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ABOUT TECHNOLOGIES OF X-RAY SYSTEMS FOR CONTROL OF ELECTRONIC COMPONENTS

Abstract

Introduction. *Radiographic methods are widely used at present in the production of various products and components of the electronic industry, including micro and nanoelectronics. One of the most informative and visual methods is projection x-ray microscopy. Specialised X-ray systems for technological control have been developed and used in industry. A key element in the design of X-ray inspection systems is the X-ray tube. In the vast majority of cases, X-ray inspection systems are built on the basis of collapsible microfocus x-ray tubes with constant pumping. This significantly complicates the design of the installation, as well as increasing its dimensions, weight and cost.*

Objective. *The present article presents an analysis of possible technical and technological solutions for improving the accessibility and affordability of X-ray systems for monitoring electronic components while maintaining monitoring informativity.*

Materials and methods. *The article presents the results of analytical studies of assessment of the degree of influence of the main parameters of the X-ray tube – the size of the focal spot and the focal length – on the resolution of the resulting X-ray images. The advantages and disadvantages of two variants of the construction of the X-ray inspection systems are described: based on collapsible and based on sealed X-ray tubes. The dependence of the size of the focal spot on the voltage on the X-ray tube and on the power supplied by the electron beam to the target of the X-ray tube is analysed. It is shown that sealed (from a vacuum pumping system) microfocus X-ray tubes can be successfully used as a radiation source in installations for X-ray inspection. It is concluded that in most cases, sealed tubes are more practical.*

Results. *In solving of most problems of non-destructive testing of electronic components in the composition of the X-ray system, X-ray sources based on sealed X-ray tubes can be successfully used. Due to this, dimensions, weight, and the cost of an X-ray system for monitoring of electronic components are substantially reduced.*

Conclusion. *Sealed X-ray tubes are an effective alternative in the development of an X-ray system for monitoring of electronic components, which enables to fundamentally increase the availability of such a system.*

Key words: *x-ray projection microscopy, sealed (closed) microfocus tubes, collapsible (open) microfocus tubes, microfocus x-ray systems, resolution*

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О ТЕХНОЛОГИЯХ РЕНТГЕНОВСКИХ СИСТЕМ ДЛЯ КОНТРОЛЯ ЭЛЕКТРОННЫХ КОМПОНЕНТОВ

Аннотация

Введение. *Рентгенографические методы широко распространены в настоящее время при производстве различных изделий и компонентов электронной промышленности, в том числе, микро- и наноэлектроники. Одним из наиболее информативных и наглядных методов является проекционная рентгеновская микроскопия. Разработаны и используются в промышленности специализированные рентгеновские системы для технологического контроля. Ключевым элементом конструкции системы рентгеновского контроля (СРК) является рентгеновская трубка. В подавляющем большинстве случае СРК построены на основе разборных микрофокусных рентгеновских трубок с постоянной откачкой. Это существенно усложняет конструкцию установки, увеличивает ее габариты, вес и стоимость.*

Цель работы. *Анализ возможных технических и технологических решений, позволяющих повысить доступность рентгеновской системы для контроля электронных компонентов при сохранении информативности контроля.*

Материалы и методы. *Представлены результаты аналитических исследований оценки степени влияния основных параметров рентгеновской трубки – размера фокусного пятна и фокусного расстояния – на разрешающую способность получаемых рентгеновских изображений. Описаны достоинства и недостатки двух вариантов конструкции СРК: на основе разборных и отпаянных от вакуумной откачной системы рентгеновских трубок. Проанализированы зависимости размеров фокусного пятна от напряжения на рентгеновской трубке и от мощности, подводимой электронным пучком к мишени рентгеновской трубки. Показано, что отпаянные микрофокусные рентгеновские трубки могут быть с успехом использованы в качестве источника излучения в установках для рентгенографического контроля. Сделан вывод о том, что в большинстве случаев отпаянные трубки являются более практичными.*

Результаты. *При решении большинства задач по неразрушающему контролю электронных компонентов в составе рентгеновской системы с успехом могут быть использованы источники рентгеновского излучения на основе отпаянных рентгеновских трубок. Благодаря этому существенно уменьшаются габариты, вес, а также стоимость рентгеновской системы контроля электронных компонентов.*

Заключение. *Отпаянные рентгеновские трубки являются эффективной альтернативой при разработке рентгеновской системы контроля электронных компонентов, позволяющей принципиально повысить доступность такой системы.*

Ключевые слова: рентгеновская проекционная микроскопия, отпаянные (закрытые) микрофокусные трубки, разборные (открытые) микрофокусные трубки, микрофокусные рентгеновские системы, разрешающая способность

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Introduction. The constant reduction of size (from micro- to nano-) of electronic components and devices used in the electronics industry has resulted in increased interest in non-destructive technologies used to detect possible defects. This demand has led in turn to the development of specialised projection X-ray microscopes with micro- and nano-focus X-ray sources.

The key structural component of X-ray inspection systems, determining the technological scope of their design, is the microfocus X-ray tube. Designers use two types of microfocus tubes: collapsible tubes with constant maintenance of vacuum using pumps (hereinafter – open X-ray tubes) and tubes that maintain vacuum by being sealed off from the exhaust unit (closed X-ray tubes).

In recent years, the range of tasks carried out by the X-ray inspection systems in the electronics industry has expanded significantly. Designers intensively develop X-ray inspection systems for control of possible defects of various components of microelectronics, as well as the quality of printed circuit boards wiring using new technologies [1].

X-ray inspection systems with open and closed X-ray tubes have significantly different functionalities, as well as consumer properties and cost. Therefore, in order to make an informed choice for the specialised area of electronics industry products monitoring it is of theoretical and practical interest to conduct a comparative analysis of both of these systems.

The present article aims to analyse possible technical and technological solutions to increase the availability of the X-ray systems for the inspection of electronic components while maintaining the information content of the implemented control.

Materials and methods. Fig. 1 depicts a functional diagram of an X-ray inspection system. Here,

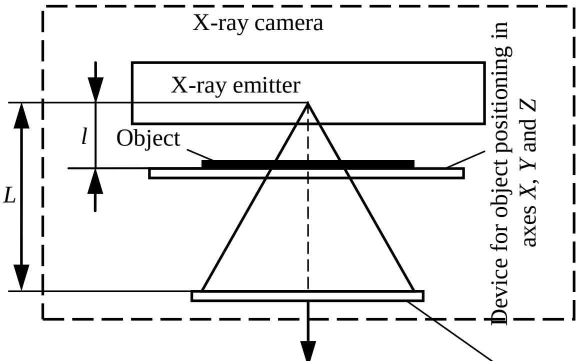

Fig. 1. Functional diagram of X-ray inspection systems

L is the distance from the X-ray emitter to the image receiver; *l* is the distance from the X-ray emitter to the object.

The X-ray emitter of the system comprises either an open or closed microfocus X-ray tube, an X-ray feeder and (for open tubes only) an exhaust unit to maintain the vacuum.

The object positioning device allows the inspected object to be set in the desired position relative to the X-ray emitter and image detector. It contains automated mechanisms that enable the x-ray emitter, image receiver and object to be moved along a given trajectory within required limits. The selection of the distance *l* between the emitter and the object, as well as the distance L between the emitter and the image receiver, provides the required magnification factor of the object image.

The function of the receiver is to convert the shadow x-ray image of an object into a digital image that is stored in the PC memory. This image is digitally processed using specialised software and reproduced on a computer monitor. The system is also controlled from the computer.

The emitter, the object, the sample positioning device and the receiver are located in a special chamber with lead-lined walls (X-ray protective chamber), which prevents X-rays from going beyond its limits.

Fig. 2 shows the example of the design implementation of X-ray inspection system of electronic components.

Fig. 2. The example of one of the design implementations of X-ray inspection system of electronic components

As a rule, X-ray inspection systems work in X-ray and fluoroscopy modes, as well as optionally providing a computed tomography mode. The main component of any X-ray inspection system is a microfocus X-ray tube, which determines the allowable zoom of an object's image as well as its quality. In X-ray systems produced by foreign (i.e. non-Russian) manufacturers, three types of X-ray tube are used: the open type with a pass-through anode and the closed type having one of two anode modifications: massive and pass-through. Fig. 3 shows the designs of X-ray tubes.

In Russia, despite the development of X-ray tubes capable of enabling the discussed devices, such X-ray systems are not currently commercially available. Fig. 4 shows the shows the example of a BS-16 (III) sealed microfocus X-ray tube of the BS family [2] *(a)* and its design *(b)*. The tube, which is designed

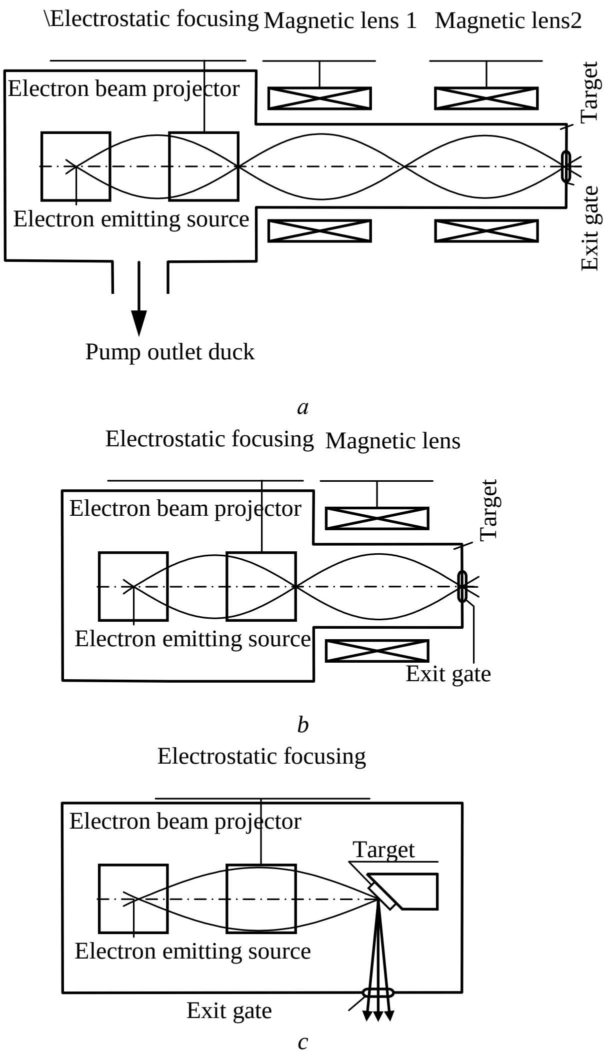

Fig. 3. X-ray tube designs: *a* – spouted tube with pass-through anode, *b* – closed tube with pass-through anode, c – closed tube with massive anode

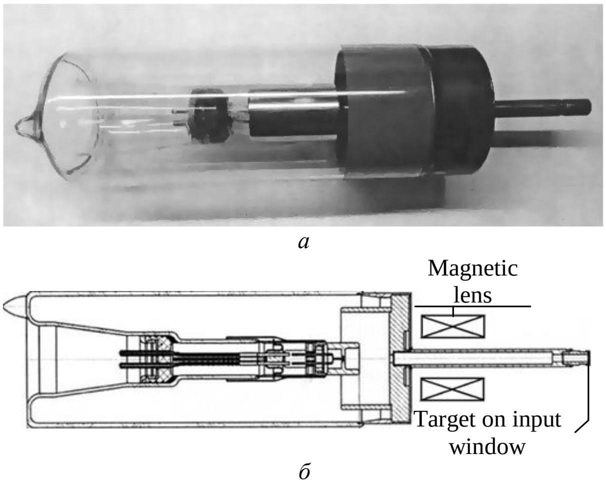

Fig. 4. X-ray tube BS-16 (III): *a* – exterior view, *b* – design

for operation at a voltage of 150 kV, has a hollowed-out anode and a through-type target located at the edge of a long anode tube.

The main parameters of tubes used in X-ray inspection systems are the focal spot size *f*, the minimum focal length *l* (i.e. the distance at which the object can be located from the focal spot of the tube) and the plate power, which provides the required radiation intensity and the specified lifetime of the anode target.

Focal spot size. The focal spot *f* size at the given resolution of the detector R_d determines the maximum projection magnification of the object m_{max} [3]:

$$m_{max} = \frac{(fR_d)^2 + 1}{(fR_d)^2}. \quad (1)$$

It is impractical to exceed m_{max}, since an increase in the magnification of the image will only increase its overall size, but the resolution of the resulting image will decrease accordingly.

With an increase of m_{max}, the total resolution of the system R_Σ [3] will be

$$R_\Sigma = \sqrt{R_d^2 + 1/f^2}.$$

For known X-ray systems $f < 10$ μm, $R_d < 10$ mm^{-1}. Then: $R_\Sigma \cong 1/f$.

In accordance with the Nyquist formula for visualisation of the object defects with a linear dimension *a*, the resolution of the image detector should be equal to $R_\Sigma = 1/(2a)$. Consequently, the minimum size of the detected defect *a* in a sample cannot be less than half the size of the focal spot $(a \geq f/2)$.

The obtained result suggests that with a decrease in the size of electronic components (as well as their possible defects), there will be a need not only for microfocus, but also for nanofocus X-ray tubes. Therefore, the question of minimising the size of the focal spot is of primary importance for X-ray inspection systems of electronic products.

However, the capacity resolution limit of small structures is determined not by the minimum size of the focal spot of the tube, but rather by the diffraction of X-rays as it passes through a non-uniform object [4]. The diffraction effect limits the minimum size of the detected defect to

$$a = \sqrt{l\lambda}, \qquad (2)$$

where $\lambda = k/U$ is the effective wavelength in the spectrum of the radiation generated by the X-ray tube, where k is the proportionality coefficient; U is the voltage on the X-ray tube.

Since, in accordance with (2), the focal length l has constructive limits, nanoscale defects in an object can be detected only at sufficiently low voltages on the X-ray tube. Therefore, nanofocus X-ray systems are more suited for laboratory research into objects having a small size and low density than for research into objects of industrial electronics.

The size of the focal spot of the X-ray tube depends on the diameter of the electron beam d on the target, the magnitude of the anode voltage accelerating the electron beam U and the power supplied to the target of the anode complex by the electron beam.

In open X-ray tubes (Fig. 3, *a*), the required diameter of the electron beam on the target of the anode complex is achieved using a rather complex electron-optical system (EOS) consisting of an electron beam projector, an electrostatic focalising system and one or more magnetic lenses. Such an EOS enables the formation of an electron beam on the target having a diameter of 1 μm or less (with slight aberrations). In closed tubes having remote anodes (Fig. 3, *b*) a single magnetic lens is generally used, which is placed on the anode tube (Fig. 4). From the point of view of achieving the minimum diameter of the electron beam on the target, the focalisation of closed tubes underperforms the focalisation of open tubes.

Regardless of the electron beam diameter d, the area of excitation (generation) of X-rays on the target (effective focal spot diameter) is considerably larger due to the diffuse scattering of electrons in the target beyond the limits of the electron beam [5]. Fig. 5 shows the trajectories of accelerated electrons in the target as a result of diffuse scattering.

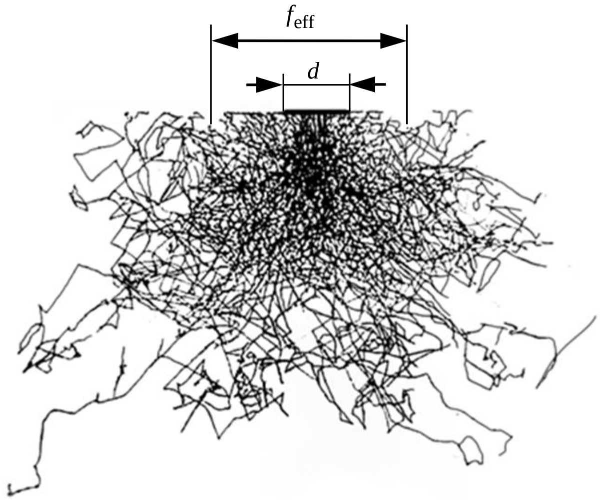

Fig. 5. Trajectories of accelerated electrons in the target due to diffuse scattering

The area of X-ray excitation is a function of the voltage on the X-ray tube: the higher the voltage, the larger the excitation area. For control of the electronic components, engineers use a voltage of 20…160 kV. Fig. 6 shows the dependences of the scattering range R (the range of accelerated electrons in a wolf-ram target) and the effective diameter of the focal spot f_{eff} from the electron beam energy E.

Secondly, the X-ray intensity is defined as

$$I = kiU_a^2 = KPU_a = KP_0 S_f U_a,$$

where K is the coefficient of proportionality; i is the tube current; U_a is the anode voltage; P is the power at the anode; S_f is the focal spot area.

The anode complex containing a tungsten target of a through-type deposited on a beryllium substrate under conditions of natural (convective) heat exchange with the environment is capable of withstand-

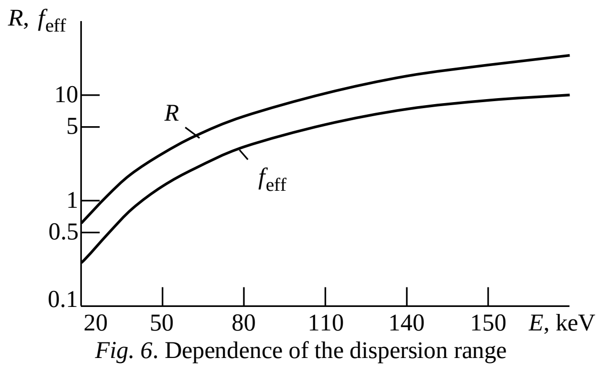

Fig. 6. Dependence of the dispersion range and the effective diameter of the focal spot from the electron beam energy

ing the unit power $P_0 \leq 1\ Vt/\mu m^2$. Exceeding this heat load leads to erosion of the target (melting, peeling, cracking, spraying, etc.), which shortens the target service life dramatically.

In order to provide the required radiation intensity and tube power, it is necessary to increase the size of the focal spot, since the power supplied to the target also determines the size of the focal spot.

Thus, the focal spot of the X-ray tube cannot have one strictly fixed size; instead, the size should be determined experimentally under the typical operating conditions of the X-ray system and this size should be indicated in the relevant documentation.

Focal spot–object distance. The projection magnification of the object is determined by the relation (1), at which the maximum possible resolution of the X-ray system is ensured for fixed f and R_d. In existing X-ray systems, the projection magnification m determined by its design is equal to the ratio of the distance between the focal spot of the tube and the receiver L to the distance between the focal spot of the tube and the object l: $m = L/l$.

The distance l must be minimised to approach the theoretical limit of the magnification factor m_{max}. The size of l also determines the size of L, which considerably determines the design of the device for positioning of the object. Currently, for tubes with a through-type target, l is 0.2…1 mm. For an object with thickness Z, an increase of its image over the thickness of a sample changes from a minimum $m_{min} = L/l + Z$ to a maximum $m_{max} = L/l$. It should be noted that for an object with thickness , an increase is equal to $m_{min} = m_{max}/2$, as a result of which there appears a pseudo-volume effect on its image [6]

Evaluation of the considered technologies. Both of the considered technologies for constructing X-ray inspection systems has advantages and disadvantages.

Due to the more advanced focusing system and possibility to select the desired anode design, X-ray systems based on open tubes allow the detection of defects smaller than 1 micron for thin samples. At the same time, the possibility of repeatedly replacing the cathode and the target of the anode allows the tube to be operated at maximum loads: emission on the cathode and thermal on the target.

However, X-ray inspection systems based on open tubes have a number of significant drawbacks in comparison with X-ray systems that use closed tubes:

– they have large dimensions, weight and design complexity associated with the use of a metal-ceramic insulator to support the full working voltage of the tube, as well as leak-tight mechanical collapsible connections of the metal tube cylinder with changeable units (cathode and anode);

– the tube has an integral structural element consisting of a specialised pumping post;

– the systems require high-voltage training of the tube following the replacement of individual nodes, imposing additional requirements on the power source generating device and the subsequent adjustment of electron-optical system;

– a possible increase in the size of the focal spot due to mechanical vibrations of the pumping post;

– high cost.

The noted drawbacks are absent in X-ray inspection systems based on closed (sealed) tubes. At the same time, systems based on closed tubes have other significant advantages to those based on open tubes for a variety of other consumer-related properties.

For example, replacing a sealed-off tube in case of its failure is technologically easier compared to replacing nodes in a collapsible tube, because:

– there is no need to carry out adjustment of the electron-optical system and high-voltage tube training;

– replacing the tube requires less time than changing the anode or cathode in a collapsible tube;

– the power consumption of X-ray systems based on closed tubes is significantly lower.

Tubes with a target placed on the anode tube are especially effective. They are stable in operation and durable, since the negative impact on their electric strength of electrons scattered on the target is eliminated by the absence of an electric field in the anode tube.

All over the world, a number of companies produce X-ray inspection systems for the electronics industry having both open [7]–[11] and closed tubes [8]–[10].

The evaluation shows that systems on closed tubes with a massive anode can detect defects up to 5 microns in size. They provide a minimum focal length of about 10 mm and are effective in enlarging an image of a sample up to 100 times.

Systems on closed tubes with a through-type target anode enable to detect defects up to 2.5 microns. Due to the smaller focal spot – object distance (about 1 mm), they are capable of enlarging the image of an object up to 1000 times.

Systems based on open tubes having a through-type target anode enable detection of defects smaller than 1 micron in size and are capable of enlarging the image by more than 1000 times.

In Russia, there is currently no mass production of X-ray inspection systems for the electronics industry. Nevertheless, hardware components for the possible production of such systems on the basis of closed tubes having a remote anode are manufactured domestically. Microfocus X-ray tubes of the BS series having a focal spot of up to 5 microns [12] are manufactured in serial production; moreover, planar detectors having resolution capabilities $R_n = 3.5 \ldots 10\ \text{mm}^{-1}$ are available along with the appropriate software. This is confirmed by the development of one of the first Russian variants of the MRCT - 01 microfocus X-ray computed tomograph [13].

Conclusion. In the electronics industry, X-ray inspection systems built on both considered technologies are in demand. For the inspection of relatively large and dense objects, where it is sufficient to detect defects with a size of 5 μm or more, systems based on closed tubes having massive anodes are effective.

In order to detect defects up to 2.5 μm in size, systems based on closed through-target X-ray tubes should be selected.

Advanced systems are based on open through-target X-ray tubes, enabling the detection of defects of less than 1 micron in size. However, the higher the resolution of the system, the worse the consumer properties such as price, size, weight, as well as translucence due to a decrease in the maximum voltage value on the X-ray tube.

Multifocal open X-ray tubes are promising in the development of X-ray inspection systems. They have different power modes for the inspection of dense or medium density objects, as well as a resolution mode for the inspection of nanostructures. Here, the modes are switched in the process of inspecting products.

However, it is worth noting that in many cases a closed tube with a hollow anode is more practical due to the possibility of adjusting the size of the focal spot with a magnetic or electromagnetic lens.

The obtained results enable an informed approach to the task of constructing X-ray inspection systems, as well as the supporting new possible fields of application depending on the size of the focal spot and the type of X-ray tube.

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