Calibration and Uncertainty Analysis of Scanning Electron Microscope Length Measurement Error

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Abstract. Based on the calibration method of scanning electron microscope length measurement error based on equidistant grid standard template, establish an evaluation model for measurement uncertainty and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the process of evaluating the measurement uncertainty of length indication error in scanning electron microscopy based on equidistant grid standard templates, calculates its extended uncertainty, and provides a reference for evaluating the measurement uncertainty of length indication error in scanning electron microscopy based on equidistant grid standard templates.

Keywords: Metrology, scanning electron microscope, length measurement error, equidistant grid standard template, uncertainty in measurement.

1. Introduction

Scanning electron microscope (SEM) is an important measuring instrument for measuring the size characteristics of nanomaterials and micro nanostructures. The instrument uses a focused electron beam to scan the sample surface point by point, and the interaction between electrons and the sample generates secondary electron signals and backscattered electron signals, thereby obtaining the surface morphology image of the measured object. Due to the nanoscale resolution of the morphology obtained by scanning electron microscopy, it has a wide range of applications in universities, research institutes, and high-tech enterprises, especially in fields such as semiconductor chips [1-2]. As a measuring instrument, scanning electron microscopy mainly traces its measurement values to national standards through equidistant grid standard templates. To achieve calibration of scanning electron microscopes, many scholars have conducted related research [2-5]. In the calibration specification JJF1916-2021 "Scanning Electron Microscope Calibration Specification" issued in recent years, metrological requirements have been proposed for parameters such as length measurement error, orthogonal distortion, and linear distortion of scanning electron microscopes [6]. On the basis of the above research, this article conducts a study on the calibration of length measurement errors and evaluation of measurement uncertainty of scanning electron microscopy based on equidistant grid standard templates.

2. Calibration Method

According to JJF 1916-2021 "Calibration Specification for Scanning Electron Microscopes" [6], calibrate the length measurement error of a certain scanning electron microscope. Select standard instruments as equidistant grid standard templates, with MPE of ±3% for grid period spacing of 100nm and 250nm, and ±1% for grid period spacing of 500nm, 1000nm, and 2000nm. The indoor temperature for calibrating the scanning electron microscope should be within the range of (20±5) ℃, and the humidity should not exceed 65%RH. The standard template used should be placed together with the tested instrument for an isothermal time of not less than 0.5 hours. The electromagnetic radiation in the laboratory should not affect the measurement results. The magnification of the calibrated scanning electron microscope is 500-1000k times, and the calibrated magnification for measuring length indication errors are 5k, 10k, 20k, 50k, and 500k, respectively. Standard templates with grid period spacing of 2000nm, 1000nm, 500nm, 250nm, and 100nm are used accordingly.

The calibration method for length measurement error of scanning electron microscope is as follows: adjust the sample stage, rotate the standard template so that the lines of the grid are along the vertical direction, and the measurement direction of the grid spacing is along the X-axis of the image. Record the scanned image and corresponding magnification, as shown in Figure 1.

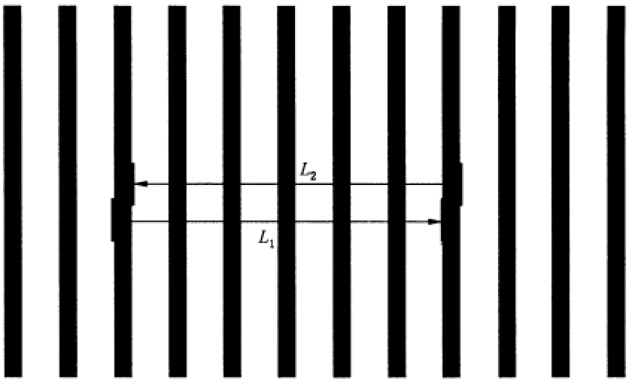

Figure 1. Schematic diagram for calibration of scanning electron microscope length measurement values

Measure the grid spacing in the X direction on the image. Select M ($M \geq 5$) grid structures on the standard template image to measure the center to center distance L of the lines. The distance L can be calculated by taking the average of the distance L_1 between the left edge and the distance L_2 between the right edge, that is, $L=(L_1+L_2)/2$. Measure continuously for 3 times and take the average. For the calibration of measurement and indication errors with a magnification of over 200000 times, L can only include one spacing. The measurement value of grid spacing is calculated according to equation as follow

$$P = L / M \tag{1}$$

The difference between the measured value and the actual value of the standard template is the measurement length indication error. Rotate the sample stage 90 ° to align the lines along the Y-axis of the image, and measure the grid spacing in the Y direction using the measurement method for grid spacing in the X direction. The difference between the measured value and the actual value of the standard template is the measurement length indication error. The schematic diagram of the calibration process for scanning electron microscope length measurement is shown in Figure 2.

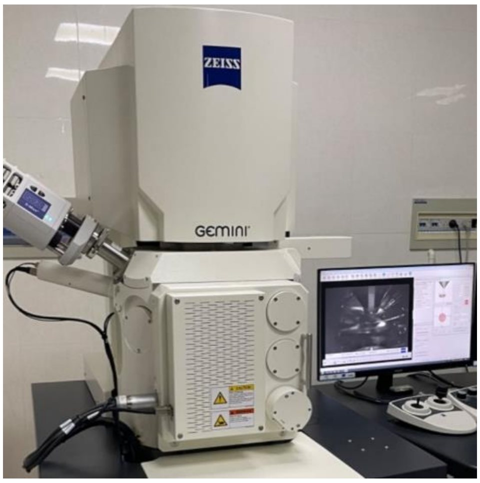

Figure 2. Schematic diagram of the calibration process for scanning electron microscope length measurement values

3. Evaluation of Measurement Uncertainty

3.1. Measurement Model

Under laboratory environmental conditions, calibrate the length measurement error of the scanning electron microscope using grid spacing according to the above calibration method. The measurement model for measuring the length indication error of scanning electron microscopy based on measurement principles and methods is obtained as follows

$$\Delta P = P_i - P_s \tag{2}$$

Where, ΔP is the measurement error of the scanning electron microscope length measurement, and P_i is the measurement error of the standard template grid spacing measured by the scanning electron microscope, P_s is the calibration value for the periodic spacing of the standard template grid.

3.2. Measurement Uncertainty Model

Based on the measurement model and sources of uncertainty, the input variables P_i and P_s are uncorrelated, and the following model is obtained from the uncertainty propagation law [7].

$$u_c^2(\Delta P) = c_1^2 u^2(P_i) + c_2^2 u^2(P_s) \tag{3}$$

Where, $u(P_i)$ is the standard uncertainty introduced by the measurement of grid spacing, and $u(P_s)$ is the standard uncertainty introduced by the periodic spacing of the standard template grid, $c_1 = 1, c_2 = -1$.

3.3. Calculation of Standard Uncertainty

3.3.1. Calculation of u(Pi)

This uncertainty mainly includes the uncertainty $u_1(P_i)$ introduced by the alignment of the grid start and end points during measurement and the uncertainty $u_2(P_i)$ introduced by the resolution of image pixels. The uncertainty $u_1(P_i)$ introduced by aligning the starting and ending points of the grid can be evaluated by repeated measurements and calculating the standard deviation. Under repetitive conditions, independent measurements were taken 10 times for grid spacing at different magnifications, and the experimental standard deviation *s* and standard uncertainty $u_1(P_i)$ at different magnifications were calculated, as shown in Table 1.

Table 1. Experimental standard deviation s and standard uncertainty u1(Pi) at different magnifications

magnification	**5k**	**10k**	**20k**	**50k**	**500k**
grid period spacing / nm	2000	1000	500	250	100
standard deviation s / nm	5.5	4.2	4.8	3.7	3.4
standard uncertainty $u_1(P_i)$ / nm	2.3	1.7	2.0	1.5	1.4

If we take the one with the highest uncertainty in Table 1 as the uncertainty $u_1(P_i)$ introduced by aligning the starting and ending points of the grid, then

$$u_1(P_i) = 2.3\text{nm} \tag{4}$$

The uncertainty $u_2(P_i)$ introduced by the resolution of image pixels can be determined by calculating the distance on the measured standard template corresponding to each pixel in the image. Taking a 20k magnification as an example for calculation, for the measurement image of image size *W* and pixel *N*, the resolution *R* is

$$R = W / N = 5385\text{nm} / 1280 \approx 4.2\text{nm} \tag{5}$$

If the measurement period is 10, the uncertainty $u_2(P_i)$ introduced by the pixel resolution of the image is

$$u_2(P_i) = \frac{4.21\text{nm} \times \sqrt{2}}{10 \times \sqrt{3} \times 2} = 0.2\text{nm} \tag{6}$$

Due to the fact that the uncertainty $u_1(P_i)$ introduced by aligning the starting and ending points of the grid is much greater than the uncertainty $u_2(P_i)$ introduced by the pixel resolution of the image, the influence of the pixel resolution of the image can be ignored. Therefore, the standard uncertainty component $u(P_i)$ introduced by grid spacing measurement is

$$u(P_i) = u_1(P_i) = 2.3\text{nm} \tag{7}$$

3.3.2. Calculation of uL

The maximum allowable errors MPE for the spacing of standard template grids with periodic spacing S of 2000nm, 1000nm, 500nm, 250nm, and 100nm are ± 1%, ± 1%, and ± 3%, respectively. If treated uniformly, the calculation results of the standard uncertainty component $u(P_s)$ introduced by the periodic spacing of the standard template grids are shown in Table 2.

Table 2. Standard uncertainty u(Ps) for different period intervals

grid period spacing / nm	**2000**	**1000**	**500**	**250**	**100**
maximum allowable errors	±1%	±1%	±1%	±3%	±3%
standard uncertainty $u(P_s)$ / nm	11.6	5.8	2.9	4.3	1.7

3.4. Combined Standard Uncertainty

According to the calculation results in Tables 1 and 2, the composite standard uncertainty of the scanning electron microscope length measurement error is calculated according to Equation (3) and is shown in Table 3.

Table 3. Combined standard uncertainty

magnification	**5k**	**10k**	**20k**	**50k**	**500k**
grid period spacing / nm	2000	1000	500	250	100
combined standard uncertainty / nm	11.8	6.2	3.7	4.9	2.9

3.5. Expanded Uncertainty

According to the results in Table 3, taking the inclusion factor k=2, the expanded uncertainty of the scanning electron microscope length measurement error is calculated as shown in Table 4.

Table 4. Expanded uncertainty

magnification	**5k**	**10k**	**20k**	**50k**	**500k**
grid period spacing / nm	2000	1000	500	250	100
expanded uncertainty / nm	24	13	8	10	6

4. Conclusion

Based on the calibration method of scanning electron microscope length measurement error based on equidistant grid standard template, establish an evaluation model for measurement uncertainty and analyze the sources of various uncertainties. Based on measurement examples, this paper elaborates on the process of evaluating the measurement uncertainty of length indication error in scanning electron microscopy based on equidistant grid standard templates, calculates its extended uncertainty, and provides a reference for evaluating the measurement uncertainty of length indication error in scanning electron microscopy based on equidistant grid standard templates.

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