

New X-ray Backscatter Imaging Technique for Nondestructive Testing of Aerospace Components

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Abstract

Critical parts in aircraft manufacturing such as stringers are very commonly used in modern aircraft structures to resist the 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 leads to weakening of the stiffness of the whole wing structure and consequently, failures may occur. Hence, the structural integrity of the stringers should be evaluated 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 this paper, we present a new X-ray backscatter technique to image the internal sections of the stringer with only a single-sided access. The whole object was inspected 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 ($> 0.5\text{MeV}$) X-rays and proved the applicability of the present technique to inspect thick carbon-fiber laminated components. In order to improve the inspection time and image quality of the backscatter image, we used high-resolution ($180\mu\text{m}$) digital detector arrays (DDAs). At the end, important applications of the presented X-ray backscatter technique to the aerospace industry are discussed.

Keywords: X-ray backscatter imaging, twisted-slit collimator, NDT, digital detector array, stringer, aerospace applications

1. Introduction

In difference to conventional transmission X-ray radiography, the X-ray backscatter technique (XBT) utilizes the scattered radiation caused by the Compton effect [1]. As the Compton-effect depends on electron density in the scattered object, low-atomic-number (Z) materials (eg. Al, PMMA, 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.

Figure 1 illustrates the main differences between existing and the new X-ray backscatter technique for nondestructive imaging (NDI) 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. [2, 3]. Here, the backscatter image is visualized using a finely collimated X-ray source (160keV) and a detector array equipped with slit collimators (see Fig. 1(a)). The main disadvantages are the reduced beam opening and collimated X-ray source resulting in poor signal-to-noise ratio (SNR), long measurement time. Figure 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 backscatter X-rays from the inspected object [4, 5]. The main limitations of this technique are fixed irradiation geometry and a single-viewing direction. Figure 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 (DDA) for the backscatter imaging of a test-object. The new X-ray backscatter camera is also equipped with a novel twisted slit collimator [6-8].

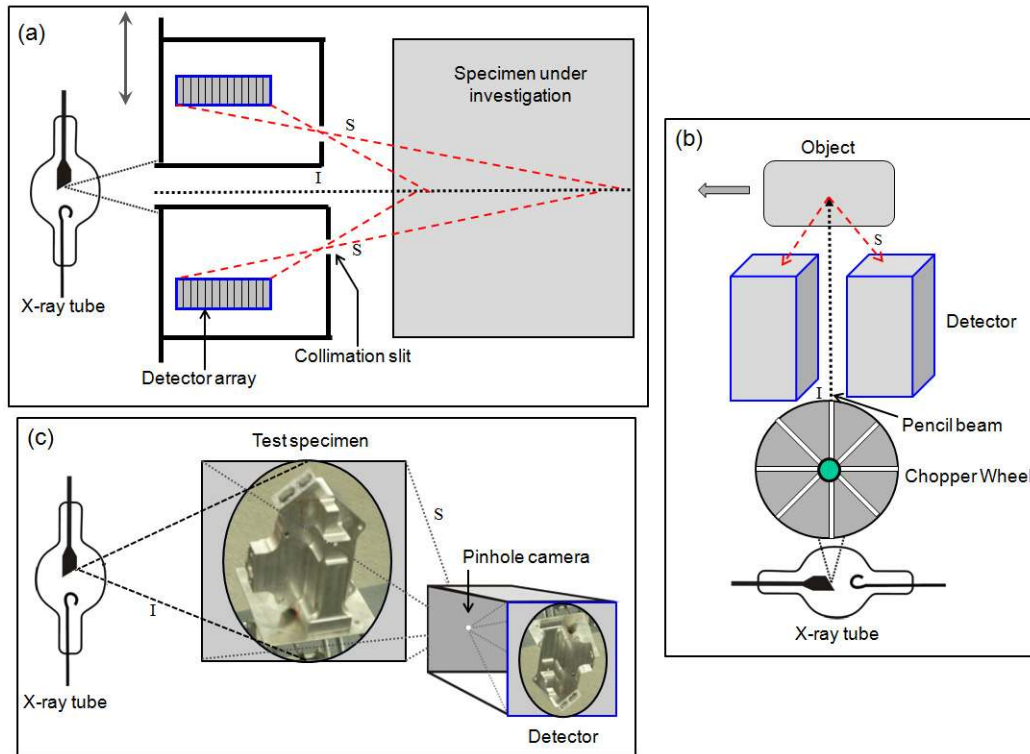


Figure 1: Imaging principles of the X-ray backscatter technique using the (a) Compton backscatter Scanner (ComScan), (b) flying-spot technique and (c) pinhole camera method. I, S represent the incident and scattered X-rays.

X-ray backscatter imaging using radiography by selective deposition (RSD) method falls between highly collimated and uncollimated techniques and was discussed in detail by Shedlock et al. [9] and Jackson et al. [10]. The main drawback of this method is that it has high image-acquisition time.

In this work, we present a new X-ray backscatter technique for the nondestructive 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 complex structured stringer component and honeycomb structures are presented. Finally, some important applications of the proposed technique in aerospace industries are discussed.

2. New X-ray Backscatter Technique for NDT of Materials

2.1 Novel Twisted-slit Collimator

Figure 2(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 [6-8]. The constructed twisted slit collimator with dimension 50 mm (length) x 50 mm (height) is shown in Figure 2(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 backside it is inclined in the opposite direction (see Fig. 2(c)). This approach results in a large angular aperture with a wall

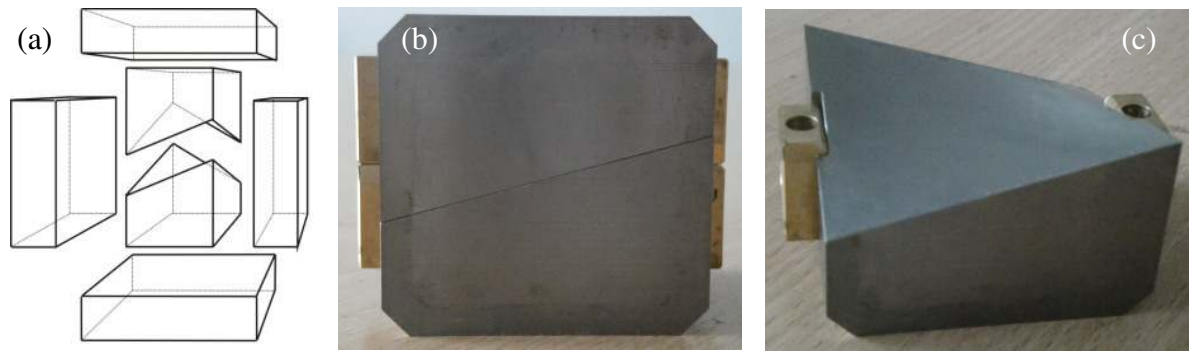


Figure 2: A new twisted-slit collimator for X-ray backscatter imaging of aerospace materials (a) schematic representation of the twisted-slit collimator showing upper and lower part of the collimator, (b) photograph of the constructed slit-collimator and (c) inner surface of the slit-collimator.

thickness adequate for shielding high-energy X-ray radiation (> 1 MeV) that bypass the slit-collimator. Additionally, the two ends of the slit collimator are equipped with a spring loaded arrangement for controlling the passage of backscattered photon flux by adjusting the gap between lower and upper part of the slit collimator (see Figure 2(c)).

2.2 Construction of the X-ray Backscatter Camera

The developed X-ray backscatter camera for the nondestructive inspection of materials is shown in Figure 3. It is embedded along with a twisted-slit collimator into the housing constructed from tungsten for reducing the undesirable scattered radiation from surroundings. The spatial resolution of the image and the backscatter signal intensity can be controlled by varying the slit opening as shown in Figure 3(a). Additionally, it consists of a 10 mm thick steel plate at the rear side in order to protect the detector-electronics against direct radiation from the X-ray source. The internal construction of the X-ray backscatter camera is shown in Figure 3(b). The importance of shielding the bolted area from the scattered X-ray radiation was evident from our investigations and hence in the final construction, the bolted area was shielded by thick lead cylinders (a diameter of 5 mm) as shown in Figure 3(b). Because of its low weight (~ 50 kg) and compact construction, the new X-ray backscatter camera can be used for mobile NDT applications.

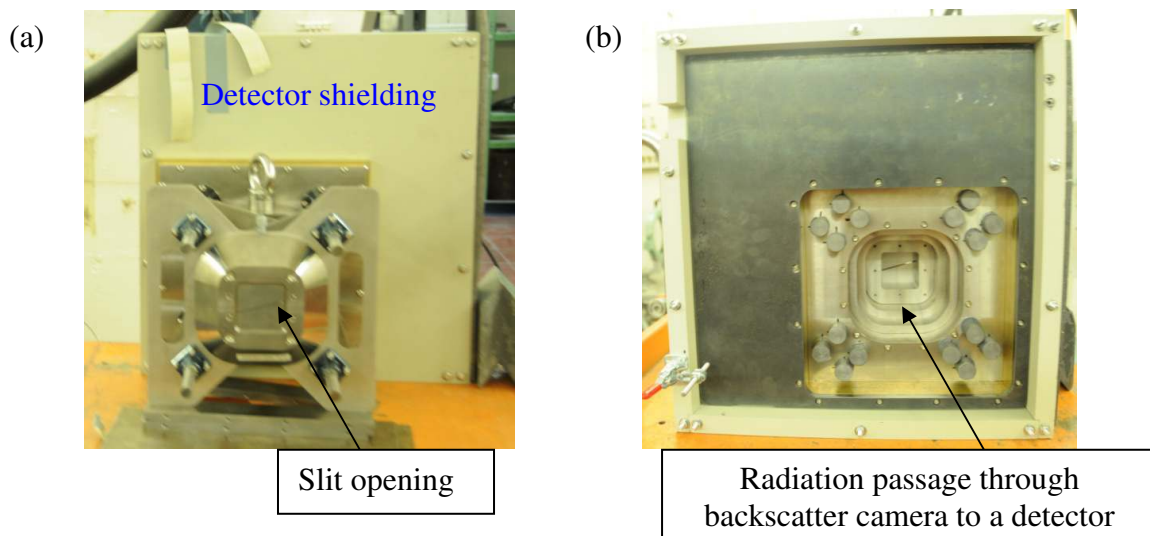


Figure 3: Constructed portable X-ray backscatter camera (a) front view and (b) internal construction.

3. Experimental Results and Discussion

3.1 Experimental Setup and Data Acquisition

Schematic of the experimental setup used for the X-ray backscatter imaging of aerospace materials is shown in Figure 4. An industrial X-ray tube (Comet MXR-600 HP/11) with a maximum voltage of 600 kV and anode current of 2.5 mA was used to irradiate the object being inspected. The focal-spot diameter (d) of the tungsten target material was 1 mm. The X-ray backscatter camera was placed near to the source side forming an angle of about 45° between incident and scatter radiation directions for imaging. The width of the twisted slit collimator is 1.4 mm. The backscatter X-ray imaging was carried out using an X-ray backscatter camera equipped with a high resolution digital flat panel detector. The reason for selecting digital detector array for measuring backscatter radiation in this study is due to its high signal-to-noise ratio (SNR) and fast image acquisition time (~ 180 sec) as compared to the conventional imaging plates [11, 12]. The X-ray imaging area on the amorphous-silicon based digital flat panel detector (VIDISCO Rayzor-X) is 22.2×22.2 cm² and it consists of 1560×1560 pixels with a pixel size of $143 \mu\text{m}$.

In the present experiments, the actual backscatter imaging area on the detector is limited by the slit collimator geometry, mainly its width. The backscatter image data was acquired using digital X-ray imaging software (XbitPro) [13]. The backscattered signals were digitized at 14 bit grey level (i.e. grey value range between 0 and 16,384) for obtaining better image quality. In order to reduce the scattered radiation from surroundings (i.e. noise in the image), we positioned a 3 mm thick Cu plate followed by a 5 mm thick Pb plate at the rear side of the digital detector array.

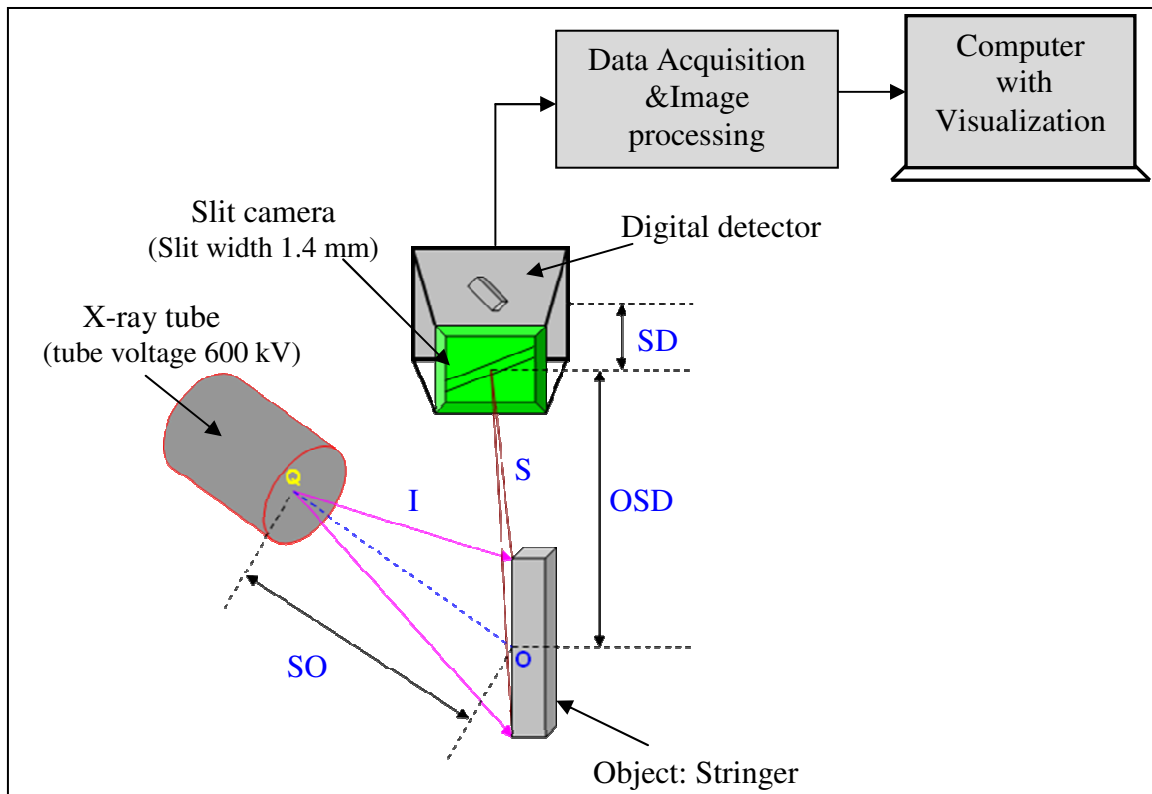


Figure 4: Schematic of the measurement setup used for X-ray backscatter imaging of the complex structured stringer component. Here, the viewing direction of the backscatter camera is variable.

3.2 X-ray Backscatter imaging of Stringer Components

Figure 5(a) shows the experimental setup used for the inspection of stringer component. The experimental investigation was carried out using 600 kV X-ray tube voltage, 2.5 mA as tube current and 3-minutes of exposure time. A slit width of 1.4 mm was used for allowing scattered radiation from the interrogated object through the X-ray backscatter camera. Figure 5(b) shows the backscatter image of the stringer component. This image was captured after successfully calibrating the unprocessed backscatter image data by using the calibration procedure [8] and subsequently applying the parallelepiped algorithm for geometrical correction. The variations in the material thicknesses and also all the stringer-skin-joints of 4-mm diameter along the stringer columns can be seen in the X-ray backscatter image. Interestingly, the scattered radiation from the steel (Fe) mounting table is also evident in the backscatter image (see Figure 5(b)). The measured backscatter intensity profiles along the two columns (represented as locations A and B in Figure 5(b)) of the stringer component are shown in Figure 5(c). A good contrast between background and skin-joint materials can be noticed in the intensity profiles. As expected, depending on the distance between object and slit camera and the angle between incident and scatter radiation, the differences in the backscatter signal intensities occur.

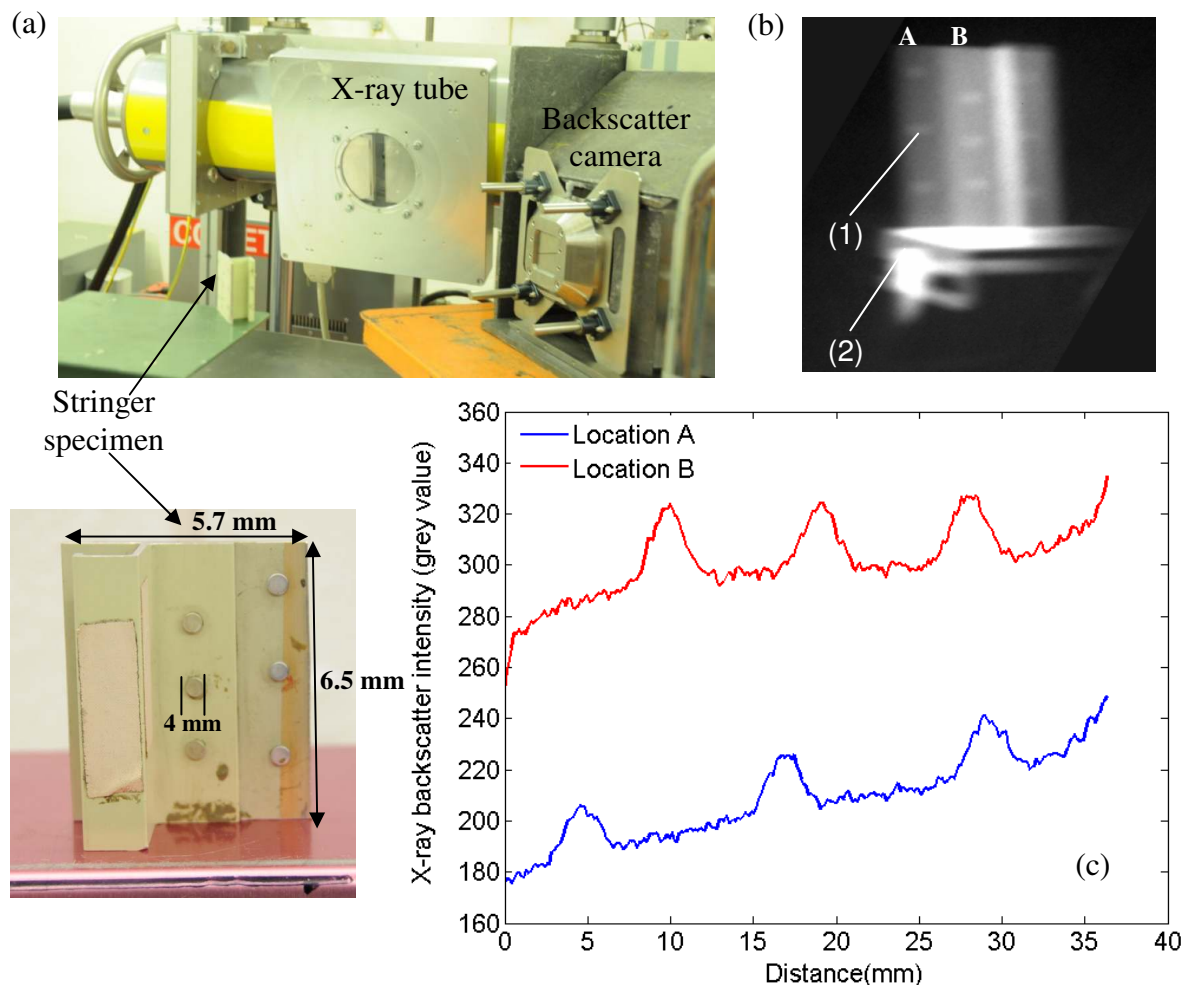


Figure 5: (a) Experimental setup for used for measuring X-ray backscatter image, (b) X-ray backscatter image of the stringer component showing the contrast between stringer skin and joints (1) and also the scatter radiation from steel mounting table (2) and (c) measured X-ray backscatter intensity profiles along the vertical columns at locations A and B in the backscatter image of the stringer component shown in Figure 5(b).

3.3 X-ray Backscatter imaging of thick Honeycomb structures

X-ray backscatter technique (XBT) has the significant advantage as compared to conventional through-transmission technique in detection of low-atomic-number (Z) materials (eg. water, moisture) in honeycomb structured plates using the unilateral access to the object. In order to validate the applicability of the present XBT to detect low- Z materials in honeycomb-structures, we investigated a 5 cm thick honeycomb structured plate which is generally used in aerospace industry.

In the first measurement, we attached lead (Pb) indicators on the front side of the composite skin plate as shown in Figure 6(a). The resulted X-ray backscatter image is shown in Figure 6(b). The lead indicators are clearly visible on the honeycomb structured plate. Interestingly, the “silhouette” of the lead indicators in the image is obvious which means that the backscatter radiation from the plate was absorbed by the lead indicators resulting in “casting shadows” in the backscatter image (i.e. the dark shadow effect in Figure 6(b)). Figure 6(c) show the experimental setup used for imaging low- Z materials in the honeycomb structured plate. Here, we attached a Polyethylene (PE) vessel filled with water on the front side of the composite skin. The backscatter image is shown in Figure 6(d). A good contrast between water and the composite skin plate can be detected in the image. As expected, due to its low absorbing properties, the silhouette of the water filled PE vessel appears in “bright shadow” in the backscatter image.

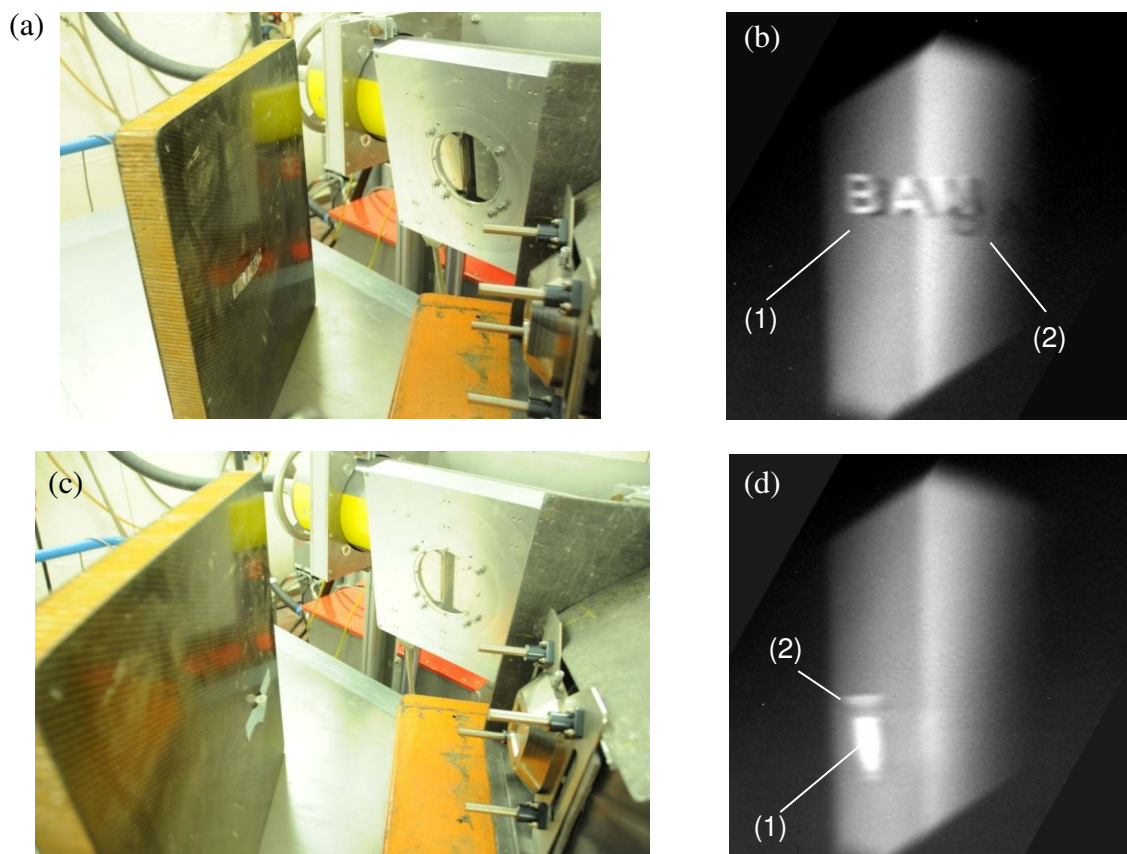


Figure 6: (a) Experimental setup used for imaging thick honeycomb structured plate with lead characters on the composite skin panel, (b) the measured backscatter image showing lead characters (1) and the casting shadows (2), (c) experimental setup used for imaging honeycomb structured plate with water filled PE vessel on the skin panel and (d) the resulted X-ray backscatter image showing detected water (1) on the composite skin panel. The plastic cap of the PE vessel (2) is clearly visible.

4. Conclusions

In conclusion, a new X-ray backscatter technique for non-destructive imaging (NDI) of aerospace materials using a novel twisted slit collimator and the digital flat panel detector was presented. For the first time, the X-ray backscatter measurements were carried out using high-energy (> 500 kV) X-ray sources. The preliminary experimental results show the ability of the present technique to image internal features of complex structured stringer component, low-density material inclusions in thick honeycomb structured plates using only a single-sided access. The measurement time was reduced to 3 minutes by utilizing the high-resolution (180 μ m) digital detector arrays.

Future work will focus on employing photon counting detectors for backscatter imaging. This detector technology is able to record only the X-ray photons and hence there is no electronic noise in the image which results in enhanced image quality of the backscatter image. The efficiency of the backscatter camera will be further improved by using multiple twisted-slit collimator. We expect that using the multiple-slit collimator not only reduces the measurement time but also improves the backscatter signal strengths. Further field trials and validations with existing X-ray backscatter imaging systems are also planned for the future work.

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