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NON-DESTRUCTIVE TESTING

CURRENT ACHIEVEMENTS IN RADIATION TESTING (REVIEW)

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A paper studies a prospective method for receiving a digital image on results of radiation testing without intermediate data carriers. Advantages of flash-radiography were analyzed, namely high productivity, low cost, possibility of on-line multiangle monitoring of welded joint internal defects; absence of intermediate data carriers. Comparison of main methods of digital image receiving was carried out. New radiation testing technology based on small-size semi-conductor detectors, named X-ray mini technology, was proposed. 24 Ref., 4 Figures.

Keywords: *non-destructive testing, flash-radiography, digital image, X-ray TV system, scintillator, solid-state detector, internal defects of welded joints, X-ray minitechnology*

Radiation testing is the most widespread type of non-destructive testing (NDT) of quality of welded joints, materials and products. NDT radiation methods can be applied to products of any materials and exceed other types of NDT (acoustic, magnetic particle, eddy-current etc.) on amount of information about defects (type, shape, size, location etc.) [1].

Significant qualitative transformations in possibilities of radiation NDT took place in the recent years due to appearance of new multi-element semi-conductor detectors of radiation images as well as intensive implementation of digital technologies of receiving, processing and analysis of the images. Ionizing radiation passed through controlled object and containing information on internal defects, is transformed with the help of electron means applying these detectors and digital technologies in electric signals array. The later are digitized, processed and used for formation of digital image (DI) of the tested object. DI contains information on internal structure of scanned object, and can be observed during exposure, i.e. on-line. Such a radiation testing method without consumables and intermediate data carriers that allows obtaining on-line DI is called flash-radiography [2]. Possibility of computer processing and DI analysis, development of electron archives of DI, their documenting and further transfer using computer networks shall be referred to important advantages of the flash-radiography.

The peculiarity of flash-radiography is absence of intermediate data carriers, namely radiography films, memory plates with photostimulation memory. Currently widespread technologies with intermediate data carriers require ambiguous operations of exposure, processing and expensive devices for reading and digitization of information for mode selection. Absence of intermediate data carriers (films, memory plates), respectively, allows an order increase of productivity and significant decrease of cost of product quality control.

Methods of DI receiving. Examination of internal defects of the object using portable X-ray television equipment with digital processing of images should fundamentally change technology of radiation NDT in the coming years. In recent time, concept of «digital image» (optical or radiation) finds more and more application in flaw detection. Hardware and software complexes for processing and digitization of X-ray films and forming DI are currently very widespread [3]. The DIs are also received using memory plates employed instead of X-ray films [4–7]. The methods and algorithms of DI processing are common for three variants of radiation testing (Figures 1–3). This is an important direction in modern radiation flaw detection. Today, in majority of cases the DIs are obtained by digitization of radiographs. Less often it is obtained in processing of latent image being read from the multiple use memory plates. The same results can be received using digital flash-radiography detectors without additional expenses related with intermediate data carriers [2, 8, 9].

Figure 1 shows typical technological scheme for DI obtaining by means of digitization of film radiographs. This traditional technology is widespread all

Figure 1. Traditional scheme of radiography testing using film and digitization of radiographs: cassette charging (*1*); exposure on X-ray film (*2*); procedure of film treatment (*3*); film scanning (*4*); DI (5)

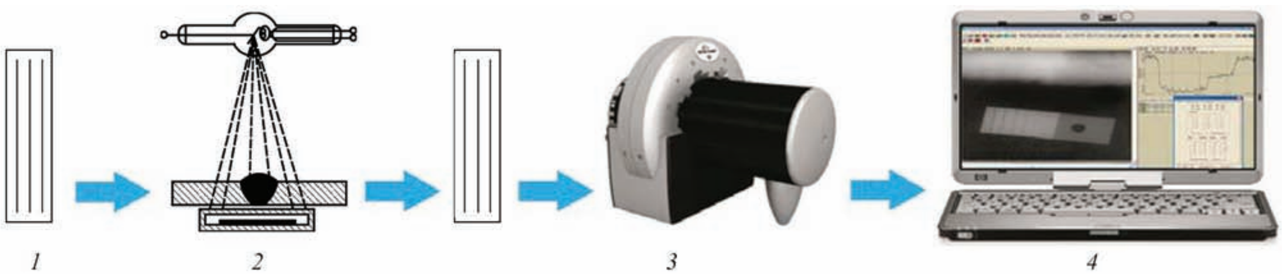

Figure 2. Scheme of exposure procedure using memory plate: preparation of cassette with memory plate (*1*); exposure on memory plate (*2*), reading from plate (*3*); DI (*4*)

over the world in all branches of industry. It requires preparation of a cassette with film and screens. The next procedures are used after exposure, i.e. chemical processing, film drying, reading of information on X-ray film viewer and digitization of the results using corresponding computer complex. This technology is mainly applied for compact archiving of NDT results in e-form and receiving additional information, which can not be gotten without digitization.

Figure 2 shows a scheme of more advanced technology of DI receiving based on memory plates (computer radiography). In comparison with the previous scheme for DI receiving this technology provides the possibility of multiple use of the intermediate data carrier (memory plate). This variant does not include wet process of development and other mandatory procedures.

Figure 3 gives a scheme of technology of instant (flash) digital radiography based on fluoroscopic and solid-body detectors [10, 11]. This is the quickest and cheapest method of DI receiving in e-form, which does not require processing and reading equipment and corresponding additional time.

Work [12] provides comparison of quality of the images obtained with the help of different detector systems. A procedure for calibration and subtraction of transducers' own noises was developed for the technology without intermediate data carriers. This is a method to enhance contrast sensitivity in such a way that it is possible to note the changes of 1/1000 radiation thickness, whereas the best films of C1 grade on European EN 584-1 and American ASTM E 1851 standards have the best contrast 1/100.

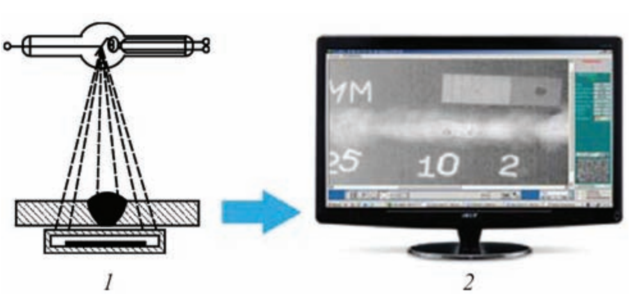

Figure 3. Exposure scheme without intermediate data carriers: exposure on solid-body detector (*1*); DI (*2*)

The quality of X-ray image can be determined on image quality indicators (GOST 7512–82). Classification of welded joints based on the results of radiography testing is carried out on GOST 23055–78. The larger density and the longer exposure are, the more information will contain the exposed film. Therefore, a good scanner is necessary for digitization of dense films and receiving more informative DI. Widespread reader units and cheap scanners can not provide high quality of digitization of radiographs if their relative density is more than 3 units. All the attempts to get satisfactory DIs from denser films were unsuccessful. Therefore, in the film version (Figure 1) satisfactory DI is possible only if film optical density is in 1.5–2.5 units range. The noises of a digitizing unit do not introduce irretrievable distortions in the DI under such values. Experience of digitization of the film images with 3–3.2 units density has already shown unsatisfactory results and it is difficult to reproduce fine information. For example, images of small pores of less than 0.2 mm and cracks with small opening are lost. Thus, digitization of the films has significant limitations. Part of the defects being detected with the help of X-ray film viewer can not be found in the DI. This is significant disadvantage of the traditional film radiography, which virtually can not be overcome in real production.

Film-free technologies on schemes of Figures 2 and 3 do not have this disadvantage, they differ by large dynamic range that expands NDT capabilities.

A special interest is the technologies based on small, several square centimeters, solid-body digital electron transducers. They do not have limitations related with cassette size, screens and memory plates. Mobile transducers can be freely moved over object surface. Such possibilities are embedded in the diagnostics of widely used in practice large customs objects, which can have significant dimensions [13]. It is virtually impossible to control similar objects using intermediate data carriers (films, memory plates). Miniature solid-body transducers can cover structures of different shape. The images from separate small transducers are connected in the one image of the complex-shape object.

Intensive works on improvement of solid-body electron transducers, and mobile X-ray television flaw detectors, which replace ultrasonic equipment due to better flaw detection capabilities [14], are carried out in the USA, Japan and other countries. This tendency will gain acceptance in other countries in time.

In the USA, Japan and Europe tens of companies have already manufactured the solid-state digital transducers virtually for any tasks of radiation testing [15–17].

Comparison of possibilities of separate methods of radiation testing needs consideration of dynamic range. These are object thicknesses, available for satisfactory analysis in one image. Large dynamic range provides substantial advantages to the technologies on scheme of Figures 2 and 3 in comparison with film radiography. Usually large dynamic range is reached by exposure dose that is limited with 3–4 units density in the film systems. Further, the films become unreadable at large film densities. In the case of digital detector systems (without intermediate carriers) «exposure», i.e. data storage has no limitations thanks to computer technologies. At that signal-to-noise ratio (SNR) grows proportional to dose square root. This is equivalent to exposure time or amount of averaged images. This is a way for reaching SNR ratio equal to several thousands and high DI quality. In practice this process is limited with contrast sensitivity of 0.1 % that corresponds to SNR of 1000 order.

Digital processing of the images is accompanied by the protocol procedures. They include operations on DI suitability evaluation, measurement of grey intensity, optical density and determination of sensitivity. Digital scale of grey is usually of 16-bits [4], has thousand of shadows and DI histogram should be located approximately in the middle of this scale in order to eliminate lack of exposure or overexposure. The central location of the histogram provides the possibility of more quality digital processing, i.e. allows carrying scaling of grey gradation. Calibration on size is applied. It allows measuring defects, fulfill other procedures, which are not typical for traditional film radiography and ultrasonic testing.

Significant achievements of radiation transducers based on movable scanning bars with the detectors, which find application in customs control [18], should be noted. All attempts to use such transducers for testing of welded joints have been unsuccessful up to the moment. These systems are continuously improved.

Recently, developers of fluoroscopic transducers on «scintillator screen–objective–CCD-matrix» have made a good progress [1, 19, 20]. Success of these transducers lies in quality of single crystal CsI (Tl) and powder $Gd_2O_2S(Tb)$, $Gd_2O_3(Eu)$ screens and enhanced video cameras. It is important to know how to select optimum screen. For that, their detection quantum efficiencies (DQE) $\eta_{q.e.}$ are compared. DQE is one of the most important complex parameters, determining efficiency of energy conversion in digital detector. DQE is determined on formula [20]:

$$\eta_{q.e} = \frac{\psi^2_{out}}{\psi_{in}}, \qquad (1)$$

where ψ_{in} and ψ_{out} are the relationships of SNR at system input and output, respectively.

DQE provides the possibility of making a conclusion on appropriateness of application of that or another screen for specific task, solved with X-ray TV system (XTVS) of «scintillator screen–objective–CCD matrix» type. Such systems have a series of advantages over other ones, namely possibility of replacement of scintillator screen, that allows varying size of working field and other parameters of the system; small time of image receiving; simple design; small dimensions and weight; low price.

Carried investigations showed that rise of value of exposure dose P_D from zero promotes gradual increase of ψ_{in} and ψ_{out} in the beginning. Dependence of SNR ratio at the input rises step-by-step and at specific value of power of exposure dose reaches the maximum and then start decreasing.

The maximum corresponds to a signal of complete filling of charge pixel of CCD matrix, further the signal is limited. Thus, drop of the value of quantum efficiency of transducer is mainly determined with a range of X-ray radiation energy, which can be absorbed by the screen, and charge in the pixel, which can be accumulated per one cycle. Such transducers due to storage using simple technical means can reach sensitivity of commercial X-ray films.

Calculated dependencies of the SNR ratio at XTVS output on the input power of exposure dose of X-ray radiation allow determining the optimum values of power of exposure dose for set durations of image storage in CCD-matrix. These values provide the highest SNR ratio and the best defect detectability. Investigations [20] showed that the quantum efficiency of X-ray TV system with Gd_2O_3(Eu) is higher than in the systems with CsI (Tl) and Gd_2O_2S(Tb) screens.

In the transducers with CsI (Tl) screen at exposure power more than 0.2 mR/s the value of quantum efficiency varies substantially less at increase of P_D than in XTVS with Gd_2O_2S(Tb) and Gd_2O_3(Eu) screens. In the transducer with CsI (Tl) screen the range of P_D variation, which has comparative consistency of quantum efficiency, depends on storage duration. Rise of storage duration in the CCD-matrix increases the value of quantum efficiency for all screens. A storage time is incommensurably lower than additional time, which is necessary for radiation testing with intermediate data carriers. Therefore, flash-radiography based on fluoroscopic transducers is of the same prospects as the transducers based on expensive solid-body detectors of direct conversion.

X-ray mini radiation testing technology. Not expensive small-size solid-body detectors can be used in modern X-ray TV systems. A new technology based on such small-size detectors is called X-ray mini [21, 22]. In contrast to traditional film radiography or computer radiography, which use expensive films or memory plates as detectors, the X-ray mini technology allows significantly reducing cost and rising efficiency of testing as well as providing virtually instantaneous results. An important peculiarity of X-ray mini technology is diminutiveness of the X-ray detector that allows carrying rapid X-ray testing of difficult-to-reach assemblies of operated planes, turbines, reactors etc.

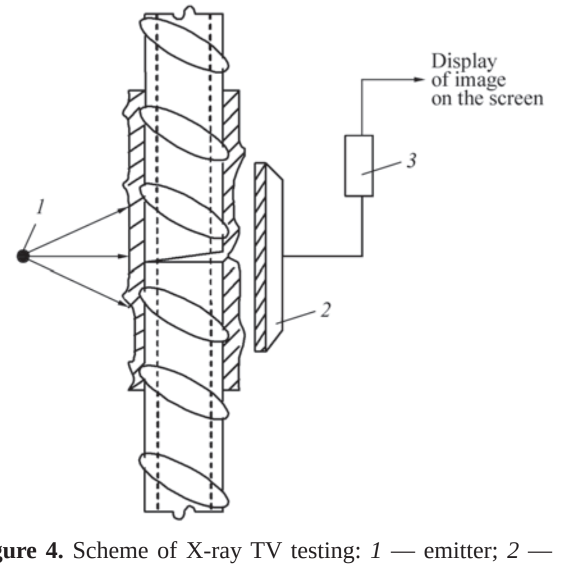

Figure 4. Scheme of X-ray TV testing: *1* — emitter; *2* — solid-body detector; *3* — electron transducer (description *1–3* see in the text)

For example, S10811-11 type detectors from Hamamatsu Photonics Company (Japan) with operating field size 34×24 mm, thickness 6 mm, pixel size 20 μm and number of pixels 1700×1200 provides testing sensitivity and resolution capacity up to 20 pairs of lines/mm. The E.O. Paton Electric Welding Institute uses such X-ray mini technology for testing of welded joints of different products, condition of honeycomb structures of aircrafts, composite structure, examination of closed spaces, where location of traditional films or memory plates is impossible.

X-ray image detector is used for the X-ray mini technology realization. Its area is two times smaller than the area of traditional cassettes with film, memory plates or solid-body detectors of standard size. Thanks to small size such miniature solid-body detector can be located in any difficult-to-reach or constricted space as well as moved on curved surface of the tested object. Such scanning allows examining found defects and inhomogeneities of the tested object in different angles. Information on internal structure of examined area of the tested object comes to a display on-line. The main difference of X-ray mini technology from known digital radiography based on solid-body detectors lies in the fact that cost of such miniature detector is ten times lower than cost of standard size detector [23, 24].

Interesting solutions based on X-ray mini technology were received in construction during control of welding quality or mechanical joints of separate parts of bearing reinforcement bars (Figure 4).

Construction of high-store buildings and other critical buildings is related with butt welding of large amount of the reinforcement bars. The most loaded butt joints shall be controlled by physical methods. In most cases, until recently, this was carried out using ultrasonic testing (UT) means. UT method is effective only in the cases when a butt joint is well dressed and treated. Corresponding claws, binding gel, clamping ultrasonic transducers for joining reinforcement bars parts are used for this. However, currently, application of UT is stopped due to lack of its effectiveness after distribution of mechanical joints of reinforcement bars with the help of crimp pipes. Ultrasonic radiation can not examine the gaps, which are natural for the mechanical joints made by crimping (Figure 4). Therefore, today such butt joints of bearing reinforcement bars are controlled using X-ray mini technology.

Application of film radiography under construction site conditions is unreasonable, since it requires special premises for chemical and other types of film treatment, X-ray film viewer for analysis of test results. Portable X-ray TV detectors, which are fixed to tested joint before testing, significantly accelerate process of quality evaluation of reinforcement bar joints. At that looseness of adjoining due to unsound crimping and bad bar mating are found at that.

The X-ray TV testing, in contrast to radiography one, provides flash result, does not require consumables and special procedures of treatment of radiography film.

Figure 4 shows the scheme of X-ray TV testing using solid-body detector. In this case, the same as in radiography testing, emitter *1* (radioisotope source or X-ray apparatus) is located in front of tested joint, on the opposite site of which is solid-body detector *2*. Image from solid-body detector through electron transducer *3* is shown on the monitor screen. Smartphone or tablet with USB interface can be used as a monitor. Thus, it is on-line control of crimp quality of joint tube (presence of butt gap, reduction of reinforcement bar section etc.).

Conclusions

1. Significant disadvantages of traditional film radiography are low productivity and high cost of testing as well as need in X-ray film viewer with powerful light sources. Exposed images can not be decoded and their digitization becomes impossible at relative density of more than 4 units. This disadvantage is absent in modern technologies based on miniature solid-body detectors.

2. Electron digital information on testing results contains visual demonstrations of internal structure of the objects, expands the capabilities of flaw detection, rises productivity and reduces cost of radiation testing of welded joint quality.

3. X-ray mini technology allows examining internal defects of the objects in different angles that is virtually impossible for other testing methods. The solid-body transducers can be located and moved in the zones, where location of cassettes with films or memory plates is almost impossible. Such technology is realized on serial equipment and allows more than order reduction of testing control in comparison with radiography based on planar detectors of standard size.

4. Scanning of complex surface with miniature detectors and joining of the images of separate exposures allows controlling extended objects from different angles. Corresponding auxiliary equipment is developed for scanning of particular objects using miniature detectors.

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