Applications of Advanced Technologies in the Residual Ceramic Cores Detection for Hollow Turbine Blades

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Abstract: The mechanism of leaching-out process of ceramic core for hollow turbine blade, as well as the causes and hazards of the residual core were analyzed in this article. The applicable scope of common residual cores detection methods was briefly introduced. By comparing the characteristics and respective applicability of high-precision advanced detection technologies such as X-ray detection, industrial CT detection, neutron radiography detection in detail, exploring the factors and methods for controlling the quality of detection images, neutron radiography was pointed out as a prospective technology in residual ceramic core detection field in the future.

Keywords: leaching-out process; residual cores; detection technologies; neutron radiography; hollow turbine blade

1 Introduction

Ceramic cores are widely used in the manufacturing of hollow turbine blades. By presetting ceramic cores, complex gas cooling internal channels are cast to improve blade cooling conditions and temperature bearing capacity, which is recognized as the most effective way to improve the inlet air temperature of the turbine and the efficiency of the engine[1]. After the casting process, ceramic cores need to be completely leached out to obtain a blade casting with designed complex cavities. Many reasons, such as extremely complex core structures, narrow and curved internal channels, stable chemical properties of core materials, make it quite difficult to leach out the cores thoroughly[2].

A core removal equipment with high temperature and high pressure is often used in the leaching-out process, meanwhile high concentration alkaline solution added as medium solvent. The essence of leaching-out process is the corrosion damage of the connections between core particles by high concentration alkaline solution, resulting in the collapse of core particles[3]. Unreacted ceramic particles and corrosion products are then peeled off from internal cavities of the casting under the flushing of high-temperature and high-pressure alkaline solution, which is a relatively slow process[4-5]. Due to the high melting point and poor solubility performance, corrosion products and ceramic particles are prone to adhere to the unreacted core interface, hindering further penetration of the alkaline solution and leading to the termination of the reaction. During the process of being flushed out from the internal cavities of the casting, corrosion products and ceramic particles are easy to adhere to the internal walls of the cavities because of their narrow and curved shapes[6-7]. The two main reasons for the formation of residual cores are illustrated above.

Residual cores in the internal cavities can block the cooling channels of the blade, affecting the smooth flow of cooling air and causing hot spots on the blade. During operation, serious damage to the blade may occur as a result of thermochemical corrosion and thermal stress[8]. In addition, residual cores will flow in the cavities under high temperature conditions, disrupting the balance and threatening the safety of the engine. Therefore, it is very necessary to conduct detection process to ensure that there are no residual cores in the internal cavities before installing the blade onto the engine.

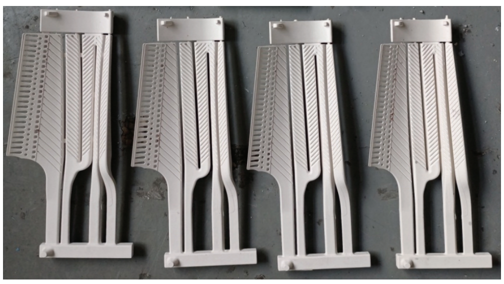


Fig.1: Large complex ceramic cores prepared by the authors' team

Common residual cores detection methods mainly include flow channel detection method, endoscopic photography method, while some advanced detection technologies include X-ray detection technology, industrial CT detection technology and neutron radiography detection technology. Among them, the first two methods are suitable for detecting residual cores of a relatively simple shaped blade, and X-ray detection method, industrial CT detection technology and neutron radiography detection technology have showed obvious advantages in detecting residual cores of a blade with complex internal cavities.

2 Common residual cores detection methods

By measuring the changes in water flow rate through the leading edge and trailing edge of the blade cavity, the purpose of detecting the blade cavity is achieved. Yuan[9] et al. and Hao[10] et al. have designed some detection processes and equipment for this method to meet production requirements.

Flow channel detection method is suitable for rough qualitative detection of hollow blade with simple internal cavities and larger residual cores. When the residual core layer is thin, the impact of the residual core on water flow becomes weaker, and the measurement accuracy will be affected.

Fig.2: Flow channel detection[11]

Another effective detection method is named as endoscopic photography. An industrial endoscopic probe is directly inserted into the internal cavities of the blade. The position and size of the residual cores can be clearly observed in real time through the camera on the endoscopic probe. This intuitive and accurate method is no longer effective due to the inability of the probe to enter small and narrow internal channels. Fig.3 shows photos of the residual cores taken by the author using endoscopic photography[12].

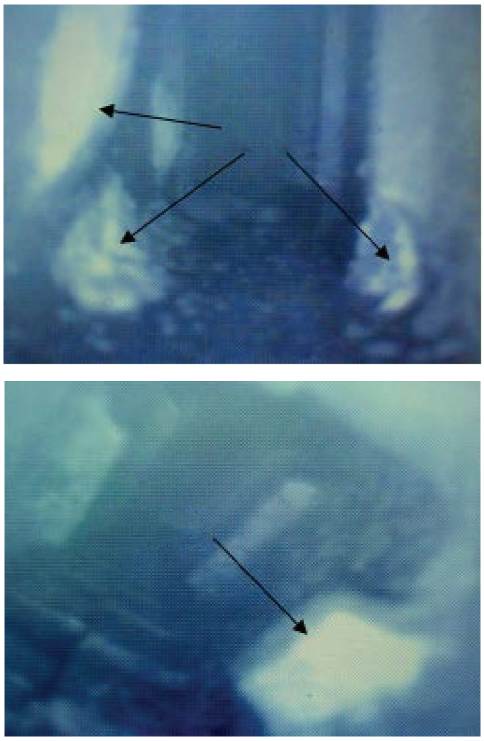


Fig.3: Endoscopic photographs of residual ceramic cores

3 High-precision advanced residual cores detection technologies

3.1 X-ray detection technology

Similar to its application in the medical field, X-ray detection technology utilizes the difference in penetrative radiation response between casting metal and core material to determine the location of residual cores within hollow blade. The detection accuracy depends on the difference in blackness on the film to a large extent. The greater the difference between the linear attenuation coefficient of the residual core and of the air is, the greater the difference in blackness on the film will be, which is more conducive to displaying the detection result and improving the detection accuracy. At present, there are mainly two types of ceramic cores used for manufacturing hollow blades: silica-based and alumina-based, with SiO_2 and Al_2O_3 as the matrix materials respectively. Linear attenuation coefficients of residual cores and air are relatively close, as a result, the accuracy of residual cores detection cannot be guaranteed. To improve the contrast ratio of radiography, commonly used methods in industry include powder filling detection, tracer detection and dopant detection.

3.1.1 Powder filling detection technology

The powder filling detection technology is to fill the metal powder evenly into the internal cavities of the casting, enrich the hollow casting, and make it approximately a solid metal casting. By adopting the difference in linear attenuation coefficient between the metal powder and the residual ceramic core, instead of that between air and the residual ceramic core, the imaging contrast can be significantly increased and tiny residual cores can be detected. The metal powder to be filled into the internal cavities must be dispersed fine powder, and its linear attenuation coefficient should be close to that of the casting metal[13]. Size and shape of the metal powder are strictly limited within a certain range. Uncompacted filling and adsorption of powder at the contour boundaries of the cavities may occur if the size and shape are not reasonable, which usually cause false detection[14]. A preferable range of powder particle size is usually between 50μm and 350μm.

Experiments have been taken by the author adopting powder filling detection technology to detect residual ceramic cores in turbine blades of a certain aircraft engine. Before operation, the metal powder should be dried at 150 ℃± 10 ℃ for 1-2hours, and then a sieve was used to remove impurities from the powder. During the detection, the blade castings vibrated within the range of 10Hz-20000Hz to expel air from the internal cavities. All the holes on the blades were sealed with polyvinyl chloride strips except for the holes for filling metal powder. Powder was continuously filled into the internal cavities and the castings were simultaneously vibrated to make the cavities compacted. Finally the castings were placed under a X-ray detection device. Fig.4 shows the photos, in which residual cores boundaries can be clearly observed at the leading edges of the blades[15].

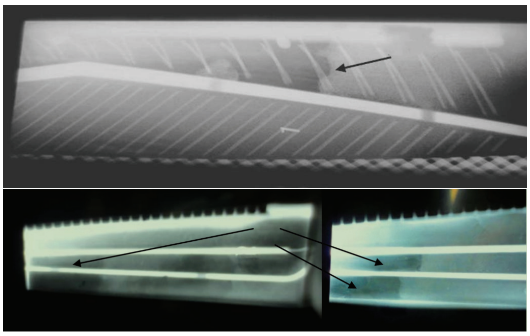


Fig.4: Detection photos of residual ceramic cores

3.1.2 Tracer detection technology and dopant detection technology

For more accurate detection of blades with more complex internal cavities, tracer detection technology and dopant detection technology were invented and have been widely used in the past decades. For tracer detection technology, casting should be immersed in a solution containing tracers to allow ceramic cores to absorb enough tracers.Tracers are generally substances with a density much higher than that of ceramic cores, which have strong absorption capacity for X-rays. They can increase the contrast of residual core images and improve detection accuracy in subsequent photographic detection processes. Tracers should be easily soluble in water or other solvents, and the solution can form soluble residues after drying, which facilitates the cleaning of residual tracers on the surface of blades. Tracers should contain elements with high atomic number to improve image contrast. Commonly used tracers include Na_2WO_4, $HfOCl_2$, $PbNO_3$, etc. For dopant detection technology, detection agent is doped into the ceramic core matrix material in advance. Photographic detection is directly conducted after the ceramic core is leached out from the casting. Due to the high density of the detection agent and its strong ability to absorb X-rays, it becomes easy to detect the presence of residual cores in hollow blade casting. The addition of dopants should not affect the strength, deflection, and other properties of the core. Dopants are generally substances with high atomic numbers, and matched with the properties of the core matrix materials. One of the commonly used dopants, for example, is HfO_2. Atomic number of Hf is 72 and thermal expansion rate of HfO_2 is $5.8\times10^{-6}K^{-1}$, which is close to the thermal expansion rate of the ceramic core matrix material (Al_2O_3 is $8.6\times10^{-6}K^{-1}$).

The US Patent 050255598Al has disclosed a new X-ray detection agent $CHnI_{4-n}$, which is a toxic and corrosive organic compound with a density about one-third that of lead[16]. However, its X-ray absorption capacity can reach three times that of lead. As a result, the detection ability of residual cores by radiation is greatly improved and the position of residual cores in other hollow castings can be easily located. The US patent NO5242007 used Na_2WO_4 as a tracer and achieved ideal detection results[17].

Yang[18] et al. adopted both tracer and doping technologies to conduct X-ray photographic detection on steel plate samples, DD6 superalloy samples, and blade samples, respectively. The tracer was $HfOCl_2$ solution, and the dopant was HfO_2. The results showed that the contrast of residual cores on the blade material increased with the increase of dopant concentration and core thickness. When the dopant concentration was 15%, residual cores with a thickness of 0.2mm could be detected on the blade material with a thickness of 1.0mm. It made significant improvement in the contrast of residual core images when using saturated $HfOCl_2$ solution for tracing treatment of hollow blades.

Zhao[19] et al. studied the permeation law of tracers in residual cores of different shapes, as well as the influence of residual core thickness, size and internal cavity thickness on the detection results. The results showed that as the permeation temperature increased, the tracer permeation rate decreased for block shaped residual cores, while that did not change significantly with temperature for powdered residual cores. When the internal cavity thickness was ≥ 2.6mm, there were no residual cores with a thickness ≤ 8.5μm detected, regardless of their sizes. When the internal cavity thickness was ≤ 3.8mm, residual core with a thickness of 17μm could be detected.

3.2 Industrial CT detection technology

CT scanning has played a significant role in non-destructive testing in the industrial field, meanwhile, it is also widely used in detecting residual cores in hollow blade. The industrial CT detection technology uses a beam of radiation to scan the blade, reconstructs the transmission image in three dimensions, obtains the overall data of the detected blade, and imports it into graphic display software to observe whether there are residual cores and their sizes at various positions inside the blade[20-21]. The position of the residual core can be observed clearly and its size can be measured thanks to the use of tomography and layer by layer slicing techniques.

Han[22] et al. conducted experiments adopting industrial CT detection technology for transmission detection of a hollow blade, and compared it with powder filling detection technology. The acquisition voltages of blades A and B were 280kV and 295kV, respectively, and the blades reconstruction time was 45 minutes. The detection images are shown in Fig.5 and Fig.6. By comparison, the images display better effect.

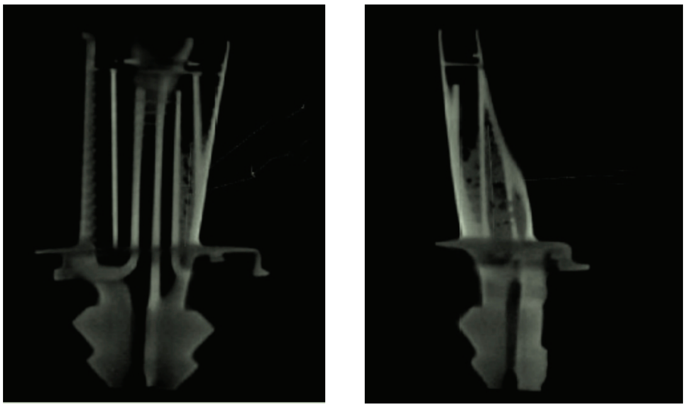


Fig.5: Detection photographs of residual ceramic cores in a certain layer of blade A

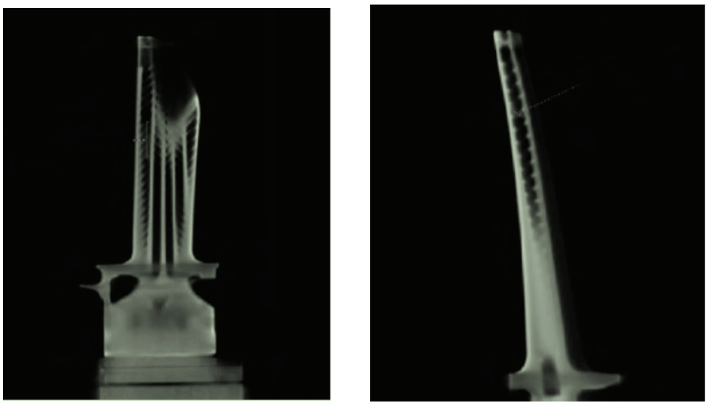


Fig.6: Detection photographs of residual ceramic cores in a certain layer of blade B

3.3 Neutron radiography detection technology

Due to the limitations of the density difference between residual cores and air, and the limited ability of X-rays to penetrate metals, X-ray detection technology is only effective when detecting cores with relatively large residual amounts in blade internal cavities with small thickness. For large-sized blades with thick internal cavities or trace residual cores, the detection result is often not ideal[23]. In response, developed countries have begun to research and adopt neutron radiography detection technology.

Similar to X-ray detection technology, neutron radiography detection technology uses a neutron beam to pass through the detected blade. The internal structural information of the blade can be reflected by the attenuation degree of the radiation intensity.The attenuation characteristics of neutron rays are quite different from those of X-rays. Neutrons can easily penetrate the electron layer of matter and react with atomic nucleus owing to their uncharged nature. The magnitude of their attenuation coefficient depends on the nuclear reaction between the atomic nucleus and neutrons[24]. Neutron radiation can easily penetrate many metallic materials, but the attenuation becomes particularly significant when penetrating some lightweight elements. Therefore, neutron radiography can detect lightweight materials wrapped in metallic materials and is suitable for detecting residual cores in hollow blades[25].

Neutrons can be classified by energy into cold neutrons(<0.01eV), thermal neutrons (0.01-0.50eV), slow neutrons (0.50-10.00eV), fast neutrons (10.00-2.00×10^{6}eV), and relativistic neutrons(>2.00×10^{6}eV). Fast neutrons, thermal neutrons, and cold neutrons are commonly used for photographic detection, with thermal neutrons being the most widely used. The properties and characteristics of common thermal neutron sources are shown in Table 1[26].

Table 1. Properties and characteristics of thermal neutron sources

Type of source	Typical radiographic intensity /(n•cm^{-2} •s^{-1})	Spatial resolution	Exposure time	Characteristics
Radioisotope	10^1-10^4	Poor to medium	Long	Stable operation, low-to-medium investment cost, possibly movable
Accelerator	10^3-10^6	Medium	Average	On-off operation, medium cost, possibly movable
Subcritical assembly	10^4-10^6	Good	Average	Stable operation, medium-to-high investment cost, difficult to move
Nuclear reactor	10^5-10^8	Excellent	Short	Medium-to-high investment cost, difficult to move

The mass attenuation coefficients of thermal neutrons and X-rays for different elements are compared in Fig.7[27], where the neutron energy is 0.025eV and the X-ray energy is 125kV. It can be seen that thermal neutrons have large mass attenuation coefficients for light elements such as H, B, Li, and rare-earth elements such as Gd, Sm, Eu, while their mass attenuation coefficients for most metals such as Fe, Pb, Cu, Ni are relatively small.

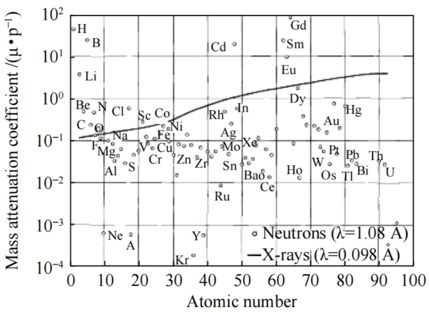


Fig. 7: Mass attenuation coefficients of neutron and X-ray for different elements

In practical operation, for the purpose of improving attenuation effect of ceramic cores on neutron rays, it is usually necessary to use contrast agents. As an ideal element with the strongest absorption of thermal neutrons and the highest attenuation coefficient of thermal neutron rays, gadolinium is regarded as a typical element that can be used in thermal neutron contrast agents. Similar to X-ray detection technology, neutron radiography detection technology is also divided into two types: tracer and dopant.

A Canadian company named Nray has provided neutron radiography services to customers worldwide[28]. Figure 8 shows the photos of the residual core inside the turbine blade of the aircraft engine adopting thermal neutron radiography detection. The blade was processed using tracing method, and the residual core inside the blade can be clearly observed in the photo. Edenborough[29] et al. from the United States doped ceramic cores with Gd_2O_3 at a concentration of 3%, and detected residual amounts of only 1mg in the ceramic cores. W.J. Richards et al. from the University of California, USA, used Gd_2O_3 to mark the surface layer material of the ceramic shell. A shell material with a thickness of only 0.075mm was detected on a titanium alloy component with a thickness of 6.25cm. Korea Atomic Energy Research Institute[30] conducted a neutron radiography detection of the residual steel balls inside the turbine blades after shot peening process. Gadolinium nitrate solution was used as developer and steel balls with a diameter of only 0.2mm could be detected, as is shown in Fig.9.

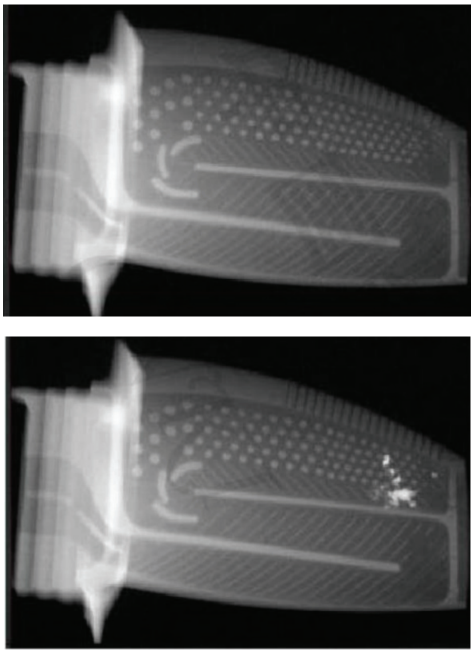


Fig.8: Thermal neutron photographs of engine turbine blades

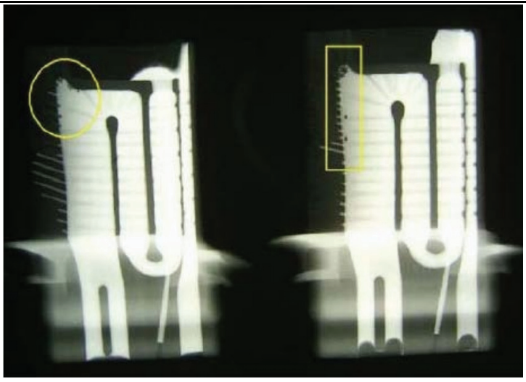


Fig.9 Neutron photographs of engine turbines blade containing steel balls

After decades of development, the neutron radiography detection technology for blade residues has become increasingly mature. Major engine companies around the world, such as GE(shown in Fig.10[31]), Pratt&Whitney, and Honeywell, have established relevant enterprise standards requiring the use of reactor neutron source to detect residual cores in hollow blade.

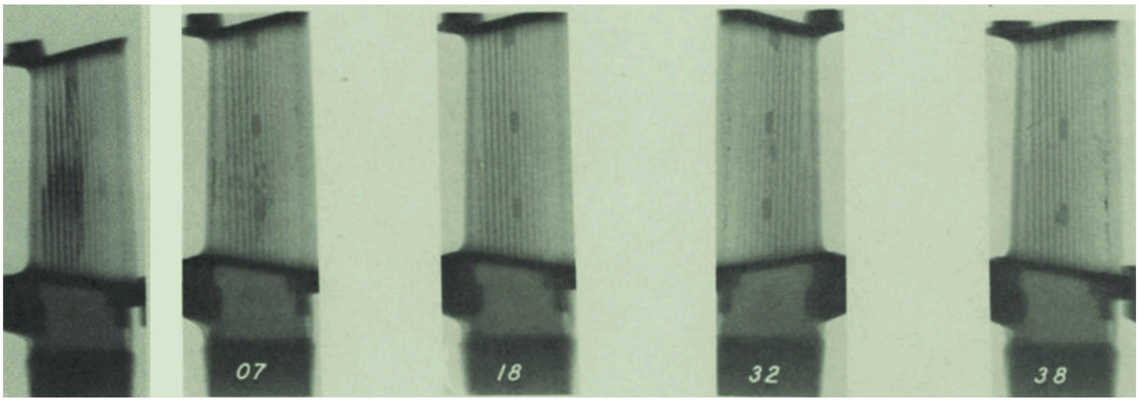


Fig. 10: Neutron radiographs of residual cores in blades of General Motors

Domestic researches on neutron radiography detection technology for residual cores in hollow blade is still in the laboratory exploration stage. It needs large amounts of experiments and further improvements before the technology can be widely applied in engineering. Taiwan Nuclear Energy Research Institute[32] conducted experiments using gadolinium nitrate solution with a concentration of 4.3% and gadolinium compounds with a mass fraction of 1.5% to 3% as tracers and dopants to trace ceramic cores. Residual cores with a minimum thickness of 0.3mm could be detected, as is shown in Fig.11. Gao's[33] researches studied the detection sensitivity of residual core with Gd_2O_3 tracer content of 3% and analyzed the quantitative relationship between sensitivity, transmission thickness, and residual core thickness, as well as the influence of blade structure on detection results. Yang[34] et al. used Gd_2O_3 with a concentration of 2% as a developer, and residual cores with a thickness of 0.2mm could be clearly observed on a blade material with a thickness of 1.0mm.

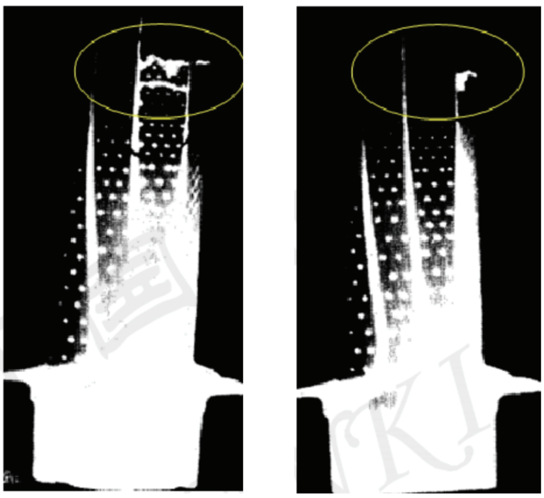


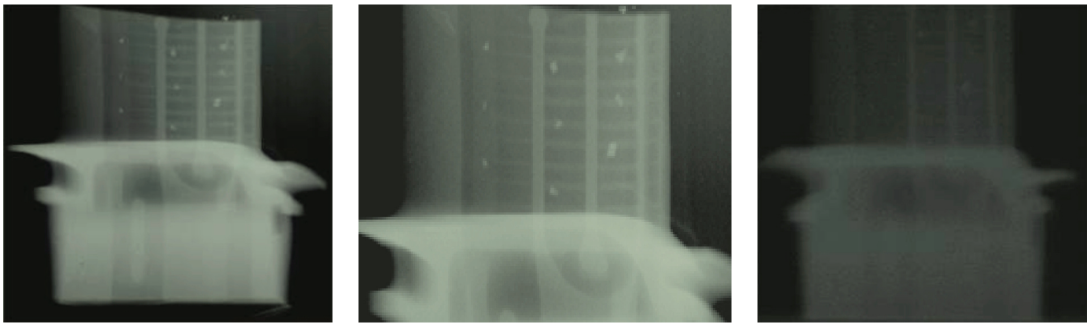
Fig.11: Thermal neutron photographs of air cooled turbine blades (left:tracer, right:dopant)

4 Quality control of residual core detection image

The quality of the detection image is the most intuitive reflection of detection accuracy. Size parameters and shape/position characteristics of residual cores, internal cavity thickness, agent concentrations and image processing technology usually play important roles in the quality control of residual core detection image.

According to the radiation attenuation theory, the thicker the residual core is, the more attenuation occurs when the radiation penetrates, meanwhile, the larger the residual core is, the more obvious the grayscale area in the detection image appears, resulting in more conducive identification and detection of residual cores. Shape/position characteristics mainly refer to the adhesion position of the residual core. In most cases, when the thickness direction of the core is parallel to that of the radiation, the image presents better quality[35-36]. A general rule of the influence of internal cavity thickness on the quality of detection image is that when the detection parameters are constant, as the internal cavity thickness increases, the brightness difference between different parts (areas with and without residual cores) decreases, resulting in poor image quality.

Another important method for image quality control is named as image processing technology, adopting various advanced algorithms for image enhancement and extraction of information to increase image contrast[37]. The image quality is usually affected by factors such as exposure time, scattered rays, film quality, development time, image acquisition equipment, and image display equipment. Problems including low contrast, low signal-to-noise ratio, and blurred defect edges usually make detection failed. Software such as Photoshop, Matlab, ImageJ, etc. can be used in image enhancement[38-39]. Different image processing technologies are introduced in Reference 37. Neutron radiographic results of hollow turbine blade specimen obtained by various imaging techniques are shown in Fig.12[40].



（a）single-emulsion film （b）double coated film （c）CCD camera

Fig.12: Neutron radiographic results of hollow turbine blade specimen obtained by various imaging techniques

5 Summary

The high-precision detection technology for residual cores in hollow blade plays a crucial role in the development and manufacturing of advanced aircraft engines and gas turbines. It has been one of of the key technologies to ensure normal operation of blades. At present, X-ray detection technology is widely used in industry for residual core detection. Through powder filling, tracing or doping, it is possible to improve the accuracy of residual core detection. Neutron radiography detection technology is charactered with high detection accuracy, but due to the limited popularity of detection equipment and high operating and maintenance costs, it is still in laboratory exploration stage and has not yet formed engineering capabilities, which is a prospective development direction of high-precision detection technology for hollow blade residual cores in the future.

Conflicts of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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