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A new X-ray backscatter imaging technique for non-destructive testing of aerospace materials

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ABSTRACT

This paper presents a new X-ray backscatter technique (XBT) for non-destructive imaging of aerospace materials with only a single-sided access. It uses a special twisted slit collimator to inspect the whole object by changing the viewing direction of the X-ray backscatter camera. For the first time, the X-ray backscatter measurements were conducted using high-energy (> 500 keV) X-ray sources. Experiments were performed on thick complex structured aluminium components, stringers and honeycomb structures to validate the applicability of the present technique to image small changes in the material properties and also to detect low-density material inclusions. In order to reduce the inspection time from hours to several seconds and to improve the image quality of the X-ray backscatter image, the backscattered signals were measured using a digital detector array with high spatial resolution (200 μm). The influence of the energy of the X-ray source and the slit width of the camera on the X-ray backscatter image were also investigated. In the proposed technique, the whole object is irradiated by an uncollimated X-ray beam resulting in a low image acquisition time of 3 min that facilitates the use of XBT for the real time NDT&E of aerospace materials.

1. Introduction

Critical parts in aircraft manufacturing industries such as stringers are very commonly used in modern aircraft structures to resist severe compressive loads caused by the aerodynamic effects. They are generally made-up of thin aluminium (Al) metal sheets and are one of the key components in the aircraft wings. Any defects in the stringer components leads to weakening of the stiffness of the whole aircraft wing structure and consequently, failure may occur. Hence, there is a need to evaluate the structural integrity of the stringers using reliable non-destructive testing (NDT) methods. Due to the complex shaped structure of the stringer, the one-sided access NDT method such as X-ray backscatter technique is more preferable for the non-destructive imaging.

In difference to conventional transmission X-ray radiography, the X-ray backscatter technique (XBT) utilizes the scattered radiation caused by the Compton scattering effect [1,2]. As the Compton scattering effect depends on electron density (ρ_e) in the scattered object, low-atomic number (Z) materials (e.g. Al, Perspex, composites and water) exhibit predominant scattered radiations compared to the heavy metals such as Fe, Cu and Pb, respectively. The efficiency of the XBT depends on how accurate and fast the scattered radiation beam from the object is realized on the detector using only a single-sided access.

Fig. 1 illustrates the main differences between existing and the new X-ray backscatter technique for non-destructive imaging of materials. ComScan (Compton backscatter scanner) a commercially available X-ray backscatter imaging system for NDT of aerospace components was presented by Harding et al. [3]. Here, the backscatter image is visualized using a finely collimated X-ray source (160 keV) and a detector array equipped with slit collimators (see Fig. 1(a)). Furthermore, ComScan visualizes 22 planes in different depth in one scan using a flying-spot arrangement for the X-ray beam. The main disadvantages are the reduced beam opening and collimated X-ray source resulting in poor signal-to-noise ratio (SNR) and long measurement time. The other operational limitation of the ComScan system is the fixed geometry between X-ray source and the detector so the whole device scans the object plane-by-plane [4]. Fig. 1(b) shows the principle of flying-spot X-ray backscatter technique which uses a highly collimated beam of X-rays and large area detectors for collecting backscattered X-rays from the inspected object [5–7]. The main limitations of this technique are fixed irradiation geometry and a single-viewing direction. Fig. 1(c) illustrates the new X-ray backscatter imaging technique which uses an uncollimated powerful (high kW) X-ray beam along with an efficient pinhole camera encompassed with a digital detector array for the backscatter imaging of a test object.

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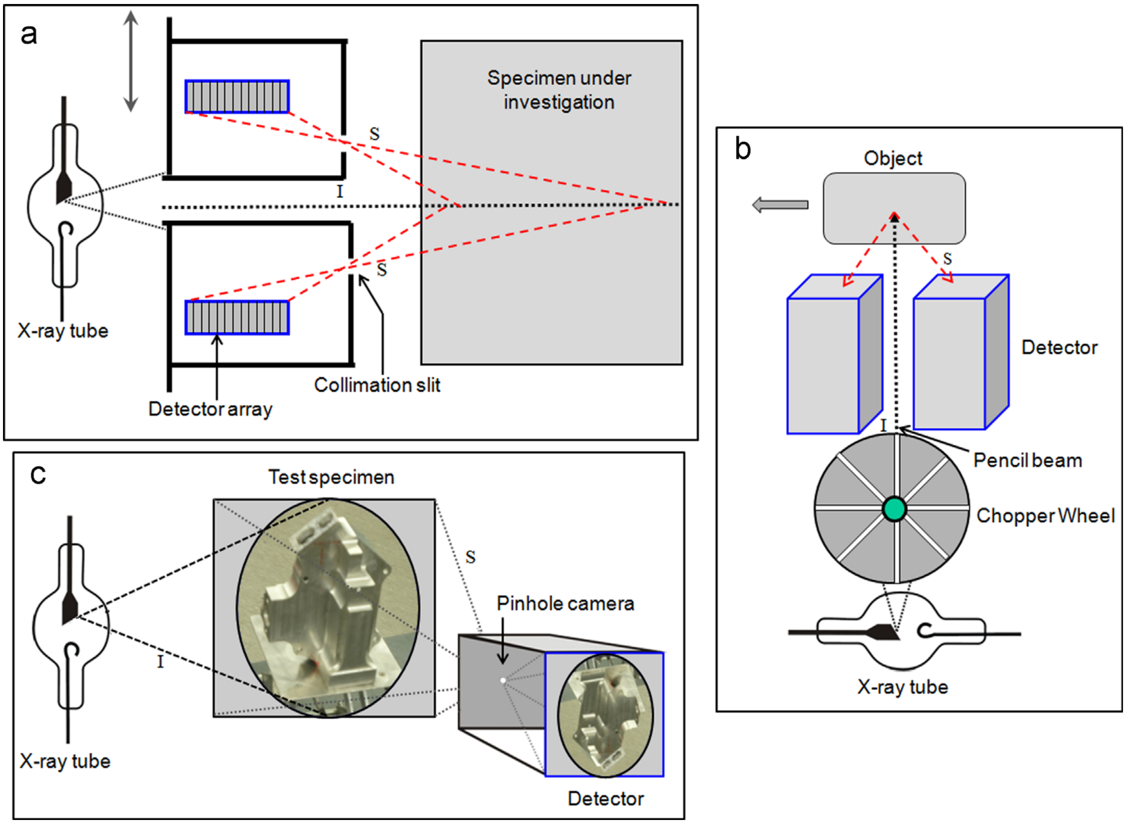

Fig. 1. Imaging principles of the X-ray backscatter technique using the (a) Compton backscatter Scanner (ComScan), (b) flying-spot technique and (c) pinhole camera method. I, S represent the incident and scattered X-rays.

The new X-ray backscatter camera is also equipped with a novel twisted slit collimator [8,9].

X-ray backscatter imaging using radiography by selective detection (RSD) method falls between highly collimated and uncollimated techniques and was discussed in detail by Shedlock et al. [10,11] and Jackson et al. [12]. The main drawback of this method is that it has high image acquisition time (on the order of hours). Strecker [13] presented the scatter X-ray images of aluminium castings using an X-ray fan-beam and a pinhole camera which allows the layer-by-layer imaging of the specimen being investigated. The low efficiency of the pinhole camera and the large measurement time are the main drawbacks of this technique.

Compton backscatter imaging for the corrosion detection in thick metals using gamma-ray methods were reported [14,15] where the scattered radiation was measured using a collimated gamma-ray beam and scintillation detectors. Generally, gamma-ray backscatter techniques are not suitable for NDT of aerospace materials because of the heavy shielding required for radioactive sources, low spatial-resolution images and large scanning time (on the order of hours). An in-line high-precision density measurement system using X-ray Compton scattering was presented by Zhu et al. [16,17]. NDT of steel/rubber composite sonar-domes using X-ray backscatter tomography was presented by Poranski et al. [18]. A review on X-ray backscatter imaging methods for the non-destructive testing and evaluation (NDT&E) was presented by Niemann et al. [19]. In addition, the X-ray backscatter technology was successfully applied in medical and security fields [20–23].

In this work, we present a new X-ray backscatter technique for the non-destructive imaging of aerospace materials. First, the X-ray backscatter imaging principle and a short discussion on the developed X-ray backscatter camera are presented. Following that, preliminary experimental investigations on stringers, honeycomb structured plates and complex structured aluminium materials are presented along with a quantitative discussion on defect detection and sizing. Then, the effect of X-ray source energy and slit width of the backscatter camera on the quality of the X-ray backscatter image is presented. Finally, some important applications of the proposed technique in aerospace industries are discussed.

2. Development of an X-ray backscatter technique for non-destructive testing of materials

The X-ray backscatter technique presented in this work uses an un-collimated X-ray radiation to irradiate the whole object being inspected. It uses a novel combination of a unique twisted-slit collimator and a digital detector array (DDA) to image backscattered radiation. Fig. 2 shows the schematic of the X-ray backscatter technique for non-destructive imaging of aerospace materials. In the following, a detailed description on the new twisted slit collimator and construction of the X-ray backscatter camera are discussed.

2.1. Novel twisted slit collimator

Fig. 3(a) shows the schematic of the new twisted slit collimator. The inside of the slit is lined with ruled surfaces consequently the linear passage of the backscatter radiation through the slit is possible only through a hole-shaped gap in any through thickness direction [9,22]. The schematic of the constructed twisted slit collimator with dimension 50 mm (length) $\times$ 50 mm (height) is shown in Fig. 3(b). Here, the slit is made from tungsten with a wall thickness of 50 mm. On the front side, the slit is inclined into one direction and on the