Application of technical vision for external view inspection of fuel pellets

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Abstract

The results of development and investigation of computer-vision systems for inspection of the external view of fuel pellets for nuclear fuel elements are presented. The systems developed utilize CCD-cameras to record the images of a fuel pellet’s external view in reflected beams that ensures high contrast of the defects in the picture area. One has developed a database containing images of simulators, as well as real pellets. Tests of an experimental set for fuel pellet inspection have demonstrated its inspection productivity to be 1 pellet per second and its detection probability higher than 95%. The research team has also developed an experimental set with higher inspection productivity (at least 7 pellets per second).

Keywords: Technical vision, fuel pellet, defects, image processing

1. Introduction

Fuel pellets are one of the main components of fuel elements for nuclear reactors. The quality of these pellets must meet stringent technical requirements. The appearance surface quality of pellets is included in the list of the quality criteria. According to the technique used at enterprises, the appearance of pellets is tested visually. Owing to the subjective factor involved in the testing procedure, some defective items may be categorized as fit-for-purpose. Moreover the efficiency of the visual inspection in use is low. These disadvantages call for automation of this testing operation. We proposed to use optoelectronic computer-vision systems combined with a mathematical apparatus for image processing. The methods for image formation, as well as a database containing images of fit and defective pellets were investigated. One also developed an algorithm to process optical information. An experimental computer-vision system for inspection the pellet’s external view with productivity up to 7 pellets per second was developed and tested. As result of testing one established that pellets detection probability to be higher than 95%.

2. Peculiarities of pellet’ image of formation

A fuel pellet under inspection is a cylinder of 9 to 12 mm height with the outer diameter of 7.6 mm and 1.4 mm hole in its center. When being fabricated the pellets moves along the production line that makes impossible to ensure simultaneous inspection of all the surfaces. It takes for an inspection system installed one has to develop a mechanism for sequential inspection of the surfaces. To inspect the face-plate surfaces the mechanism should turn a pellet on 90 degrees to the flow, then digital cameras could take images of the surfaces. One can obtain the image scanning of the lateral surface either rotating a pellet and taking the image with a linear camera or recording its sectors simultaneously for further conjugation
with software tools. In the second case a pellet continues its movement in the flow along its axis.

The effectiveness of implementing any computer-vision system substantially depends on the quality of the image obtained. Under development of inspection system, different methods for image formation of real pellets and their simulators were investigated. The aim of the experiments was to obtain stable images with a high degree of repeatability and sufficient resolution, which would be fit for the subsequent efficient and reliable mathematical processing. The images should be of such quality that the results of the processing were not affected the specific features of particular pellets and their batches.

The existing engineering solutions [1, 2], which involve detection of the radiation scattered along the pellet surface, failed in obtaining high-contrast images. Positive results were obtained with the scheme where the surface was illuminated and the image was recorded at the same angle with respect to the normal to the surface inspected (reflective require).

In case one is taking an image of the end face of a pellet (Fig. 1), the light source (1) illuminates the face end of the pellet (2) at the angle $\varphi$ to the normal. The light reflected from the flat part of the end face is recorded by the video camera (3). The flat part of the end face, which acts as mirror, appears in the image like a bright area rimmed with a darker bevel, and any surface flaw appears as a contrast dark spot due to the light scattering in different directions (Fig. 2). Moreover, the inner irregularities of a flaw may reflect light in the direction of the camera, but to detect the flaw only the dark rim on the flaw boundary is important.

The mirror properties of the end face of a pellet are explained by the manufacturing process (pressing of a fine powder). According to experimental data, the reflective properties weakly depend on such factors as dust pollution and tarnish. The image-taking technique described, which is based on the basic law of geometric optics, yields a uniquely interpretable image of the flat surface of the end face. The disadvantage of the method is an extension of its advantages. The bevel in the images taken has proved to be illuminated in a nonuniform manner. Moreover, it is not possible to make an unambiguous conclusion about the presence of a flaw on the bevel. As a result, the image of the bevel can not be processed. However, any flaw that is located on the bevel and does not extend to the flat part of the end face is not detected and, therefore, the pellet is automatically categorized as fit-for-purpose since the flaw’s dimensions do not exceed the flaw dimensions set by the rejection conditions. The area of the parts of a flaw that extend from the flat part of the end face to the bevel is calculated indirectly with some overestimation. This approach may result in some excessive rejection, but a defective item will not be categorized as quality one.

![Fig. 1. Layout for obtaining images of end faces: 1 - illuminator, 2 - pellet and 3 - video camera.](image1)

![Fig. 2. Examples of pellet end faces images: (a) a cleavage extending from the end face to the bevel; (b) a cleavage extending from the end face to the bevel and the side surface.](image2)
The technique for scanning the image of the side surface of a fuel pellet is shown in Fig. 3. The light source (1) extended along the generatrix of the pellet is illuminating a segment of the side surface (5) of the pellet (4) through the matted diffuser (2). The light reflected from the surface is recorded by the linear CCD camera (3). Examples of the images taken are shown in Fig. 4. The very small solid angle within which most of the light is reflected is a distinctive feature of the method offered. As a result, the light source must be extended along the entire angular segment (the second row of light sources should be added) and matted. In this way, a lighting zone may be created where a quality image of the side surface of a pellet may be obtained even if it is positioned incorrectly; however, in this case, contrast is somewhat reduced. Some flaws are depicted in the images as light spots rather than dark spots. During the scanning procedure, the vision angle constantly changes and, at some moments, the flaw surface behaves as a mirror. This circumstance has been taken into account during processing; dark and light fragments are sought independently.

3. Generation of the database. The algorithm for image processing

The methods described above have been used to take images of the surfaces of more than 1000 defective items and the items free of flaws. The array of the images was uploaded to a specially developed database. It was used for developing programs to identify flaws. Additionally, images of the pellet imitations made of different materials were uploaded to the database. All of the images were divided into categories (i) for identifying characteristic types of basic (specified in the handbook of indicators for rejection of substandard items) and additional (found during operations that do not require an item to be rejected but affect the process and the result of image processing) deviations of appearance and (ii) for testing operations of the processing algorithms for different types of flaws. In the process of categorization, the characteristic features of the manifestation of flaws on images were identified.

The algorithm for processing images of the fuel pellet end face comprises the following stages: search for the external contours of the white segments, determination of the boundary of the white segment, adjustment of the boundary of the flat part of the end face, search for the boundary of the hole, search for flaws, and rejection. The decision to reject an item is performed, via the image-identification technique based on logical decision rule [3]:

\[
\text{If}(s > s_1), \neg(V(S > S^*)) \Rightarrow \neg(\text{Reject});
\]

where \(s\) is the area of an individual flaw, \(s_1\) is the permissible area of an individual flaw, \(S\) is the total area of flaws, \(S^*\) is the permissible total area of flaws.

Fig. 3. Layout for obtaining scanned images of the side surface: (1) illuminator, (2) matt diffuser, (3) linear CCD camera, (4) pellet, and (5) segment of the side surface.

Fig. 4. Examples of images of the side surface of pellets: (a) a split pellet and cleavages, (b) crumbling.
The algorithm for processing images of a side surface comprises the following stages: search for the boundaries of the side surface, rejection based on the image width, rejection based on slipping, identification of dark flaws, identification of light flaws, determination of the dimensions of flaws, exclusion of minor and false flaws, and exclusion of embedded flaws. For the rejection based on cracks and other flaws, the following logical decision rule is used:

\[
\text{If } (s_i > s_o), \ V(S_p > S_{p0}), \ V(l_j > l_o), \ V(L_q > L_{q0}), \text{ then «Reject»;}
\]

where \(s_i\) is the area of the \(i\)th flaw, \(s_o\) is the permissible area of an individual flaw, \(S_p\) is the total area of all \(p\) flaws, \(S_{p0}\) is the permissible total area of all flaws, \(l_j\) is the length of the \(j\)th crack, \(l_o\) is the permissible length of an individual crack, \(L_q\) is the total length of all \(q\) cracks, and \(L_{q0}\) is the permissible total length of all the cracks.

The described algorithm for image processing has been used in the experimental set for fuel pellet inspection with productivity of 1 pellet per second. Its principle of operation is successive displacement of pellets by the rotary transporter along the inspection positions. The images of the end-faces are being recorded by the two-dimensional CCD cameras, and the side surfaces recorded by the linear camera. In this case a pellet is rotating on 360° at the inspection position. The images obtained are processed by the computer. The pellet rotation limits the set’s inspection productivity by 1 - 2 pellets per second.

4. High-productivity method for side-surface inspection

To solve the problem of fast registration of fuel pellets’ side surfaces the authors has developed a method utilizing special lens.

![Fig. 5. Optical lay-out for image taking of a fuel pellet’s side surface.](image)

The fuel pellet (1) is being transported along a hole prism (not depicted) along the pellet’s axis. The fragment of the image is being formed by the special lens (2) and the standard camera lens (5). Then the fragment is being recorded by the linear camera (6). One uses the LED (3) as a light source, which is illuminating the side surface of the pellet through the semi-transparent mirror (4). Having used 4 such channels in one plane one can obtain a panoramic side-surface image while the pellet is being transported. A half of such an image is presented in Fig. 6a.

Before applying the algorithm for flaw detection one should perform image preprocessing that includes background subtraction (in the absence of the pellet); image brightness normalization (using the image of the pellet that has no flaws, Fig. 6b-6e). The preprocessing ensures the quality of image processing when the algorithms described above are applied (Fig. 6f).

5. Test results

The tests for flaw detection reliability were performed with the use of actual fuel pellets at the experimental set with inspection productivity of 1 pellet per second.

Three batches of pellets were formed for system tests. Batch no. 1 comprised 90 pellets that were rejected because of their appearance. Batch no. 2 contained 101 pellets that successfully passed visual inspection and were categorized as fit-for-purpose. Batch no. 3
comprised 385 pellets that did not pass visual inspection. Pellet batches were subjected to the automatic-testing procedure. The tests exposed the following results: (i) 97% of pellets were rejected in batch no. 1 and 3% were categorized as fit (underrejection). (ii) 5% of pellets were categorized as fit and 5% were rejected (overrejection) in batch no. 2. (iii) In batch no. 3, the quality of testing was checked afterwards by visual inspection, 97% were rejected correctly and 3% were rejected incorrectly.

Thus, the tests have proved the reliability of the inspection set, operation with detection probability over 95%.

![Fig. 6. Image preprocessing: original image (a), the background (b), image with the background subtracted (c), sample-pellet image with the background subtracted (d), the image preprocessing (e), results of image detection (f).](image)

6. Conclusion

The article presents the results of development and investigation into computer-vision systems for inspection of the external view of fuel pellets for nuclear fuel elements. The authors have developed the experimental set with inspection productivity of 1 pellet per second which utilized two-dimensional CCD cameras to record the images of pellets' end faces. Side-surface image scanning is taken by the linear camera carrying out line-by-line scanning of a pellet rotating. To obtain a high-quality image a pellet’s surfaces are illuminated by inclined beams. The images recorded are processed by the computer in accordance with the algorithm developed. The test results demonstrated the detective probability to be over 95%. To increase the inspection productivity the authors have developed the fast image recording method utilizing 4-channel optical system. The images are conditioned to be fit for further image processing. The results reported have been used to develop industrial sets for external view inspection of fuel pellets.

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