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Checking the possibility of controlling fuel element by X-ray computerized tomography

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Abstract. The article considers the possibility of checking fuel elements by X-ray computerized tomography. The checking tasks are based on the detection of particles of active material, evaluation of the heterogeneity of the distribution of uranium salts and the detection of clusters of uranium particles. First of all, scheme of scanning improve the performance and quality of the resulting three-dimensional images of the internal structure is determined. Further, the possibility of detecting clusters of uranium particles having the size of 1 mm3 and measuring the coordinates of clusters of uranium particles in the middle layer with the accuracy of within a voxel size (for the considered experiments of about 80 μm) is experimentally proved in the main part. The problem of estimating the heterogeneity of the distribution of the active material in the middle layer and the detection of particles of active material with a nominal diameter of 0.1 mm in the "blank" is solved.

1. Introduction

The number of industrial applications of X-ray computerized tomography has increased significantly and continues to grow rapidly, as evidenced by numerous and various examples of application of the method in manufacturing industries, machine building, production of promising materials, and the food industry. The problems of development of tomography as a method of visualization of the internal structure of the tested objects and as one of the most powerful measuring instruments are discussed.

X-ray computerized tomographs can be used both at the stage of total output inspection of finished products and in the technological process with the purpose to introduce perturbations promptly to adjust the parameters of the technological process in order to maintain the quality of fuel elements at a given level.

The system of X-ray computerized tomography should solve a number of tasks specific to the object under test. In this article, these tasks include the following:

1. Detection of particles of active material with a nominal diameter of 0.1 mm in the "blank" part of the article with a confidence probability of 95%;
2. Estimation of heterogeneity of distribution of uranium salts in the middle layer by the coefficient KT (relative error is not more than 5% with an averaging area of 50 mm2);
3. Detection of clusters of uranium particles with a confidence probability of at least 95% and measurement of coordinates of uranium particle clusters in the middle layer.

2. Scheme of scanning

It is necessary to determine the scheme for obtaining the initial information for the X-ray computerized tomography, that is, with the scanning scheme at the first stage. The scheme of scanning significantly affects the performance and quality of the resulting 3D images of the internal structure. The following effective scheme was chosen based on the results of the study.

A panel detector or a matrix of radiometric detectors serve as an X-ray logger in the scheme. The natural requirement for the size of the detection system is that the shadow from the monitoring object should be completely placed on the frontal surface of the detection system. Compliance with this requirement makes it possible to exclude linear displacements of the object, and leave only rotational (Figure 1).

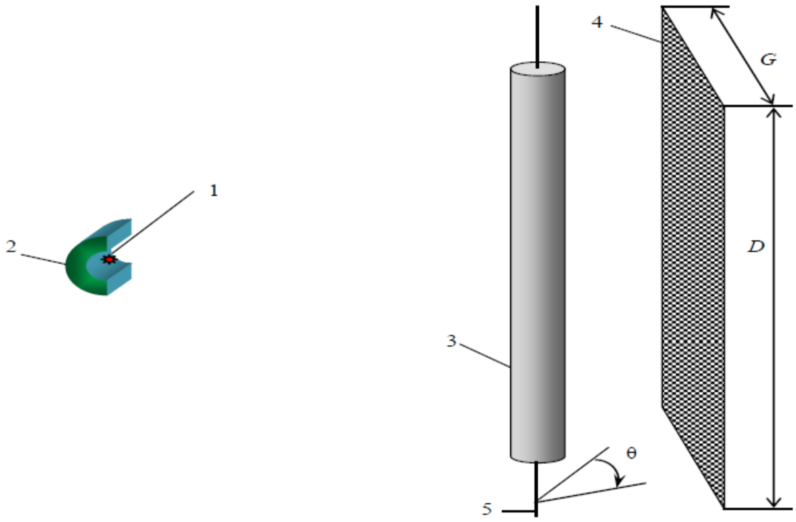

Figure 1. Continuous (discrete) rotation with the formation of two-dimensional projections: 1 – radiation source; 2 – source radiation protection; 3 – Object of inspection (OI); 4 – detector panel (matrix); 5 – axis of rotation of OI

In this scheme, the OI rotates discretely or continuously and, as a result, two-dimensional projections are obtained.

The time of scanning T is determined by the length L of the object under inspection, the time within which the line of detectors occupies one position (the time of formation of one projection) t0, the time within which the system source - line of detectors moves from one position to another Δt, pitch by the angle of rotation Δθ.

The formula for calculating the scanning time T is as follows:

$$T = t_0 \times \frac{180}{\Delta\theta} + \Delta t \frac{180}{\Delta\theta} + t_0 \times k. \quad (1)$$

where k is the number of time intervals required for calibration by "black" and "white".

3. Experimental verification of the possibility of controlling fuel elements by X-ray computerized tomography

3.1. Simulator with large inclusions

Hollow cylinder with the diameter of 30 mm from aluminum alloy with a wall thickness of 2.6 mm was taken as a simulator of fuel element. Large-size stone salt with a bulk density of 1.6 g/cm^3 was used as a matrix. Particles of heavy metal simulated a lead shot with a diameter of about 4 mm. The length of the filled part of the cylinder is about 100 mm.

The studies were carried out on the X-ray computerized tomograph Orel-MT (Continuous (discrete) rotation with the formation of two-dimensional projections) with a limiting resolution of 5 μm. The maximum energy of X-ray emission is E_{max} = 150 keV. Rotation to full cycle is 360°. Step scan by the angle is 0.3°. The low radiation intensity of the X-ray apparatus was compensated by averaging over three frames. The low-energy part of the spectrum was filtered with a copper foil 50 μm thick. The total scan time was about 20 minutes. The thickness of one layer at the inspection site, calculated from the pellets, was 80 μm. The maximum size of the cross section of the image of the pellets was about 50 pixels. It should be noted that pellets have a shape close to an ellipsoid.

Three to five pellets were placed in layers of salt, with random mutual arrangement in the process of making a test sample. The filled volume of the cylinder was fixed with a stopper with vigorous shaking during fixing. Figure 2.a - 2.i show images of several characteristic layers of the test object. More dense materials correspond to lighter parts of the images in Figure 2.

Figure 2.a shows the bottom of a cylindrical beaker. It is noticeable that the density of the cylindrical layer is substantially higher than the actual bottom part. The image in Figure 2.b perfectly illustrates the heterogeneity of the grain structure of the salt layer. Figure 2.c - 2.i show images of layers with one, two, three and four pellets. Figure 2.e, 2.g, 2.h and 2.i show images of pellets. The distance between them is from 0.2 to 0.4 mm. It is possible to draw the conclusion about the presence of noticeable artifacts caused by dense inclusions from the analysis of the data presented by images 2.c - 2.i. The visual manifestation of these artifacts is quite diverse and depends on the number of dense inclusions and their mutual arrangement relative to each other. Nevertheless, it can be considered proven that dense inclusions differ separately if the distance between them exceeds 0.2 mm. In reality, we can talk about a smaller distance, if we analyze the sequence of layers preceding and following the layer, in which dense fragments are as close as possible. Figure 3.a - 3.f show images of the sequence of the corresponding layers to illustrate this conclusion.

Separate detection of inclusions in the image of Figure 3.c is very problematic, and does not present any complexity on the whole set of images of close layers.

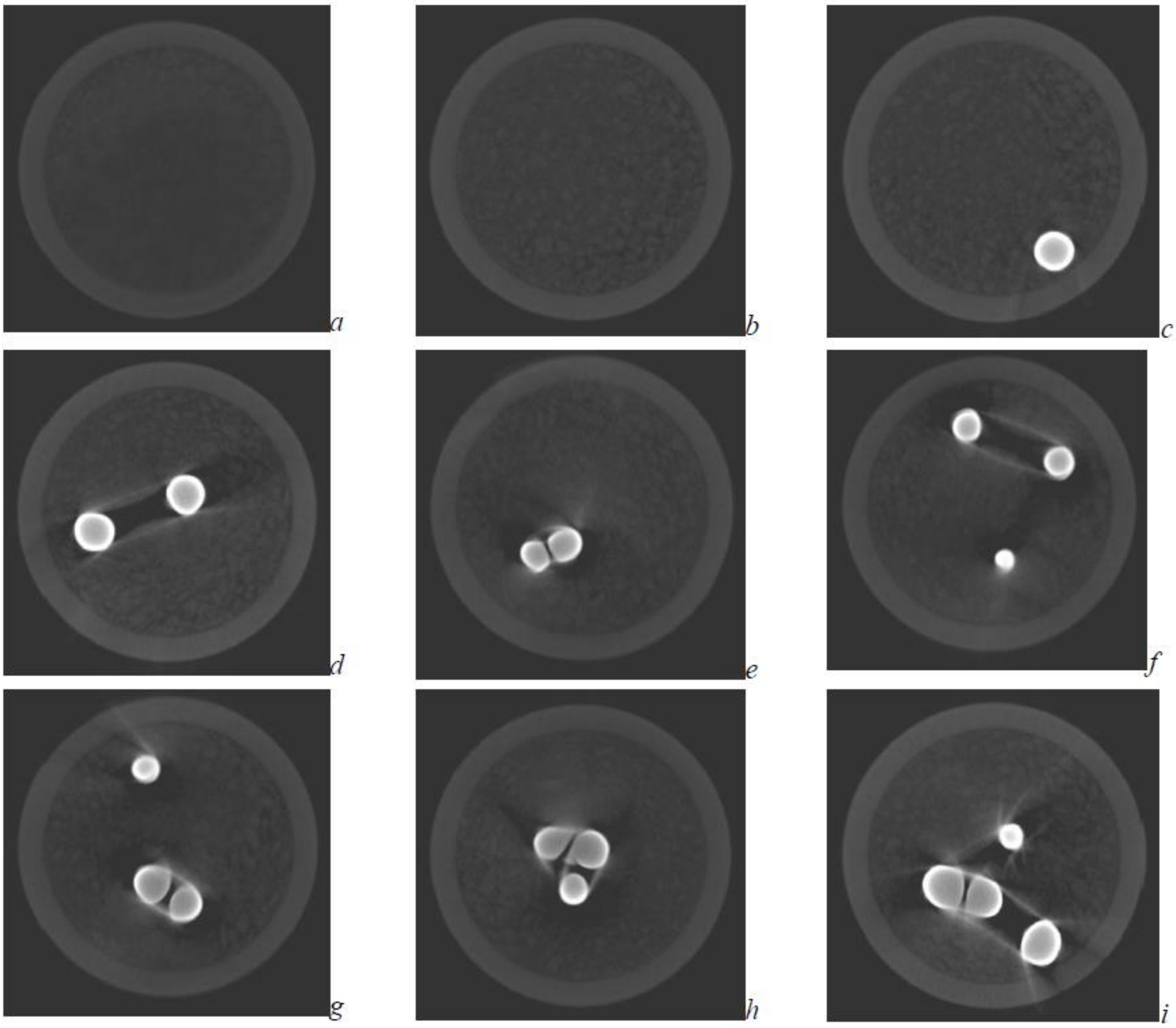

Figure 2. Images of layers of test object:
a–bottom of text object; *b*–salt layer; *c*–one pellet; *d* − two remote pellets;
e − two close pellets; *f*–three remote pellets; *g* − three pellets, two of which are closely spaced;
h − three closely spaced pellets; *i*–four pellets.

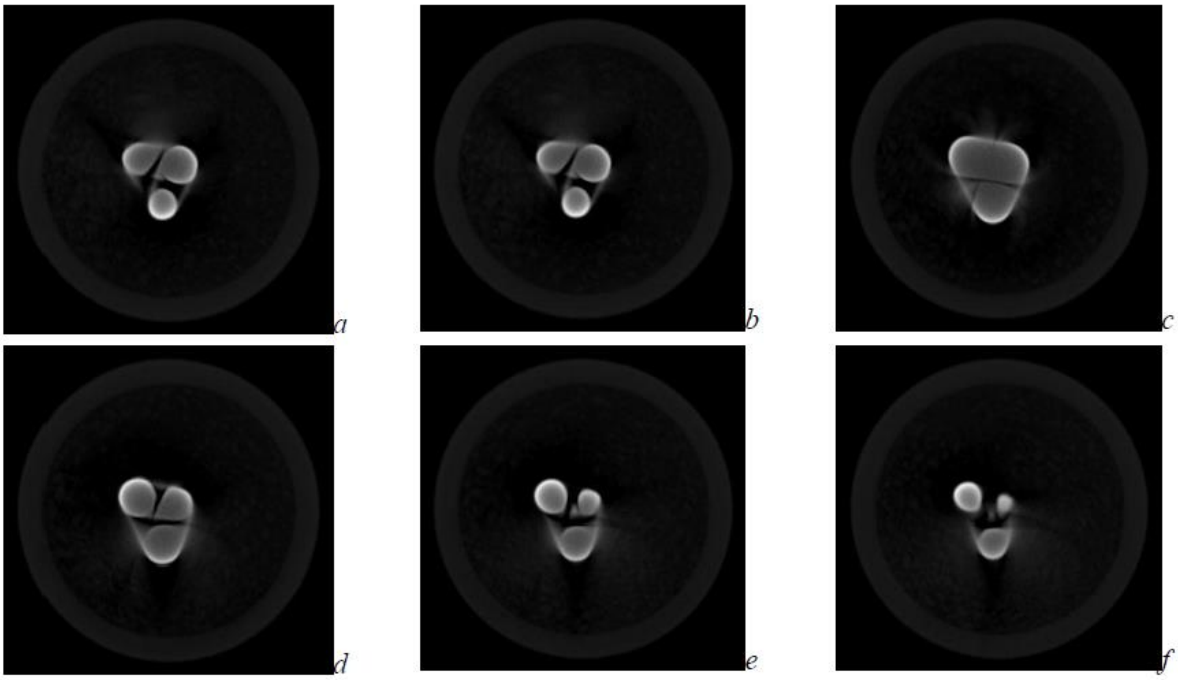

Figure 3. Images of consecutive layers of a test object with closely spaced inclusions.

3.2. Simulator with small inclusions

A test sample with smaller lead inclusions was developed for a more realistic model. The main part of inclusions in the middle layer has dimensions from 0.3 to 1 mm. Several lead grains were placed in the "blank" part of the fuel element simulator with a nominal diameter of about 0.1 mm to assess the possibility to solve task 4, i.e., detecting particles of active material with a nominal diameter of 0.1 mm in the "blank" part of the object with a confidence probability of 95%. To compare the grain sizes in the "blank" part of the simulator, a pellet with a shape close to a sphere with a diameter of 2 mm was introduced.

The maximum energy of X-ray radiation is 150 keV. The low-energy part of the spectrum was filtered with a copper foil 250 μm in thickness. Step by the angle is 0.3°. Accumulation is made by two frames. Figure 4 shows a three-dimensional image of a test object without a matrix material. All the small grains in the "blank" part of the simulator are observed.

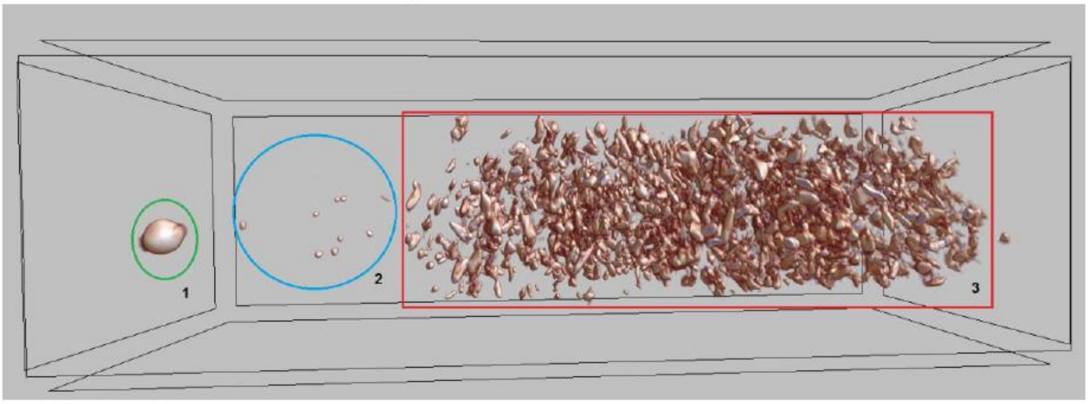

Figure 4. Three-dimensional image of the test object: 1 − lead pellet with a diameter of 4 mm; 2 − small active inclusions in the "blank" part; 3 − active inclusions in the middle layer of the fuel element simulator

Images of layers show noticeable artifacts, caused by the difference in attenuating properties of lead and matrix material. These artifacts practically do not affect the separation of grains of dense particles.

4. Conclusion

A number of conclusions can be drawn concerning the tasks formulated above as a result of theoretical and experimental research.

The task of detecting particles of active material with a nominal diameter exceeding 0.2 mm in the "blank" part of the object with a confidence rob ability of 95% can be considered solvable.

The task of estimating the inhomogeneity of the distribution of active material in the middle layer with respect to the coefficient K_T with a relative error not exceeding 5% at averaging volume of 300-350 mm3 is theoretically solved, but additional experimental studies are necessary with materials close to natural materials, strict formalization of the notion of inhomogeneity of distribution of active material and the development of an appropriate algorithm.

The possibility of detection of clusters of 1 mm^3 of uranium particles with a confidence probability of not less than 95% and the measurement of coordinates of uranium particle clusters in the middle layer with the accuracy to a voxel size has been experimentally proved (for the experiments under consideration of about 80 μm). The formalization of the concept of "cluster" is required.

With a certain degree of certainty, we can consider the problem of measuring the thickness of the shell with an error of not more than 0.06 mm and the thickness of the middle layer with an error of not more than 0.1 mm solvable with the limitation. Additional factors that will help increase confidence in success are the following: the production of special standards that will allow us to evaluate the function of blurring the boundaries of media sections; the development of an algorithm for accounting for this blurring.

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