Detection technology of micro residual core in small inner cavity of complex castings

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Abstract: A new technology for detecting a tiny residual core in the small inner cavity of complex castings is proposed. The residual core is identified by using image recognition technology. Tracer processing and image signal processing are combined to enhance the image contrast. The relationships between the concentration of tracer, the size of the residual core, the wall thickness of the castings and the contrast were obtained. Based on the experimental data, the minimum detectable amount of residual core under different conditions was obtained. The results show that the minimum detectable amount decreases from 4.398 mg to 0.438 mg for the 1.0 mm wall thickness casting when the concentration of tracer increases from 0% to 20%. The signal-to-noise ratio (SNR) of the detection results increases by 27.010 by means of average filtering and linear point operation. The subtraction of image and image background was performed, and then the boundary extraction was carried out to obtain a clear and reliable result. The experimental results show that the non-traced residual core cannot be detected for a blade with a thickness less than 5 mm. The residual core of 1 mm thickness can be barely identified by artificial recognition after tracer processing and image processing, while the residual core of 0.6 mm thickness can be detected clearly using image recognition technology.

Key words: hollow blades; X-ray detection; residual ceramic core; tracer; image processing

CLC numbers: TG221

Document code: A

Article ID: 1672-6421(2018)04-307-07

The engine turbine blades with complex structure are usually prepared by precision casting. The internal structure used for an air cooling channel can easily cause a residual core, owing to its internal structure features such as bending, and blind and micro cavity^[1]. These residual cores are difficult to detect. The residual core in the blade will form a flow hot spot in a high temperature environment, which destroys the balance of the engine and influences the heat dissipation, thus worsening the service performance of the blade. It will also cause inestimable damage to the engine and even cause an accident^[2]. In order to ensure the safety of the flight, the detection of the residual core in the blades has become a necessary operation process^[3].

Due to the low attenuation coefficient and the low contrast of the core material, traditional X-ray detection can only detect a bulk core. For a micro residual core,

the cold light source method, endoscope method and iron powder filling method^[4] are generally adopted at present. Cold light source and endoscope can only detect the structure with larger aperture, and so cannot be used for the detection of the structure with a small aperture and large bending. The iron powder filling method is affected by the density of iron powder and the compactness of filling, which is highly likely to produce false inspection. Furthermore, the cleaning of iron powder after testing is very difficult. If the iron powder remains inside the blade, it will cause more serious harm than the residue of a micro core. The structure is more complex for the new type of blade with the air cooling channel having a cover plate. The holes on the plate are very small, and neither the endoscope nor the iron powder can enter the air cooling channel. The neutron radiography method is used abroad for residual core detection, which cannot be used in our country due to the limitation of neutron source^[5-6]. The existing methods can only detect greater than 1 mm thick core blocks, even in ideal conditions. So, a more accurate method is urgently needed for the detection of micro residual cores in blades with the new structure.

Presently, the detection of castings is still mainly based on artificial recognition. The sensitivity of the testing is greatly influenced by the experience and

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Received: 2018-01-29; Accepted: 2018-04-24

technology of the inspectors. The replacement of artificial recognition by computer recognition has become a requirement for intelligent manufacturing. Image recognition technology has been widely used in welding seam detection^[7], license plate recognition^[8] and so on. Ray digital imaging detection (DR) is the development trend of future detection, but the results of detection often overlay the noise which cannot be excluded. If the residual core information is inundated in the noise, it will not be detected^[9].

In this study, an element with a high atomic number is used to improve the contrast between the residual core and the castings^[10-11]. Then, image processing technology was used to suppress the noise and further enhance the contrast between the core and castings^[12-13]. Finally, sensitivity of recognition and detection reliability has been tested by using image recognition technology^[14]. The main idea for this research is, based on the above technologies, to find a reliable and sensitive detection method which can be applied to the new type of blade.

1 Experimental procedures

1.1 Sample preparation

The doped tracer in ceramic core material should not only contain the elements of high atomic number, but also match the criteria set of the core material. HfO_2 and Al_2O_3 are the

main components of ceramic core. The atomic number of hafnium (Hf) in HfO_2 is 72, and the melting point of HfO_2 is 2,850 °C (above 1,600 °C). The liner expansion coefficient of ceramic core material Al_2O_3 is $8.6 \times 10^{-6} \text{ K}^{-1}$, and that of HfO_2 is $5.8 \times 10^{-6} \text{ K}^{-1}$; the liner expansion coefficient is similar to that of matrix material (ceramic core). HfO_2 and Al_2O_3 have similar properties: their structures and chemical properties are stable at high temperature^[15]. Moreover, HfO_2 can be removed by hydrofluoric acid. Therefore, HfO_2 is suitable as a tracer.

The DD6 alloy plate specimen with sizes of 35 mm × 30 mm (length × width) and a thickness from 0.8 to 1.6 mm was used. The chemical compositions (mass fraction) of DD6 alloy are: Cr 4.3%, Co 9.0%, Mo 2.0%, W 8.0%, Ta 7.2%, Re 2.0%, Hf 0.1%, Al 5.7%, and the balance is nickel^[16]. The experiments were carried out in 5 groups according to the different concentrations (20, 15, 10, 5 and 2 mass%) of tracer (HfO_2) and each group contains five samples. An EDM (Electrical discharge machining) method is used to make the slots. The thickness of the sample and the depth of the slots are shown in Table 1. The ceramic material is mixed with silica sol to form a paste, and then the tracer was added and filled the slot of the sample. Only half length of the slot was filled so that the unfilled half can be used to simulate the part without the residual core. The sample was scraped to make the core thickness equal to the depth of the slot, and then it was put in the drying box at 150 °C for at least 2 h. The picture of samples with dried paste is shown in Fig. 1.

Table 1: Size of DD6 superalloy specimens

Specimen No.	Length (mm)	Width (mm)	Thickness, B (mm)	Slot depth, c (mm)	Residual thickness of specimen at slot place (mm)	Value
#1	35	30	0.8	0.2, 0.2	0.6, 0.6	2
#2	35	30	1.0	0.2, 0.4	0.8, 0.6	2
#3	35	30	1.2	0.2, 0.4, 0.6	1.0, 0.8, 0.6	3
#4	35	30	1.4	0.4, 0.6	1.0, 0.8	2
#5	35	30	1.6	0.6	1.0	1

Fig. 1: Samples without and with 2% tracer concentration

1.2 Residual core testing method

The 160 X-ray detection apparatus produced by Xinli Equipment Co. Ltd. was used. The samples with different tracer concentrations were photographed by X-ray, and the photographic results were digitally converted. In order to facilitate comparison and reduce the influence of unrelated factors, only the uniform thickness of the dried paste in the groove was analyzed. ImageJ software was used to establish the area for gray value selection and extract the gray value of the samples with and without residual core.

2 Results and discussion

In the ray detection theory, the image quality is mainly related to the contrast, the spatial resolution (SR_b), and the signal-to-noise ratio (SNR) of the image. The SR_b is related to the pixel size as the pixel size of a certain detection system is determined. The relationship between the contrast and $SNR^{[17]}$ is as Eq. (1):

$$C_s = \left[-\frac{1+n}{\mu} \right] \frac{GBV}{SNR} \cdot \frac{1}{T} \times 100\% \quad (1)$$

where C_s is the sensitivity of contrast; GBV is the critical value of contrast noise ratio caused by small thickness difference ΔT ; T is the penetration thickness of ray; n is the scattering ratio; and μ is the attenuation coefficient of object. It can be seen that improving the object's attenuation coefficient and SNR of the images are the two main ways to enhance the quality of image detection. In this study, a tracer is added to increase the attenuation coefficient of the residual core and the SNR is improved by image processing. Thus, the sensitivity of the detection might be improved.

2.1 Tracer test and analysis

When the X-ray penetrates the object, it interacts with the electrons from the atom of the object, which weaken the strength of X-ray. The scattering cross section of the attenuation coefficient is much smaller than the absorption cross section. Ignoring the scattering part while not considering the absorption edge of the X-ray source, the relationship of the attenuation coefficient (μ), the atomic number (Z) and the X-ray wavelength (λ) are as Eq. (2) ^[18]:

$$\mu = KZ^{3.94}\lambda^3 \quad (2)$$

where K is the constant coefficient. Equations (1) and (2) indicate that the contrast sensitivity has a power law relationship with atomic number. Thus, selecting the large number of atoms as tracers and adding them into the core can significantly improve the core attenuation coefficient and enhance the contrast.

In order to eliminate the uneven mix of HfO_2 with paste, which would lead to the wide fluctuation of gray value, the selected area in imageJ to extract gray value should be as large as possible. The size of the selected area is chosen as 300 pixels $\times$ 800 pixels based on the size of image. The results of the experiments with 10% HfO_2 are shown in Fig. 2, in which the white box represents the selected area. C is the gray value of the non-residual core area, C' is the gray value of the residual core area, $\Delta C = C - C'$. The intensity of ray is transformed into the image brightness (i.e. gray value) through the radiant receiver and the A/D conversion. The values of each group were recorded at different concentrations, as shown in Fig. 3.

Fig. 2: Test results with HfO_2 concentration of 10%: (a) Al_2O_3 without tracer; (b) B-c: 0.6-0.2 mm; (c) B-c: 0.6-0.4 mm; (d) B-c: 0.6-0.6 mm; (e) B-c: 0.8-0.2 mm; (f) B-c: 0.8-0.4 mm; (g) B-c: 0.8-0.6 mm; (h) B-c: 1.0-0.2 mm; (i) B-c: 1.0-0.4 mm; (j) B-c: 1.0-0.6 mm

According to the research on visual characteristics of human eyes, the gray resolution of human eyes has a nonlinear relationship with the background brightness; and this relationship is called Weber-Fechner law ^[9,18,19]. In the luminance range of $4.84 \times 10^{-3} - 1.167 \times 10^6 \text{ cd} \cdot \text{m}^{-2}$, and the background gray value is i , the just noticeable difference (JND) of the human eye can be

calculated by Eq. (3) ^[20-22]:

$$N(i) = \frac{f_c[f_b(i)]}{H(i)} \quad (3)$$

where $N(i)$ is the gray difference that the human eye can distinguish when the background gray value is i , f_c is the ratio of just noticed luminance difference and brightness, $f_b(i)$ is the

Fig. 3: Change of gray value and minimum detectable amount under different conditions (a) $B=0.6$; (b) $B=0.8$; (c) $B=1.0$; (d) minimum detectable amount (when the area is $0.3572 \text{ mm} \times 0.3572 \text{ mm}$, $\Delta C=C-C'$)

brightness value when the gray value is i , $H(i)$ is the luminance difference between the gray value i and the adjacent gray value. In the case of high or low gray value, the JND of the human eye is high (high JND means poor recognition ability). When gray value is near 100, the JND of the human eye is minimal^[23]. So the background gray value is selected as 100. Besides, the effect of noise on the quality of the picture is very little, which is not considered. It could be calculated according to Eq. (3) that the critical value of the human eye gray value is approximately 20. As shown in Fig. 3, the dotted line indicates the minimum difference in the gray value that the naked eye can distinguish when the background gray value is 100. The dash-dotted line indicates the gray value difference produced by the non-traced ceramic core. Under the test parameters, the gray difference in 0.2 mm thick non-traced residual core on 0.6 mm thick casting (residual thickness of slot) is only 2–3, which cannot meet the recognition range of the naked eye.

The contrast of the core gradually increases with an increase in the concentration of tracer and the core thickness, while gradually decreases with an increase in the wall thickness of the casting. When the tracer concentration is 10%, the residual core with the thickness of 0.2 mm on the 0.6 mm casting can already be observed by the naked eye. The image pixel $P=0.1786 \text{ mm}$ based on SR_b value, and according to the SR_b definition, the critical area is $0.3572 \text{ mm} \times 0.3572 \text{ mm}$. Without considering the system noise, when the tracer concentration is 5%, the minimum detectable amount is 0.552 mg for the DD6 superalloy with the thickness of 0.6 mm. When the tracer concentration is 10%, the minimum detectable amount is 0.308 mg, as shown in Fig. 3(d). When the tracer concentration is 20% and the wall

thickness of the casting is 1.0 mm, the minimum detection amount is 0.438 mg, while without tracing, the minimum detection amount is 4.398 mg.

2.2 Image processing

There are two kinds of noise generated by X-ray image. One is generated by the X wave quantum fluctuations, and subject to Poisson distribution, classified as white noise. According to the randomness of the noise airspace, the multi-frame average method can be employed to effectively reduce the noise. The other kind of noise is produced by A/D conversion components classified as Gauss noise, which has a certain regularity of distribution and must be eliminated by filtering^[24]. This study mainly focuses on how to deal with the Gauss noise.

Noise is a random pixel changed rapidly in the gray value of the image, which belongs to a high frequency signal. Low pass filtering can be used to eliminate or suppress the signal above the threshold value. Besides, mean filtering also has a good effect on eliminating noise. Its rationale lies in that the image could be processed by a template operation which is based on the average value of pixels to smooth noise. Both filtering and contrast enhancement belong to linear point operations, and their mathematical expression^[25] is as Eq. (4):

$$B(x, y) = f[A(x, y)] = \alpha A(x, y) + \beta \quad (4)$$

where $A(x, y)$ is the gray value of a pixel in the original image, and the $B(x, y)$ is the gray value of the pixel after the point operation. α is the contrast coefficient, and β is a constant. The contrast is improved by repeating the linear point operation, and the subtraction operation is carried out with the

standard background. This will weaken the interference of the background on the residual core and further improve the contrast between the target and the background.

Image edge is the most basic feature of an image and edge detection can be used to extract an edge. There are many kinds of edge detection operators. Taking the Canny operator as example, we calculate the amplitude and direction of the gradient using a partial derivative finite difference, and connect the edge with a double threshold algorithm after non maximum value of the gradient is suppressed.

A detection image with a difference of 20 in gray value was

established, and a variety of graphs were drawn to simulate the residual core. The real residual core must be the overlay of one or more of the images. Gauss noise of 0.02 variance is added to the image, as shown in Fig. 4(a). The image frequency spectrum was obtained by Fourier transform, and the low pass filtering and mean filtering were used. The filtered image was transformed by linear point transformation. The results of enhancement and subtraction are shown in Fig. 4(b) and (c). Finally, 'Canny' operator is used to detect the boundary, and the boundary was extracted as shown in Fig. 4 (e) and (f). The image spectrum obtained by Fourier transform is shown in Fig. 4(d).

Fig.4: Comparison of different filter processing results: (a) original test, (b) ideal filter processing, (c) mean filter, (d) Fourier transform spectrum, (e) ideal filter processing boundary extraction, (f) mean filtering boundary extraction

From Fig. 4(a), it is difficult to distinguish the graphic information of the images with noise. The signal to noise ratio $SNR1 = -0.0282 < 0$, calculated using MATLAB software, indicates that the amount of noise information in the picture is more than 10% of the signal information, and the effective signal has been covered by the noise, so the effective signal is difficult to extract. In the residual core detection, the residual core contrast is the effective signal, and the residual core information is difficult to detect when the noise is too loud. After the ideal filtering, the signal to noise ratio ($SNR2=0.0994$) is improved by 0.1276, which indicates the signal information is only slightly higher than the noise information. Although the graphic contour is maintained, the noise is not smooth enough. The noise contrast is also improved after the linear point operation. Boundary extraction can extract the boundary of the graph, but the noise boundary is also extracted at the same time, so the boundary of the graph cannot be identified. Although the mean filter is more ambiguous than the ideal filter, the

$SNR3=26.9822$, increased by 27.0104, indicates the significant noise suppression influence. The boundary extraction results show that although the figure boundary has a little distortion, the edges are accurately extracted. In the actual normal detection, the actual noise value is far less than the artificial added value of the test picture, so the image processing results will be more significant, and the distortion of the graphics is smaller.

2.3 Application of tracer and image analysis detection technology to blade casting

First, a casting which is determined by cutting to have no residual core is obtained as a standard background. It is necessary to ensure that each test casting's position and angle of exposure remain the same. The total thickness of the two sides of the casting is more than 5 mm and the widest inner cavity is only 2 mm. According to the laws in Fig. 3, the concentration of tracer is slightly increased from 20% to 30%. Because rubber has better plasticity than Al_2O_3 , it is more suitable to be processed into

a sample. The tracer is added into the rubber, and because the rubber has a lower atomic number, the change of the gray value is less than that of the alumina core. If the low gray value change can be detected, in theory, the greater gray value change will be more easily detected. For example, the detected substance is the residual core which can be traced. Then the rubber is processed

into a rectangular specimen with a specific thickness. The test results of a blade with residual core are shown in Fig. 5. The results of filtering and linear point operations are shown in Figs. 6(a) to (d). The final boundary extraction results are shown in Figs. 6(e) to (f).

Fig. 5: Test results of blade: (a) position of simulated residual core, (b) 0%–2 mm, (c) 30%–0.6 mm, (d) 30%–1.0 mm (thickness of residual core)

Fig. 6: Image enhancement and final detection results: (a and d) 0%–2.0 mm, (b and e) 30%–1.0 mm, (c and f) 30%–0.6 mm

In digital ray detection, the area of the residual core has no effect on the contrast of the image, which is different from traditional film imaging. The process of film evaluation is used to identify the residual core by computer. The minimum resolution size of the detection system (the spatial resolution of the system) has been introduced in detail in the ray theory. Therefore, the practical application focuses on the testing of the core of different thickness. As the test block is a standard rectangular block, its position is known. If the size, shape and position of the test results are in accordance with the preset ones, the results of the computer recognition can be proved to be correct.

From the above results, as the attenuation coefficient of the residual core without tracer is too small, although the thickness of the residual core is 2.0 mm, there is still insufficient contrast, which cannot be detected either by artificial or by computer recognition. After tracer processing, the contrast is beyond the range of the gray fluctuation of the image itself. Furthermore, using the image enhancement to amplify this difference, the 1.0 mm thickness residual core can be identified by artificial recognition. However, the specific shape and size of 1.0 mm thickness residual core cannot be judged. The residual core of 0.6 mm thick cannot be observed by artificial recognition. Using the computer boundary extraction technique to detect the residual core, the contour and position of the prepositioned residual core were successfully extracted. It can be found that the 0.6 mm thick residual core can be accurately detected on the casting with 5 mm wall thickness, as shown in Fig. 6 (f).

3 Conclusions

A new detection method for a tiny core in a complex cavity is proposed. It overcomes the disadvantages of the traditional method that cannot detect the micro residual core in blade and of low detection efficiency. The tracer is used to make the contrast between the residual core and the casting, and the image processing technique is used to amplify this contrast. Tracer processing and image processing are both essential for detection of a very small amount of residual core.

(1) The relationship among the concentration of the tracer, the size of the core, the wall thickness of the castings and the contrast were obtained by tracer treatment. According to the experimental results, the minimum detectable amount under different conditions was obtained. When the tracer concentration is 20% and the wall thickness of the casting is 1.0 mm, the minimum detection amount is reduced from 4.398 mg to 0.438 mg.

(2) The signal-to-noise ratio (SNR) is effectively improved (increases 27.010) by means of mean filtering and linear point operation of the detected image in this study. The result of computer recognition is clear and reliable.

(3) The experiment result shows that the artificial identification can barely distinguish the 2 mm thick residual core on the 5 mm wall thickness blade. While by using computer recognition technology, the 0.6 mm thick residual core can be easily detected on the 5 mm thick blade.

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This work was supported by the National Natural Science Foundation of China (No. 51475120) and Major Program of National Natural Science Foundation of China (No. U1537201).