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APPLICATION OF DIGITAL RADIOGRAPHY IN MATERIALS ENGINEERING

Abstract. The article describes the principle of digital radiographic methods and research methodology. It also presents the capabilities of digital visualisation with regard to designing ballistic protection components. Results are presented of X-ray analyses of composite sandwich structures consisting of squeeze cast plastic worked elements and elastomeric compounds bound using innovative adhesive binding methods. Capabilities are also presented of qualitative analysis of steel welded joints for military applications.

Keywords: digital radiography, sandwich panels, ballistic protection

1. INTRODUCTION

The purpose of non-destructive testing, applied when the area to be tested is not directly accessible, is to determine possible volumetric defects present inside the tested part. It is reasonable to use equipment for non-destructive testing, especially the portable equipment, when speed is the priority, and the procedures enable instanaeous availability of test results. The range of non-destructive tests is quite broad and includes analogue and digital X-ray methods, thermovision, pyrometry, ultrasonic methods, etc. Thus, they offer a broad spectrum of research and testing abilities in such branches of industry as metallurgy, construction industry, chemical and petrochemical industries or the defence industry, and also in welding, electronics or power industry [2][3]. There are now seven main groups of non-destructive testing (NDT) methods: ultrasonic, radiographic, eddy current, magnetic, penetrant, visual and leak tightness testing [2][3][4].

The group also includes temperature measurement by means of thermographic cameras and pyrometers based on infrared radiation, which is currently the safest method of thermal analysis applied in power engineering, construction industry or foundry engineering [5].

Development of X-ray diagnostic methods is a particular example of the evolution that has led to quality improvement in the manufacture of automotive parts, critical components for military applications, civil aviation or structures for the space industry, contributing to improved durability and safety of use of the various types of transport means.

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The evolution consisted in the transfer from analogue image amplifiers with light-sensitive emulsions to digital detectors that enabled live observation of the product's structure during the test. Thus, digital radiography became a very efficient research and diagnostic tool used for testing structures, welds, iron castings, metal-ceramic composites, polymer castings, or even plastics. Being one of the non-destructive methods, digital radiography now serves as a tool for instant testing of structural discontinuities, such as porosity, blowholes, inclusions, cold shuts, shrinkage porosity, as well as cracks and structure defects.

The radiography of present is based on physical phenomena known since the discovery of radiation by Wilhelm Roentgen in 1895. X-radiation is formed in vacuum as a result of accelerating to a level of 1012 of a stream of electrons between two electrodes: cathode and anode. The radiation beam generated during the deceleration of the electrons on the anode (disk) causes the formation of the so-called braking radiation. In addition, as a result of interaction between the electrons and the material of the anode, characteristic radiation is emitted. The effect of such combination is the formation of a continuous characteristic of the braking spectrum and of peaks derived from the characteristic spectrum [1]. The disk of an X-ray tube must be of special design; in stationary design the disk is usually made of tungsten and is positioned at an angle of 45° to 65° to the radiation beam and is connected to a heat abstraction system that ensures stable exposure conditions during operation. In portable tubes, where weight and speed of conducting the tests are important, rotating anodes are used which ensure that the radiation beam is not directed to the same point and does not burn the material. Manufacturers of such equipment usually require that routine, periodic (semi-annual or annual) inspections be carried out, in particular of the focal spot size, to ensure repeatability and to maintain the level of detection [6].

What was impossible in analogue radiography, that is magnifying the image (which was affected by image blurring caused by geometric blurring resulting from the size of the focal spot of the tube), became possible in digital radiography, where X-ray tubes of the smallest possible focus size are used (0.4, 1.0 mm). This enables reducing the distance between the tube and the tested part and reducing exposure parameters, which in effect results in improved level of detection and image sharpness [7].

The heart of digital radiography is the flat panel digital detector array (DDA) which converts X-ray radiation into visible light on scintillation foil. The level of light is evaluated by an array of photodiodes and finally the image is converted into a digital signal. This signal, after processing into an image, is displayed on a screen [8][9].

Modern DDAs consist of an array of photodiodes that are arranged close to one another and cover the whole tested area, ensuring thereby great precision and speed of action. In addition to standard parameters of DDA, such as pixel size and number of frames per second, every manufacturer also specifies other parameters, such as: basic spatial resolution, contrast sensitivity, signal-to-noise ratio and specific material thickness range in accordance with ASTM E2597 [10]. All of the listed parameters are presented on a spider net graph.

A properly selected detector, appropriate for the materials to be tested and energies applied, is characterised by extended life. This is usually demonstrated by the reduced number of dead pixels or clusters which form dead zones within the tested area. The X-ray tube selection should also be done properly. A properly selected X-ray tube, particularly with regard to the type of materials tested and to the size of parts tested, enables conducting standardised inspections and tests which contributes to improved quality of manufacture.

Digital radiography works best under the conditions of pressure die casting, such as castings that are subject to special requirements by the automotive, household appliance or aviation industries. Quality control carried out using this method during or at the end of the production cycle releases properly made castings for further applications, allowing to set apart those of high tightness while eliminating defective products. "Tight", or even "super tight" pressure castings are largely devoid of the gas porosity formed during the casting process due to gas occlusion. Pressure castings are subjected to porosity assessment in accordance with standards such as: ASTM 2973, which replaced E 505, and VDG P201/VW 50097 and P202 / VW50093 [11][12][13]. Compliance with these standards translates directly into operating safety of the individual parts used in automotive engineering [14]. There are also results of radiographic tests of iron or steel castings that require significantly more powerful X-ray tubes than in the case of non-ferrous metals [15].

2. TESTS OF COMPOSITE STRUCTURES

The subject of tests carried out at the Foundry Research Institute in Kraków were protective sandwich panels constructed within the MODPANC project and selected components of a system for fastening these panels to the protected objects. Tests were carried out using an MU2000 industrial X-ray system from Yxlon Industrial GmbH (Fig. 1) designed for inspecting and controlling the quality of castings, forgings, welds, ceramics, etc. The purpose of conducting X-ray tests was to disclose imperfections in the form of cracks, misalignment, insufficient filling with adhesive or elastomer, shrinkage porosity and blowholes, as well as delaminations formed as a result of vibration acting on the structure of sandwich panels. The types and extent of deformations were studied on panels subjected to ballistic tests and the quality of welds was assessed on the primary armour used for attaching fixtures for additional sandwich panels. The tests were performed by moving in six axes a table-mounted manipulator of the tested object. A semiautomatic program was used that enabled repeatable and systematic operations and manual settings for changing DDA parameters and adjusting geometric magnification to the task performed. Specifications of the measurement instrument are given in section 2.1.

2.1. MU 2000 specifications

1. Closed X-ray tube Y.Tu160-D06 with an accelerating voltage of 160 kV.
2. Small focal spot 0.4 mm (according to EN 12543).
3. Large focal spot 1.0 mm (according to EN 12543).
4. Tube output with small focal spot 0.8 kW.
5. Tube output with large focal spot 1.8 kW.
6. DDA with working area dimensions: 200x200 mm.
7. Frame rate (sampling frequency): up to 25 fps at full resolution.
8. Maximum size of single pixel: 200 μm.

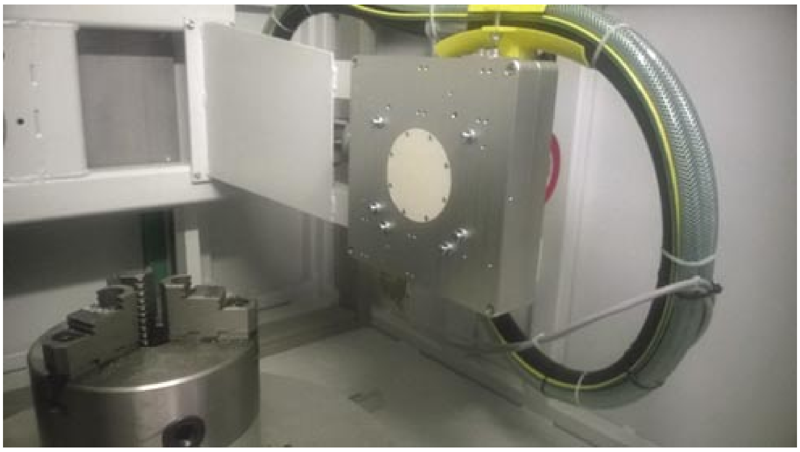

Fig. 1. Interior of MU 2000 instrument – 160 kV X-ray tube

2.2. Applied settings of test instrument

1. Voltage: 82 - 160 kV.
2. Current: 2.0 mA.
3. Focal spot: 0.4 mm (acc. to EN 12543).
4. Tube – detector (FFD) distance: 700 mm.
5. Magnification: M = 2.
6. Integration time: 133 msec.
7. Detector sensitivity: 50%.
8. Pixel size: 200 x 200 µm.

2.3. Research methodology

Parts to be tested are usually prepared after the client defines the expected quality levels and assessment classes adopted for the materials of the parts. In the case of sandwich composite structures X-ray tests do not fall within the existing standards and only present a qualitative picture of the structure. It is therefore possible to state that a certain system of substructures or individual elements remains in line with the design principles or has been altered by external factors arising from previous test conditions (mechanical tests, ballistic tests, etc.). Therefore, establishing test parameters, which enable the detection of non-compliance will be carried out on the run, in line with the expectations of the operator. After initial selection of exposure parameters, such as voltage and current, system settings of offset calibration and image amplification are made. In the case of monolithic castings that are homogeneous in terms of their building material, after the system is prepared for the tests, the quality of the images obtained is verified by checking the detection level using wire-type or hole-type image quality indicators according to standards. The system thus prepared is ready for inspecting the parts either by direct viewing or by taking photographs. However, in the case of composite materials, identical with those described here, the problem is much more complex because of the diversity of materials used in the construction of the panels. The use of wire-type and/or hole-type indicators seems reasonable when the operator chooses to study a panel based on parameters adjusted to one selected material of which a component of the composite system is made. It should, however, be borne in mind that each of the structural materials used is characterised by a different spectrum of physicochemical properties, density being one of them.

3. RESULTS

The tests of sandwich panels which resulted in digital photographs are shown in Fig. 2.

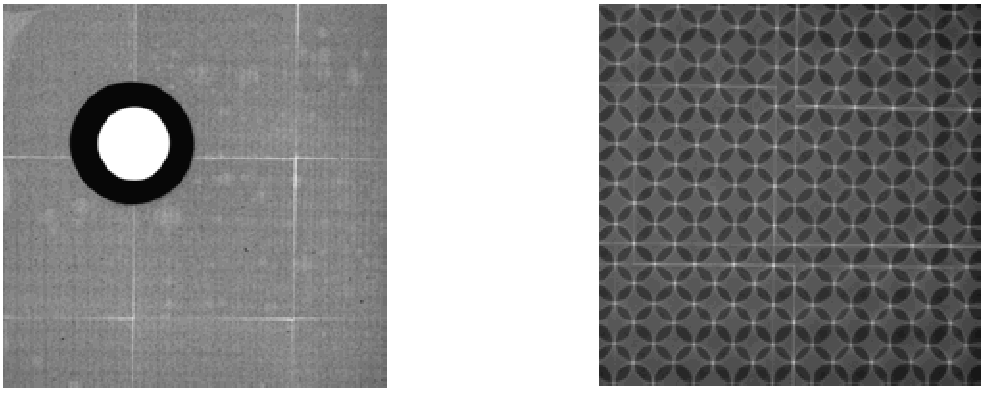

Fig. 2. Digital X-ray images of protective sandwich panels

a) IMN OML Skawina sandwich armour module with fixing opening

b) IOD armour module comprising a system of ceramic blocks in a ceramic matrix

Figure 2a shows a sandwich panel fabricated by adhesive bonding. Light areas suggest adhesive delamination formed as a result of repeated application of variable loads during a vibration test.

Figure 2b shows a sandwich panel fabricated by casting. Darker areas indicate the location of ceramic spheres. Grey shades of the background around the spheres indicate varying thickness of the metal matrix of the module.

Despite the considerations described in section 2.3, the digital radiographic analysis enables definitive identification of the type and extent of armour destruction resulting from previous ballistic tests. The through hole from a projectile, the peeled away plate with embedded semi-spheres and fragments of damaged ceramic blocks dispersed in the structure are clearly visible in the X-ray digital image presented in Figure 3a. An image documenting the effects of armour penetration by a projectile may be recorded from multiple positions, as it is possible to control the sample fixing system and the source-detector set in any axis, as shown in Figure 3b.

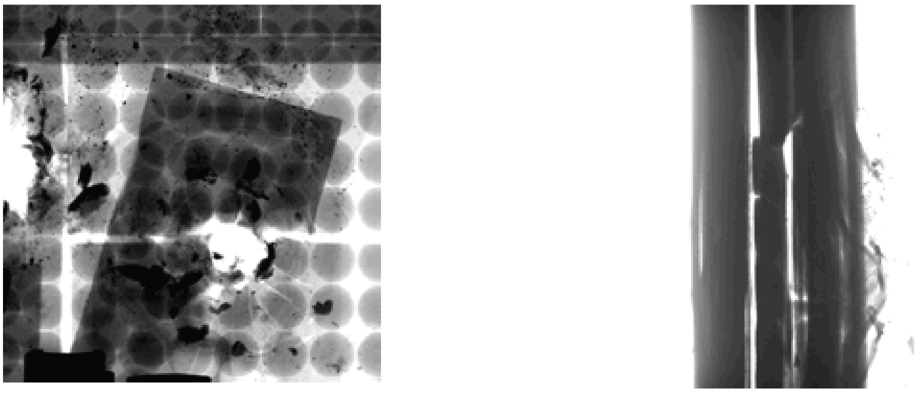

Fig. 3. Digital X-ray images of armour sandwich modules subjected to ballistic tests

a) view of area of destruction in an IOD module

b) the same module viewed at an angle of 90°

When assessing components such as a weld with a spacer pin mounted on steel armour, because of the density of the steel used to fabricate the pin and plate and the weld itself, the maximum voltage (160 kV) available for the MU 2000 X-ray tube had to be used. For this reason the digital X-ray image presented in Fig. 4 shows a high level of noise resulting from the magnification.

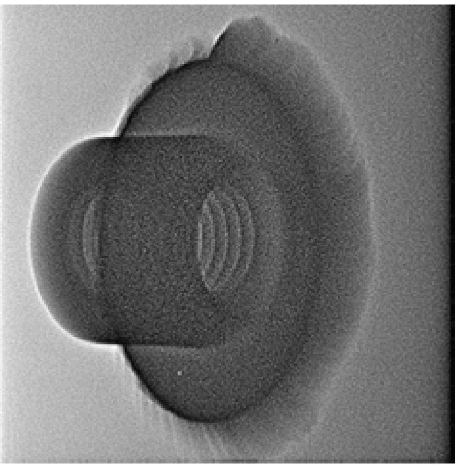

Fig. 4. Magnified X-ray image of weld

While maintaining a certain level of detail that would allow for determining uniformity in the weld position, resolution that could enable identification of minor discontinuities, such as pores and cracks, was lost.

4. SUMMARY

Quality control using an X-ray instrument equipped with a system of digital filters has enabled, in a reproducible and reliable manner, to identify areas of increased discontinuity, allowing thereby identification of areas damaged during mechanical and ballistic testing, and as a result, permitting thereby to formulate recommendations for possible changes in panel design.

Digital radiograph allows for analysis of the propagation of cracks, as well as traces generated by mechanical interactions, such as vibrations, shocks, impacts and thermal effects, such as melting, porosity, etc. Internal structure of protective sandwich panels, shown in Figs. 2 and 3, is usually not visible to the naked eye.

X-rays enable assessment of correct fabrication of panels, degree of order of components and the quality of joints (Figs. 2a, 2b). It also enables evaluation of the effects of destruction of the armour modules resulting from ballistic tests, and determination of the extent of the damaged area, the extent of penetration by fragments and by the projectile itself (Fig. 3). X-ray testing may also include analysis of welded joints (Fig. 4) of the fastening arrangement for additional armour.

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