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DEVELOPMENT AND RESEARCH OF TECHNOLOGY FOR AUTOMATION OF THE CALIBRATION AND ACCOUNT OF DIGITAL SEM IMAGES HAVING GEOMETRIC DISTORTION OBTAINED WITH JCM-5000 (NeoScope) (JEOL, JAPAN)

Purpose. Solids microsurface digital images obtained with scanning electron microscopes (SEM) are characterized by significant geometric distortions, which must be defined and taken into account when determining the quantitative parameters of microsurface solids with high accuracy. Therefore, this problem is so important and urgent, especially during the high-tech quality control of production processes using nanotechnology, particularly in mechanical engineering, aircraft construction, and for creating space and military equipment. It is also important to perform SEM images measurements and obtain quantitative parameters of the studied microsurface in automatic mode that would allow processing of the data much faster without operator intervention. Therefore, the aim of this work was to develop and research the effective technology for automated calibration and account for the SEM images geometric distortion as well as the creation of a software package that would implement it. **Methods.** Digital SEM images processing and their transformations were used to automate the measurement. **Results.** The developed automation technology for digital SEM images measurement was tested and studied in the treatment of SEM images of the reference test object with a resolution of r = 1425 lines/mm, obtained with SEM using the JCM-5000 (NeoScope) in the range of magnifications from $1{,}000^x$ to $15{,}000^x$. Accuracy and quantified characteristics of SEM images, in particular, their scales along the axes of the image, as well as their geometric distortion, are comparable to measurements made by hand. Automation of this process eliminates monotonous work, especially in the processing of SEM images in a range of relatively small increases in M=1000h-5000h, significantly reducinge the measurement time, and avoiding human errors that can occur. **Scientific novelty.** The developed technology for automation of the measurement of digital SEM images and to determine their geometric parameters is executed for the first time in Ukraine. The proposed technological measurement automation scheme of SEM images, and the creation of this authoring software show its efficiency and expediency. **The practical significance.** This technology allows you to automatically and accurately determine the true value of the SEM images increase (scale), the value of their geometric distortion. These values use determine with high accuracy of the quantitative spatial parameters of micro surface solids to increase the reliability end efficiency devices, mechanisms, and materials made from them.

Key words: scanning electron microscope (SEM); the test object; SEM digital image; geometric distortion SEM images; fractal dimension; measurement automation.

Introduction

Modern high-tech industry, particularly in such areas as engineering, microelectronics aircraft construction, the creation of military equipment and in other fields using nanotechnology requires quality control of technological processes used in scanning with electron microscopes.

SEM is widely used for research of micro surfaces of various objects and materials to obtain quantitative parameters of these surfaces with high accuracy on the micron and submicron levels.

In these studies, it is important to establish the real scales of the SEM images, and take in to account their geometric distortions. These studies are laborious, require highly skilled researchers, and require considerable time. Therefore, the authors set themselves the task to develop technology to automate the measurement of SEM image micro surfaces research objects that would enable, with the required accuracy, the determination of their quantitative parameters, and significantly reduce the time of receipt.

Purpose

Research metric characteristics of SEM images, i.e. setting the values of their scale and geometric distortion, as well as future methods are considered by scientists from both abroad and in Ukraine. In particular, [Boyde A., 1975; Burkhardt R., 1980; Ghosh S. K., 1975; Nagaraja, 1976; Howell P., 1975; Kalantarov E. I., Sahyndykova M. J., 1983; Sokolov V. M., Shebatinov M. P., 1984], Ukraine – [Melnyk V. M., 1984, 2009; Finkovskyy V. Y., 1984, Shostak A. V., 2009, 2012] and others.

Measurements automation for problems solving with SEM-photogrammetry have not been given sufficient attention in the past, according to the literature review.

The purpose of this work was to develop technology and automated processing of digital SEM images of the standard test object with a resolution r = 1425 lin/mm, which would enable finding the real image scale and the necessary elements automatically recognized for acquiring their actual proportions for geometric distortion, and take them into account in determining the quantitative parameters of micro surface research objects.

For research, we have used digital-SEM images obtained from the SEM JCM-5000 (NeoScope) which increase in range from 1000x to 15000x.

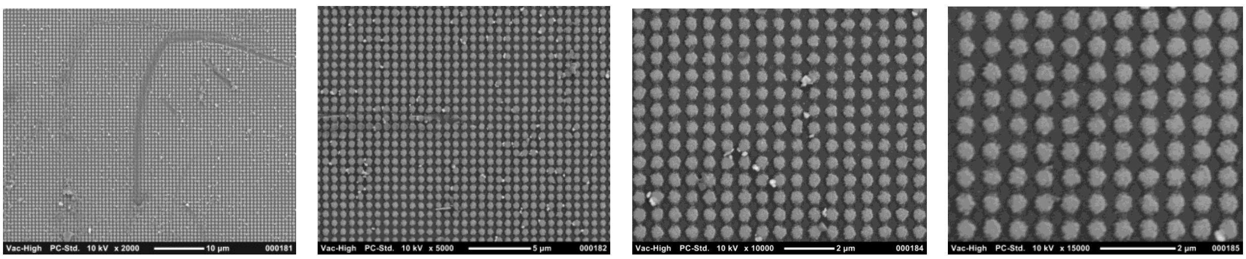
Methods

Brief description of the test object

To determine the actual value increases (scales) of digital SEM images of geometric distortion a test object is needed with a standard distance between its elements (lines, nodes). This test object was first established in Ukraine in the 1980s. It is a glass plate on which is laid a layer of "semiconductor-metal" as a lattice (grid), which looks like a globular hemisphere (Fig. 1). Technology of "semiconductor-metal" was first proposed at the Kiev Institute of Physics of Semiconductor National Academy of Sciences of Ukraine at the lab. of Prof. M. T. Kostyshyn and Ph.D. P. F. Romanenko and used to record holograms of spatial objects [Kostyshyn, 1982]. O. M. Ivanchuk proposed the idea of creating standard test objects in technological materials for calibration and determination of their increases in SEM and SEM geometric distortion images. Using the action of laser beams on the sputtered layers of silver and semiconductor, Ph.D. P. F. Romanenko received the reference test objects as a regular matrix, consisting of hemispheres (nodes) which are fused layers of silver and a semiconductor of arsenic and sulfur (Ag-As_2S). Using several types of lasers with different wavelengths it received test objects of varying density (resolution): 1370 lin/mm, 1425 lin/mm, 3530 lin/mm. SEM-holographic images of test objects with a resolution of 1425 lin mm were used.

Characteristics of SEM images

The SEM JCM-5000 (NeoScope) received 12 images of test objects with resolution r = = 1425 lin / mm in digital TIFF format with fixed values of the increase established on the scale of the device: 1000x, 2000x, 5000x, 8000x, 10000x, 15000x, 20000x, 24000x, 27000x, 30000x, 34000x and 40000x. For the experiment the first 6 images were selected. Conditional size of the digital SEM images and their processing by a PC program "Test-Measuring" make up 116.95 mm × 98.67 mm (1280 × 1080 pixels). The pixel size was – 0.09136 mm.



a – M = 2000^x *b* – M = 5000^x *c* – M = 10000^x *d* – M = 15000^x

Fig. 1. Digital SEM images of the test object with a resolution r = 1425 lin/mm at different M^x

The sequence of automated operations transforming and processing of the SEM images

The experiments used automated SEM image processing technologies developed by the authors using 6 SEM images with the increase from 1000x to M = 15000x (fold).

The problem of automated processing of SEM images is reduced with three basic operations:

1. Automatic recognition nodes of holographic test objects (test grid).
2. Measuring the coordinate nodes and definition using these measurements real values of the increase SEM image along two dimensions $\boldsymbol{x}, \boldsymbol{y}$ and the value`s geometric distortions of the image.
3. Approximation of the geometric distortion of the general polynomial of the 3rd degree.

The sequence of automated operations will be shown below in figures obtained during the processing of SEM images with increasing M = 10000x.

1. The problem of the automated recognition of nodes is one of the important steps in finding coordinates of the centers nodes of the test object images using different scaling.

For solving this problem, we used digital image processing techniques (in particular, filtering, segmentation, morphological processing). The task is further complicated by the presence of defects in the images of the test object, so there is a need to develop a universal algorithm for the removal of damaged nodes. Some defects (bridges between nodes, spots from dust, cavities) are eliminated by morphological processing. To remove other defects such as those that have nodes fused together, the calculated average of the radii of the circles close to the contour of the image nodes. The node for which the radius of the circle is greater than the average radius by a predetermined amount is eliminated.

As a result of the program, written in MatLab system are the defined coordinates of the center circles and centroid`s nodes test grid in the image.

The algorithm calculating coordinates of the centers consist of the following steps:

1. The calculation of the test grid spacing is in microns.
2. The calculation of the test grid spacing is in pixels for scale series 1000x, 2000x, 5000x, 8000x and 15000x.
3. Reading and displaying images of the test grid.
4. Smoothing the image (except M = 1000x) with a low-pass Gaussian filter specifying an m x n pixel size window and an σ scalar value for standard deviation. (Using square windows: m = 3, σ = 1 in range 1000x – 8000x; m = 15*,* σ = 5, for 10000x, 15000x). The result is an image prepared for binarization [González, 2005] see Fig. 3.
5. Convert the smoothed SEM image to a binary image using the automatic threshold selection method Otsu [Otsu, 1979].
6. Implementation of morphological open operation using the structural element (primitive) known as DISK(R) in MatLab. [González, 2006]. (Using R=2, 3 pixels for 1000x, 2000x; R=7, 8 pixels for 5000x, 8000x; R=20-25 pixels for 10000x, 15000x).
7. Definition of coordinate centroid and contour points of the nodes of the test object in the image. [González, 2006].
8. Selection of circles for the dedicated contour nodes of the test grid in SEM image. Determining the coordinates of the centers of circles and the radii using the method of least squares [Zhuravel]. Removing the nodes for which the radius of the circle is greater than the calculated average radius of the circles on the value specified tolerance: $\left|r_i - r_{med}\right| \geq e$, where r_i is the value of radius circle i; r_{med} is the average value of r_i; e is tolerance value. (Using tolerance value (pixels): e = 1-2 for 1000x, 2000x; e = 3 for 5000x, 8000x; e = 5-6 for 10000x, 15000x⁻e = 5–6).
9. Comparison of the coordinate`s center of nodes test object using the value of the average distance between the recognized and measured nodes in the SEM image (Table 1).

As you can see, the value of the average distance between the centers recognized and the manually measured nodes test object is in the range of 1-2 pixels that correspond to the measurement accuracy in a given scale.

10. Save coordinate centers of the recognized nodes in the file.

To evaluate the values of geometric distortions requires finding the coordinates of the corresponding nodes of real test-objects by the coordinates center of recognized node of the test-object in image. As shown in [Ivanchuk 2013] values of real scale SEM images are non-integer numbers and are different from the set on the device scale. On the basis of the research we accepted the assumption that increasing the SEM images are fractal in nature. Based on the empirical relation obtained by Richardson [Richardson, 1961] we received the following relationship between the real increase value and the fixed (integer) increase on the device scale in SEM:

$$M_f = A \cdot M^{2-D}, \qquad (1)$$

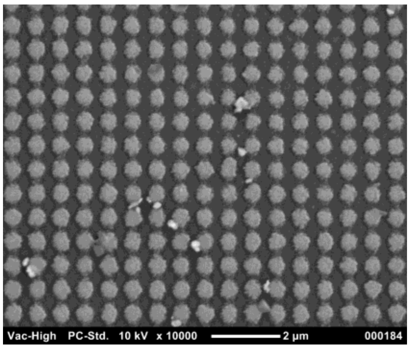


Fig. 2. SEM images of test object in scale M = 10000x

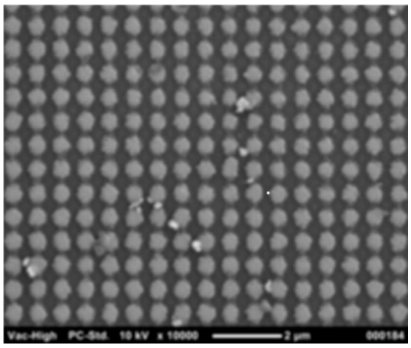


Fig. 3. Smoothed SEM image of the test object using a low-pass Gaussian filter

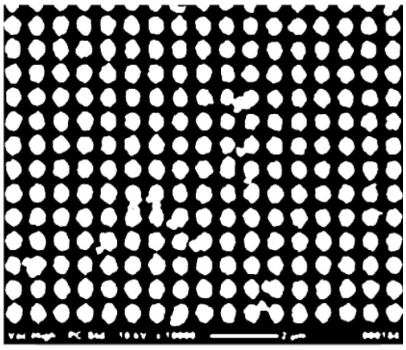


Fig. 4. Binary SEM image of test grid

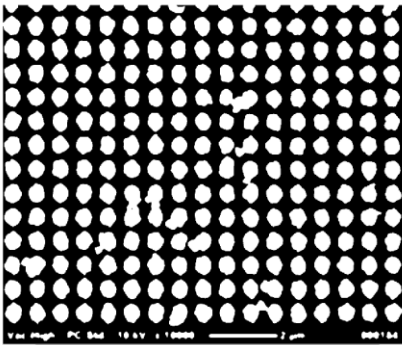


Fig. 5. Morphological open filtering SEM image of test object using the primitive DISK(20)

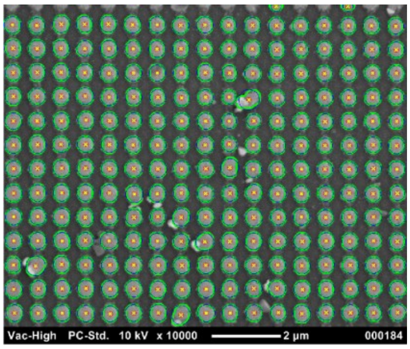


Fig. 6. The selected contours of nodes of the test grid (green) and circles around them (blue) in the SEM image

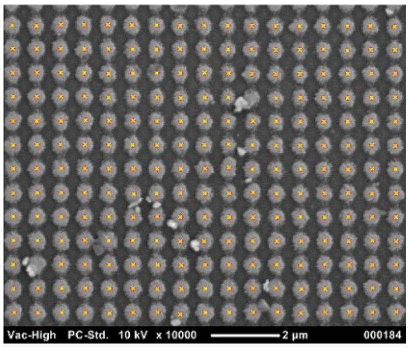


Fig. 7. Result obtained by calculating coordinate center nodes of the test grid (yellow "cross" is the center of the circle, a small red circle is centroid) in the input SEM image

Table 1

The value of the average distance between the centers of the recognized and measured test object

Scale SEM images	Number of nodes in the test object along the *x* and *y* axis in the SEM image	Number of recognized nodes	Number of nodes after removing the average radius	Number of the measured nodes	The average distance between measured and recognized nodes of the test object
1000^{x}	167×141	19434	18492 (95.2 %)	357 (301)*	0.58
2000^{x}	83×67	5343	4699 (88.0 %)	357 (298)	0.74
5000^{x}	33×27	729	729 (100 %)	240 (240)	1.19
8000^{x}	21×17	351	351 (100 %)	351 (351)	1.37
10000^{x}	17×13	221	221 (100 %)	221 (221)	1.29
15000^{x}	11×9	99	99 (100 %)	99 (99)	2.15

* In parenthesis are indicated the number of measured nodes that correspond to the remaining recognized nodes after removing the distorted nodes.

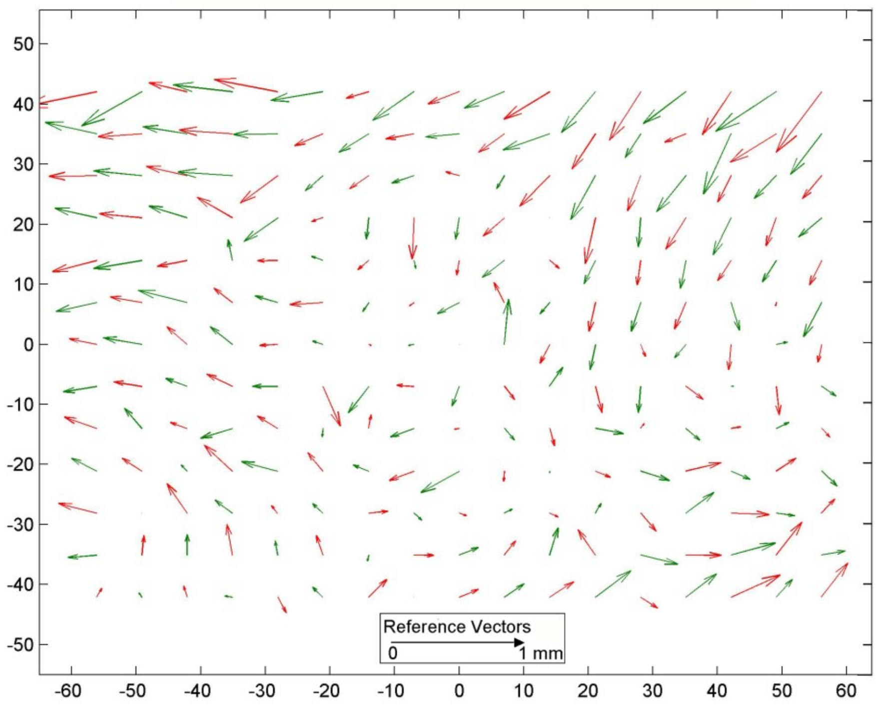


Fig. 8. Vector diagram distortion of SEM images before polynomial approximation

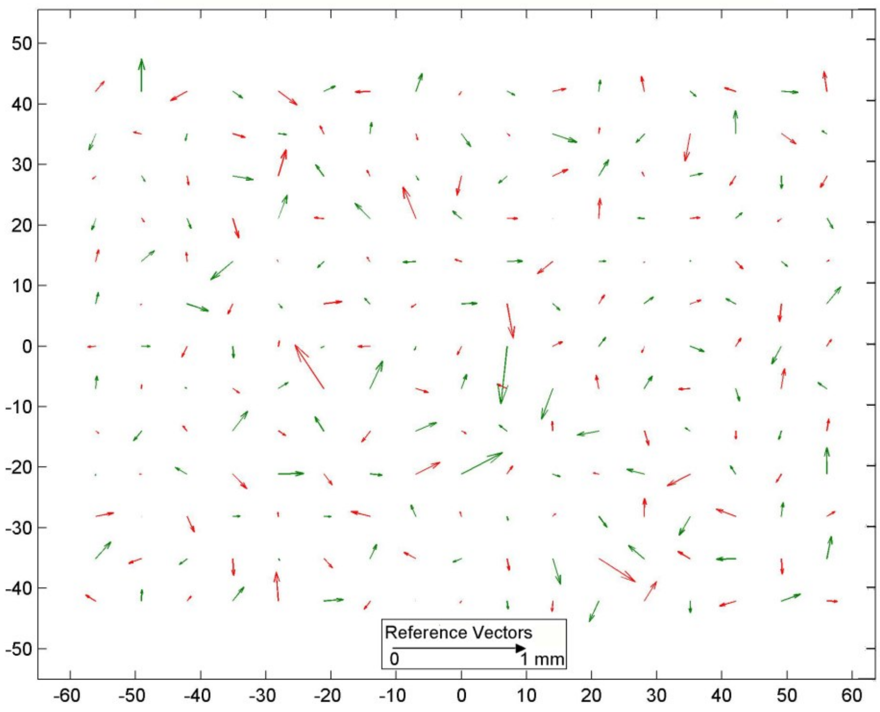


Fig. 9. Vector diagram of residual distortions in the SEM image after the polynomial approximation

Table 2

The results of the approximation of geometric distortion SEM images of the test object with r = 1425 lin/mm for control points that measured by hand and recognized by automatically

№ p/p	M_{SEM}	Manually measured points				Automatically measured points			
		Before approximation		After approximation		Before approximation		After approximation	
		$m_{\Delta x}$, mkm	$m_{\Delta y}$, mkm	$m_{\delta x}$, mkm	$m_{\delta y}$, mkm	$m_{\Delta x}$, mkm	$m_{\Delta y}$, mkm	$m_{\delta x}$, mkm	$m_{\delta y}$, mkm
1	1000^x	103.7	52.4	35.4	33.6	106.0	55.3	27.2	29.0
2	2000^x	39.9	21.2	16.2	16.0	47.8	23.2	24.8	19.7
3	5000^x	78.0	82.7	45.6	41.4	89.4	126.7	64.5	80.0
4	8000^x	69.1	331.7	55.9	64.1	101.3	390.7	10.0	115.2
5	10000^x	172.3	94.7	48.9	41.3	184.8	153.3	82.9	107.2
6	15000^x	131.6	106.1	96.4	78.1	209.7	199.3	164.6	121.1

where M_f is real scale; M is a fixed increase value; A is a proportionality constant; and D is a power factor. After denoting the length of the spacing between nodes the real test grid as h, then the increase of the length of a spacing in M, according to (1) is

$$M_f \cdot h = A \cdot (M \cdot h) \cdot M^{1-D}. \quad (2)$$

In paper [Mandelbrot, 1983] interprets the exponent D as a decimal value that represents a fractal dimension. The dimension exponent D can be calculated [Cromley, 1992]:

$$D = \log(n_2 / n_1) / \log(x_1 / x_2), \quad (3)$$

where n_1 is the number of units of the first unit length; n_2 is the number of units for the second unit length; x_1 is the first unit length; and x_2 is the second unit length.

Based on the real values of the increase obtained in [Ivanchuk, 2013] are defined the coefficients A and the exponent D for SEM JCM-5000 (NeoScope): A_x = 1.042468, D_x= 1.00547185 for scale along x; A_y = 1.042589, D_y= 1.00547337 for scale along y.

Analysis of the results approximations in ranges from 1000x to 15000x obtained using the measured real scale and calculated by (1) experimentally confirmed the relationship between the value of the real increase with the fractal dimension.

By using the automatically calculated coordinates of nodes of the test-object and the real values scale we have evaluated the magnitudes of geometric distortion of the SEM-images. A vector diagram illustrates the values of the geometric distortion (Fig. 8). Vectors length is increased by 20, for clarity.

In further examination the values of the geometric distortion of the SEM images were approximated through the general polynomial 3rd degree using the created software. The values of the residual distortions are also illustrated as vectors (Fig. 9)

Comparing Fig. 8 and Fig. 9 we see that the magnitudes of distortions after approximation of polynomial are reduced in 2–10, confirming the effectiveness of this action.

The results of calculations that prove the effectiveness of approximation are summarized in Table 2.

Conclusions

1. The authors developed a technology to automatically determine the geometrical parameters of SEM images (real increases and geometric distortions) using standard test objects, and has shown its efficiency and high accuracy, confirmed by numerous experimental studies.
2. The analytical relationship between the real increase SEM images and the increase that set on the device scale wer established. The experimental work confirmed the relationship between the real increase to the fractal dimension.
3. Analysis of studies given in Table 2 show that the *rms* value of the geometric distortion digital SEM images, which were measured manually by the operator and obtained automatically using the developed technology, before and after their approximation by the polynomial general form of the 3rd degree, have the same order and are close together.

4. The residual *rms* values of geometric distortion digital SEM images in a range of magnifications M = 1000x, 15000x are within the 0,025–0,165 mm, are within the accuracy of measurement that of 1–2 pixels (1 pixel = 0.091 mm). A maximum value of the residual distortion does not exceed 3 pixels.

5. To perform the measurement of SEM-image test object manually by the operator in order to find its real scale and geometric distortion (using the "Dimicros"), takes from 30 to 60 minutes. In automatic mode utilizing the developed technology and software the process takes only a few minutes.

6. SEM JCM-5000 (NeoScope) (JEOL, Japan) can be considered one of the best in modern microscopes using a metric that does not require constant calibration of the increase to determine the geometric distortion of SEM images before SEM-scanning of each test specimen. The maximum geometric distortion increases in range from M = 1000x to M = 15000x which is relatively small and usually does not exceed 1 mm on the edges of the SEM-image 120×90 mm in size, and is not more than 10 pixels. They also remain stable for a long time during the operation.

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РОЗРОБЛЕННЯ ТА ДОСЛІДЖЕННЯ ТЕХНОЛОГІЇ АВТОМАТИЗАЦІЇ КАЛІБРУВАННЯ ГЕОМЕТРИЧНИХ СПОТВОРЕНЬ ЦИФРОВИХ РЕМ-ЗОБРАЖЕНЬ, ОТРИМАНИХ НА РЕМ JCM-5000 (NeoSkope) (JEOL, ЯПОНІЯ) І ЇХ ВРАХУВАННЯ

Мета. Цифровим зображенням мікроповерхонь твердих тіл, отриманим на растрових електронних мікроскопах (РЕМ), притаманні суттєві геометричні спотворення, які необхідно встановити і врахувати під час визначення кількісних параметрів мікроповерхонь твердих тіл з високою точністю. Тому це завдання є важливим і актуальним, особливо під час контролю якості процесів високотехнологічного виробництва з застосуванням нанотехнологій, зокрема, у машинобудуванні, літакобудуванні, під час створення космічної та військової техніки. Важливо також виконувати вимірювання РЕМ-зображень і отримувати кількісні параметри мікроповерхонь у автоматизованому режимі, що дало змогу б їх виконати значно швидше і уникнути похибок оператора. Тому метою цієї роботи є розроблення та дослідження ефективності технології автоматизованого калібрування геометричних спотворень РЕМ-зображень і їх врахування, а також створення пакета програм, які б її реалізували. **Методика** полягає у застосуванні для автоматизації вимірювань методів цифрового опрацювання РЕМ-зображень і різноманітних їхніх перетворень. **Результати**. Розроблену технологію автоматизації вимірів цифрових РЕМ-зображень апробовано і досліджено під час опрацювань РЕМ-зображень еталонного тест-об’єкта з роздільною здатністю r = 1425 лін/мм, отриманих на РЕМ JCM-5000 (NeoScope) в діапазоні збільшень від $M = 1000^x$ до $M = 15000^x$ крат. Точність вимірів і встановлених кількісних характеристик РЕМ-зображень, зокрема їхніх масштабів уздовж осей знімка, а також геометричних спотворень, співмірні з вимірами, виконаними вручну. Автоматизація цього процесу дає змогу замінити рутинну працю вимірювань цифрових РЕМ-зображень, особливо під час опрацювання РЕМ-зображень у діапазоні порівняно невеликих збільшень $M = 1000^x$–5000^x, суттєво зменшити час вимірювань, а також уникнути суб'єктивних помилок, які при цьому виникають. **Наукова новизна.** Розроблена технологія автоматизації вимірів цифрових РЕМ-зображень і визначення їх геометричних параметрів виконана вперше в Україні. Запропонована технологічна схема автоматизації вимірювань цифрових РЕМ-зображень та створене для цього авторське програмне забезпечення показали його ефективність і доцільність. **Практична значущість.** Застосування цієї технології дає змогу автоматично і з високою точністю визначати дійсні значення збільшень (масштабів) цифрових РЕМ-зображень, величини їхніх геометричних спотворень, а також враховувати їх під час отримання кількісних просторових параметрів мікроповерхонь твердих тіл з високою точністю, а отже, підвищувати надійність і ефективність виготовлених з них пристроїв, механізмів, матеріалів, тощо.

Ключові слова: растровий електронний мікроскоп; тест-об'єкт; цифрове РЕМ-зображення; геометричні спотворення цифрових РЕМ-зображень; фрактальна розмірність; автоматизація вимірювань.

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