to carry out SNR data.
Figure 4. Test result of partial area using two kinds of SNR calculation method, corresponding to Figure 2(a).

(a) defect  (b) calculates size

Figure 5. Test accuracy comparison of actual sample defects

Due to the resolution of industrial CT, some metal entities inside the defect cannot be distinguished from the defect, resulting in a large defect measurement area. According to the actual test defects of the sample, combined with the defect size analysis method used in this article, the defect area identification effect diagram of the test, the test result is 1.105mm², the error is less than 10%, see the Figure 5.

In order to verify the effectiveness of the above-discussed quantitative detection method for internal defects of metal materials, the calculation results of the method in this paper and the traditional half-width method are compared, and the curve of the two methods is compared with the variation of the defect size and slice thickness. Figure 6 shows the true value/measured value comparison curve of the two methods when the slice thickness is 0.5mm. It can be seen from Figure 6 that in the case of large defects, the measurement results of the PSF approximate calculation method and the half-width method are relatively consistent; but when the defect size is less than 0.4mm, the measured value of the half-width method increases rapidly. The measurement result of the method in this paper is closer to the true value.
Figure 6. Comparison curve of real value/measured value of defects of different sizes under slice thickness 0.5mm

5. Conclusion
Based on the application of industrial CT testing in additive manufacturing parts. We carried the experiment in the existing industrial X-ray CT inspection equipment, under the premise of removing artifacts, this paper studies the measurement methods of small defects, and analyzes the uncertainty of the test results by designing a comparison test block. This paper combines theoretical analysis and experimental research, and compares the test results with the half-width method to study the accuracy of the test method. This project uses statistical methods to count the defect area to achieve accurate measurement of additive manufacturing product defects. The test accuracy for 1mm² irregular shape defects is less than 10%, which meets the actual application requirements.

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References
[1] I. Maskery, N.T. Aboulkhair, M.R. Corfield, et al. Quantification and characterisation of porosity in selectively laser melted Al–Si10–Mg using X-ray computed tomography. Materials Characterization, 111(2016) 193–204.
[2] Anton du Plessis, Stephan G. le Roux, Johan Els, et al. Application of micro-CT to the non-destructive testing of an additive manufactured titanium component. Case Studies in Nondestructive Testing and Evaluation, 4(2015) 1-7.
[3] Xingfang Cai, Andrew Alexander Malcolm, Brian Stephen Wong, et al. Measurement and characterization of porosity in aluminium selective laser melting parts using X-ray CT. Virtual and Physical Prototyping, 10:4, 195-206.
[4] Du Plessis A, Meineken M, Seifert T. Quantitative determination of density and mass of polymeric materials using microfocus computed tomography.J Nondestruct Eval, 2013;32(4)
[5] Zhang Chaozong, Guo Zhiping. Industrial computed tomography (ct) technology and the principle [M]. Beijing Science Press, 2009.
[6] E. Yasa, J. Deckers, J.P. Kruth. The investigation of the influence of laser re-melting on density, surface quality and microstructure of selective laser melting parts. Rapid prototyping J., 17(2011) 312-327.
[7] Salvo L, Cloetens P, Maire E, Zabler S, Blandin JJ, Buffière JY, et al. X-ray micro-tomography an attractive characterisation technique in materials science. Nucl Instrum Methods Phys Res, Sect B, Beam Interact Mater Atoms, 200(2003)273-86.

[8] B. Song, S. Dong, B. Zhang, et al. Effects of processing parameters on microstructure and mechanical property of selective laser melted Ti6Al4V. Mater. Des., 35(2012)120-125.

[9] ASTM E 1441 Standard Guide for Computed Tomography (CT) Imaging[S]. American Society for Testing and Materials, 2005.

[10] Ben Vandenbroucke, Jean - Pierre Kruth. Selective laser melting of biocompatible metals for rapid manufacturing of medical parts, Rapid Prototyping Journal, 4(2007) 196- 203.