Measurement Techniques, Vol. 47, No. 7, 2004

MEASUREMENT OF THE PARAMETERS OF THE FOCAL SPOT OF AN X-RAY TUBE USING KUMAKHOV OPTICS

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UDC 621.386

A technique of determining the parameters of the focal spot of an x-ray tube by obtaining its image by means of Kumakhov optics is described. Through the use of the image thus obtained, it is possible to determine the size and shape of the effective focal spot. Results of investigations of different x-ray tubes are presented.

Key words: *x-ray tube, focal spot, Kumakhov optics.*

It is well known [1, 2] that the size of the focal spot and its shape are the most important parameters of an x-ray tube. These geometric parameters of the focal spot are important, for example, for x-ray flaw detection where they serve as a means of determining the resolution of the analysis [1]. Knowledge of these parameters is also necessary in the use of x-ray optics together with an x-ray tube, for example, when conducting testing of the x-ray optical systems of Kumakhov optics. That is, in order to determine the transmission of the Kumakhov lens the size of the focal spot of the tube must be no greater than the corresponding focal spot of the lens [2, 3].

Obviously, these geometric parameters as well as the distribution of intensity across the spot may be easily determined from the distribution of the intensity of x-radiation across the area of the focal spot. This distribution, which constitutes the x-ray image of the focal spot, may be obtained through the use of Kumakhov optics.

Kumakhov optics consists of different systems of hollow glass tubes, or capillaries [5–7]. The operating principle of Kumakhov optics is based on the transformation of radiation by means of multiple reflections from the internal walls of the capillaries at low angles that do not exceed the critical angle. With the use of angular filtration of the polycapillary system by low-angle reflection, it is possible to obtain an image of the focal spot of the x-ray tube formed by quasi-parallel rays. An analysis of this image provides a number of required parameters of the focal spot. Thus, based on polycapillary structures of Kumakhov optics it is possible to create a convenient, precise, and quick technique of determine a number of parameters of the focal spot.

Principle of Measurement. Let us consider the physical foundations of the technique. Note that the technique utilizes the fact that the x-ray image, a plane distribution of radiation intensity, may be formed and transmitted for some distance by means of Kumakhov optics [5–9]. As has already been noted, Kumakhov optics constitutes a collection of tubes, usually of glass, formed into beams of different configurations [5–7]. Note that the basic characteristics of the variation in the propagation of x-radiation that is achieved, in particular, the production of convergent, parallel, and divergent beams, depends on the form of the particular configuration. In this case, propagation of radiation is based on the effect of total external reflection, an effect that arises at low angles of slide. As a result of such multiple low-angle reflection by the curved surface of the internal walls of the capillaries, radiation propagates along a required direction. The value of the greatest angle of gliding incidence (expressed in radians) at which the effect of total external reflection (critical angle) arises for the wall may be estimated by means of the formula

$$\theta_{cr} \approx 30/E,$$

Translated from Izmeritel’naya Tekhnika, No. 7, pp. 20–22, July, 2004. Original article submitted February 24, 2004.

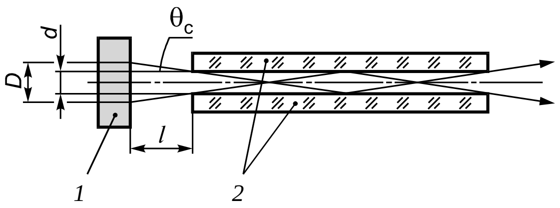


Fig. 1. Geometric scheme of collimation by an individual capillary: *1*) focal spot of x-ray tube; *2*) glass walls.

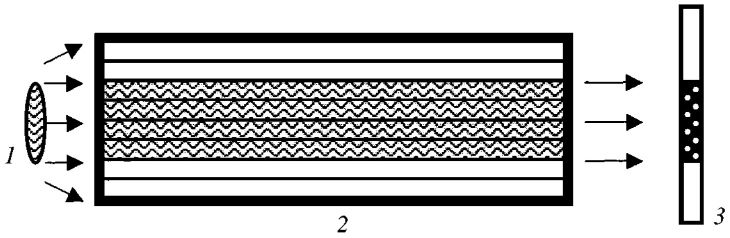


Fig. 2. Formation and transmission of image of spot of polycapillary structure: *1*) focal spot; *2*) polycapillary structure; *3*) detector.

where E is the energy of an x-ray quantum, eV. For example, for the energy of the characteristic radiation of the K series of copper, $\theta_{cr} \approx 4$ mrad. Thus, the angle of capture by an individual capillary equal, obviously, to two critical angles, is very small. At the exit from the capillary system, we also obtain low divergence of the beam of x-radiation, the value of which within the framework of a geometrico-optical treatment is equal to the critical angle. In contrast, in the individual cases described by the wave theory the divergence of the beam of x-radiation may be even less than the critical angle [10].

Using angular filtration of a polycapillary system based on low-angle reflection, we obtain an image of the focal spot of the x-ray tube formed by the quasi-parallel beams emanating from the surface of the anode in the area of interaction with the electron beam and traveling in a direction of interest. This projection of the image is called the effective focal beam.

Each capillary captures radiation traveling in a small solid angle on the order of $2\theta_{cr}$ and thus creates a minimal part of the image of the spot, or pixel. The radiation intensity corresponding to this pixel at the exit from the capillary is proportional to the radiation intensity from the corresponding area of the spot. The geometric scheme of the capillary is presented in Fig. 1. The linear dimension of the spot, radiation from which passes through the capillary (effective size of capillary), is determined from the formula $D = 2l\tan\theta_{cr} + d$, where l is the distance of the source of the radiation to the inlet to the capillary; $\theta_{cr} = 4 \cdot 10^{-3}$ is the critical angle of the total external reflection of $\mathrm{Cu}K_\alpha$ radiation; d, distance between the walls of the capillary. Thus, with a distance $l = 0.5$ mm, the effective size of the capillary $D = 2 \cdot 500 \cdot 4 \cdot 10^{-3} + 5 = 9$ μm.

Through the use of a set of strictly oriented and densely packed capillaries having a polycapillary structure, it is possible to obtain a complete image of a spot consisting of the pixels formed by the individual capillaries (Fig. 2). An increase in the dimensions due to the presence of a gap between the anode and the entry to the capillary system as well as between the exit from the capillary system and the detector is also easily computed on the basis of the critical angle; specifically, it is equal to the angular component $2l\tan\theta_{cr}$.

The distribution of radiation intensity that is thus obtained and, consequently, the desired dimensions and shape in the case of a sufficiently regular structure are in good agreement with the corresponding characteristics of the focal spot of the x-ray spot. Thus, based on the capabilities of Kumakhov optics described earlier, it is possible to realize a simple, reliable, and quick technique for the analysis of the focal spot of an x-ray tube. In this technique, the polycapillary structure plays

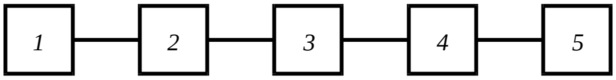


Fig. 3. Flow chart of plant: *1*) x-ray tube; *2*) cylindrical polycapillary structure (collimator); *3*) test object; *4*) image detector; *5*) device for analysis of image.

the role of a collimator, thus representing a further development of the techniques used in the measurement of the dimensions of the focal spot of a slit collimator [2, 11] tending towards greater ease, precision, and speed of measurements.

Equipment. A flow chart of the plant in which the measurements are conducted is presented in Fig. 3. The flow chart is realized on the base of an automated bench for investigating the optical parameters of Kumakhov optics [3]. A polycapillary collimator *2* is situated in a special holder that may be moved in three orthogonal directions. This makes it possible to precisely adjust the collimator relative to the focal spot of the x-ray tube *1*.

A Kumakhov optics system is used to implement the technique, namely a polycapillary structure (polycapillary column). The column is in the form of a parallel assembly of polycapillaries consisting, in turn, of capillaries, or hollow glass tubes 5 μm in diameter. The length of a column is 5 cm.

We require an x-ray image detector that is linear with respect to amplitude as well as having low aberration of the image transmission channel. An x-ray visualizer based on a scintillation shield, light guide, image converter tube, and television cameras, the signal from which is transmitted to a computer, is used. The linear resolution of the visualizer in the working range of the x-radiation is on the order of 20 μm. We may either use a calibrated visualizer or perform independent calibration by obtaining an image of a test object with known dimensions.

Measurement Procedure. We mount a capillary structure in front of and at some distance from the anode, the detector system being placed at the exit from the capillary structure. It is best to employ an image detector, or x-ray visualizer, as the detecting system to achieve quick estimation. Comparison of the dimensions of the image of the focal spot thus obtained with the dimensions of the image of a control object or use of a calibrating visualizer allows us to determine the absolute dimensions of the spot.

Scanning methods for the analysis of the distribution of the intensity of x-radiation at the exit from the polycapillary structure may also be used. With this technique, it is possible to determine the linear dimensions of the spot along the scanning direction in the “knife method” or, by scanning the diaphragm, to obtain a two-dimensional distribution of the intensity across the spot with precision determined by the dimensions of the diaphragm [3].

Emitters of x-radiation with different dimensions and shapes of the focal spot were used. Magnetic lens were employed to produce additional focusing and variation of the shape of the electron beam.

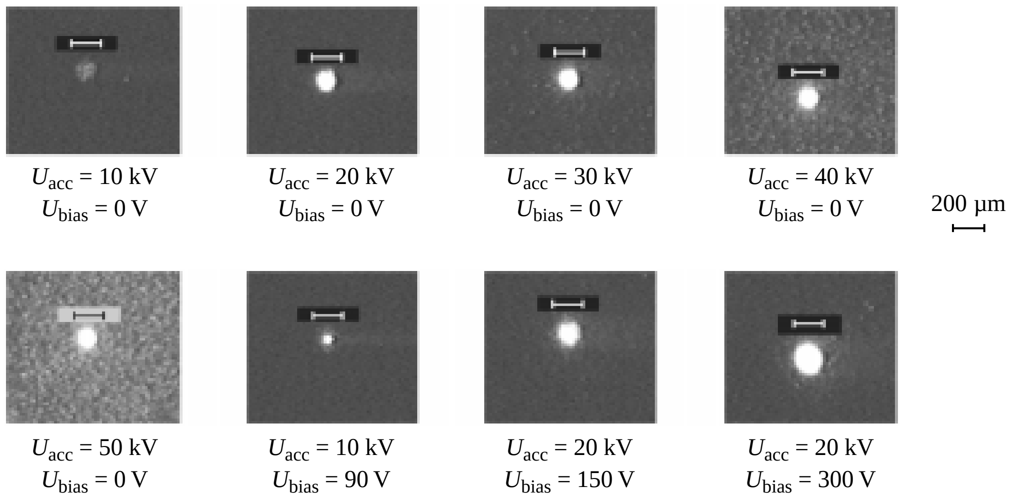
Examples of images of the focal spot of a micro-focal x-ray tube for different values of the adjusting parameters obtained on the basis of the technique that has been described here are presented in Fig. 4. The values of the following parameters were varied: accelerating voltage U_{acc}; bias voltage U_{bias}; filament voltage U_{fil}; and tube current I_{tube}.

Through the use of a video camera, it is possible to monitor variations in the image of a spot over time as a function of the parameters that are being varied.

Photometric processing is performed after the images have been obtained. Using a curve that describes the distribution of the intensity along the axis of the spot, it is possible to achieve a precise quantitative determination of the required dimensions.

Advantages and Precision of Technique. As a result of low-angle filtration, the intensity at the exit of the capillary structure is significantly less than the total flux emanating from the surface of the anode. In certain cases, this is useful since it is then no longer necessary to install additional x-radiation attenuators for the purpose of preventing overloading of the detector systems.

The precision of the technique and the minimal threshold of the dimensions of the spots are limited by the dimension of the element of the transmitted image, or effective dimension of the channel, i.e., the resolution of the given optics (cf. Fig. 1).



U_{acc} = 10 kV U_{bias} = 0 V

U_{acc} = 20 kV U_{bias} = 0 V

U_{acc} = 30 kV U_{bias} = 0 V

U_{acc} = 40 kV U_{bias} = 0 V

U_{acc} = 50 kV U_{bias} = 0 V

U_{acc} = 10 kV U_{bias} = 90 V

U_{acc} = 20 kV U_{bias} = 150 V

U_{acc} = 20 kV U_{bias} = 300 V

Fig. 4. Example illustrating the variation in the image of a circular spot of a microfocal x-ray tube as a function of the adjusting parameters.

Technological difficulties related to maintenance of regularity in the structure arise in micrometric measurements of the channel. A violation in regularity significantly reduces the transfer functions of the given structures and, consequently, decreases the sensitivity and precision of the technique. Therefore, it is necessary to use tested, calibrated capillary structures that satisfy stringent requirements as regards the uniformity of transmission across the inlet area.

Such a property of Kumakhov optics systems as selectivity in terms of energy [12] also imposes certain constraints. As a consequence of a decrease in the critical angle with increasing radiation energy there occurs a cut-off in the high-energy part of the spectrum by the capillary structures. Such a cut-off also occurs as a result of the lesser efficiency of the scintillator at high energies and, consequently, this error, which is introduced by the capillary structures, is not very substantial.

Moreover, high-energy x-ray quanta will pass through the glass walls of the polycapillary structure and this will cause the image of the focal spot to become “blurred,” which restricts the use of the present technique at high voltages of the tube [9]. The approximate working range of Kumakhov optics is 1–100 keV. Polycapillary structures with increased content of lead in the glass must be employed to achieved harder voltage [9].

With the use of divergent polycapillary systems, it becomes possible to achieve an increase in the x-ray image of the spot, which in turn makes it possible to expand the range of spots employed towards lesser dimensions [8]. According to the data presented in [8], it is possible to obtain images with submicrometric resolution.

Thus, through the use of the polycapillary structures of Kumakhov optics it is possible to implement a precise, reliable, and quick technique for determining the parameters of the focal spot of an x-ray tube. The method is a development of the technique of slit collimators that produces greater precision, higher information content, and convenience. The technique may find application both in the manufacture of x-ray sources, for purposes of testing, as well as among users, during the tuning period.

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