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Microbeam analysis — Scanning electron microscopy — Methods for the evaluation of image sharpness

Analyse par microfaisceaux — Microscopie électronique à balayage — Méthodes d'évaluation de la netteté des images

ICS 37.020

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Contents

Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

ISO 24597 was prepared by Technical Committee ISO/TC 202/SC 4, *Microbeam analysis*, *Scanning electron microscopy*.

Annexes E, F, G, H and Bibliography are for information only.

Introduction

The International Organization for Standardization (ISO) draws attention to the fact it is claimed that compliance with this document may involve the use of patents concerning the evaluation method using contrast-to-gradient (CG) method given in **6.4**.

ISO takes no position concerning the evidence, validity and scope of this patent right.

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Patent holder: Hitachi, Ltd.

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Microbeam analysis — Scanning electron microscopy — Methods for the evaluation of image sharpness

1 Scope

This International Standard specifies the methods to evaluate the image sharpness of digitized images generated by a scanning electron microscope (SEM) by applying Fourier transform (FT) method, contrast-to-gradient (CG) method and derivative (DR) method.

2 Normative references

The following normative documents referenced in the text herein, constitute provisions of this International Standard. For dated references, subsequent amendments to them, or revision of any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent edition of the normative document indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 16700 :2004, *Guideline for calibrating image magnification.*

ISO 17025 :1999, *General requirements for the competence of testing and calibration laboratories.*

ISO / FDIS 22493 : *SEM Terminology.*

3 Terms, definitions and abbreviated terms

Definitions and abbreviations of the terms referred herein are listed in document 22493 (SEM Terminology, ISO/DIS 22493) and ISO 16700:2004.

Additional definitions and abbreviations required for this standard are listed below.

3.1
pixel
smallest non-divisible image-forming unit on a digitized SEM image

3.2
pixel size
specimen length (nm) per pixel in an SEM image

NOTE Horizontal and vertical pixel sizes should be same.

3.3
binary SEM image
a converted SEM image in which there are only two brightness levels

3.4
convoluted image
an image obtained by convolution of a binary SEM image with a two-dimensional Gaussian profile

3.5
sharpness factor
twofold standard deviation (2σ) of Gaussian profile used to make the convoluted image

3.6
image sharpness
$2\sigma/\sqrt{2}$, namely, the sharpness factor divided by the square root 2, where the sharpness factor of SEM image being regarded as same as that of the convoluted image by Gaussian profile with standard deviation σ

3.7
contrast-to-noise ratio (*CNR*)
ratio of $I_A - I_B$ to σ_n, where I_A and I_B are image intensities for the object and the background, and σ_n is the standard deviation of image noise

3.8
Fourier transform method (FT method)
method for evaluating the image sharpness by comparing Fourier transform profiles of an SEM image with those of the convoluted images

3.9
contrast-to-gradient method (CG method)
method for evaluating the image sharpness using weighted harmonic mean gradients of the two-dimensional brightness distribution map of an SEM image

3.10
derivative method (DR method)
method for evaluating the image sharpness by fitting error function profiles to gradient directional edge profiles of particles in an SEM image

3.11
field of view
area of a specimen that corresponds to the whole SEM image

4 Steps for acquisition of SEM image

4.1 General

For SEM image acquisition, it is important to first adjust the microscope conditions (for example, see Annex B in ISO 16700). Image sharpness is dependent upon (i) the specimen itself, (ii) structural smoothness of the foreground and the background of the image, (iii) brightness and contrast and (iv) contrast-to-noise ratio (*CNR*). Therefore, follow the procedures described in **4.2** to **4.10** corresponding to the above factors for evaluation of image sharpness by all the three methods described herein. Particular attention must be paid to the adjustment of electron probe current and focussing conditions in order to obtain optimum requirements for brightness and contrast (**4.6**) and contrast-to-noise ratio (**4.7**).

4.2 Specimen

At the date of publication of this document there is no designated Certified Reference Material (CRM). Acceptable results can be obtained using a specimen prepared by the method described in Annex G. Select a specimen with a smooth and flat surface. For evaluations of the image sharpness, choose a part of the specimen which contains circular particles deposited on the substrate. Obtain desirable images at the chosen magnification, in accordance with **4.4**.

NOTE Sensitive material for electron dose is not suitable as a specimen for the evaluation of image sharpness.

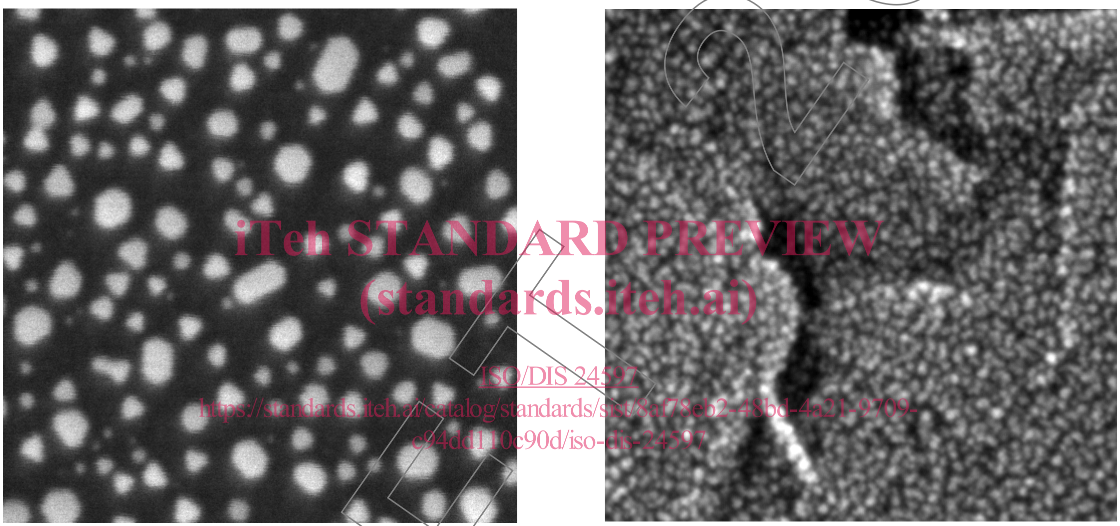
4.3 Specimen tilt

Set the specimen tilt angle at 0 degree (non-tilting condition).

NOTE Error within +/- 3 degrees in tilt angle of the specimen will not affect the evaluation of image sharpness.

4.4 Selection of the field of view

Select the field of view containing a flat and smooth surface, because image sharpness varies with the uneven features of the surface structure. Figure 1 (a) and (b) show the acceptable and unacceptable fields of view, respectively. Choose particles extending to several ten pixels (see Figure 1(a)).



(a) Acceptable image (b) Unacceptable image

Figure 1 — SEM images with (a) acceptable and (b) unacceptable structured foreground images

4.5 Selection of the pixel size

Before evaluating the image sharpness, it is necessary to calibrate the image magnification and/or the scale marker accordingly with ISO 16700.

4.5.1 Determination of the pixel size from a field of view

The pixel size L_p (nm) is determined from the formula:

$$L_p = \frac{L_{FOV}}{N_p},$$

where L_{FOV} (nm) shows the horizontal size of the field of view on an SEM image, and N_p is the number of pixels covering to the horizontal field of view.

4.5.2 Determination of the pixel size from a scale marker

The pixel size L_p (nm) is calculated by using a scale marker as follows:

$$L_p = \frac{L_{scale}}{N_{scale}},$$

where L_{scale} is the “indicator” value (e.g. nominal value in nm) of the scale marker and N_{scale} is the number of pixels covering to the length of the scale marker.

4.5.3 Conversion of the pixel size

The image sharpness as derived by the methods described herein (R_{PX}) is in “pixel” unit. The image sharpness R_L in “nm” unit is then converted by the expression:

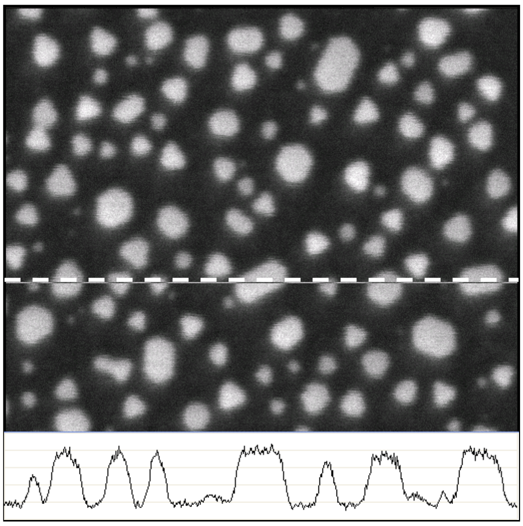
$$R_L = L_p \cdot R_{PX} ,$$

where L_p is the pixel size.

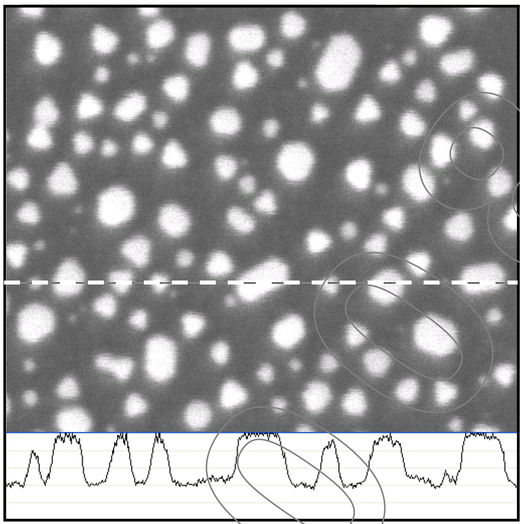
NOTE Set pixel size about 40% of the expected value of the image sharpness. For example, set the pixel size 0,8 nm when the image sharpness is expected to be 2 nm.

4.6 Brightness and contrast of the image

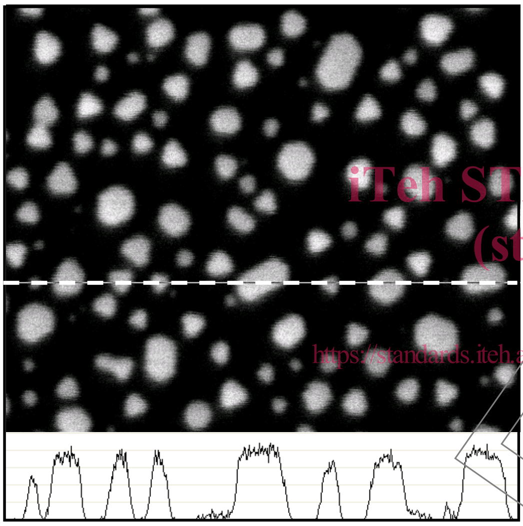
The signal intensity of the image should be widely distributed. Figure 2 (a), (b), (c) and (d) show examples of images with acceptable and unacceptable brightness and contrast. Line profiles along the dotted lines at the same vertical position for their images are shown as eye guideline.



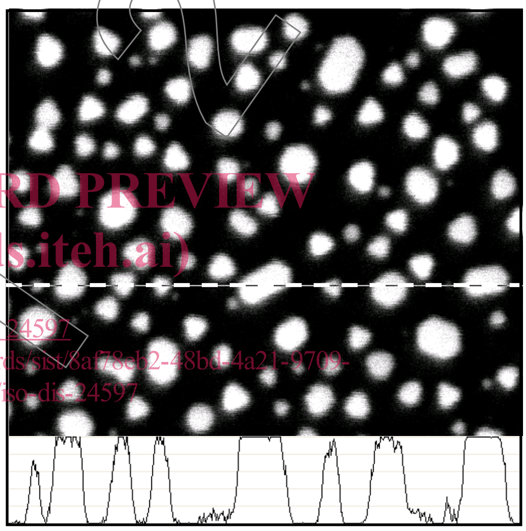
(a) Acceptable image



(b) Unacceptable (over-saturated) image



(c) Unacceptable (under-saturated) image



(d) Unacceptable (both-saturated) image

Figure 2 — SEM images with acceptable and unacceptable brightness and contrast

4.7 Contrast-to-noise ratio of the image

Contrast-to-noise ratio (*CNR*) of the image must be 10 or larger. Here, the *CNR* is defined as a ratio of the image contrast (C_{image}) to the standard deviation (σ_n) of the image noise (see Figure 3).

$$CNR = C_{image} / \sigma_n.$$

Procedures for the *CNR* evaluation are given in Annex A.

Figure 4 shows the simulated appearance of the images with *CNR* of 5, 10, and 50.

Figure 5 shows examples of SEM images with different *CNR* of about 4 and 30.

NOTE In order to obtain SEM images with good *CNR*, it is necessary to adjust the probe current and/or the image acquisition time. One should be aware of the fact that variations in the above parameters will affect the evaluation results of image sharpness.

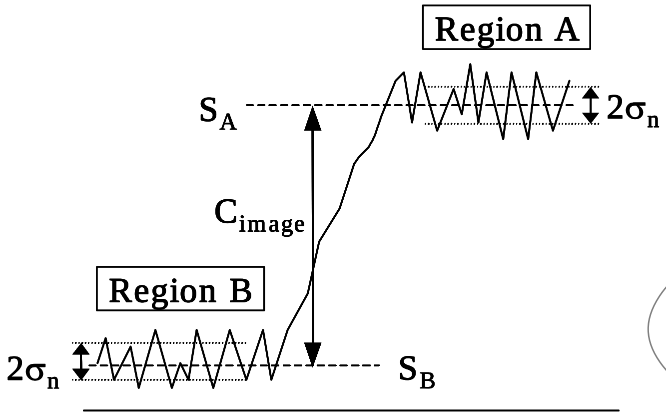
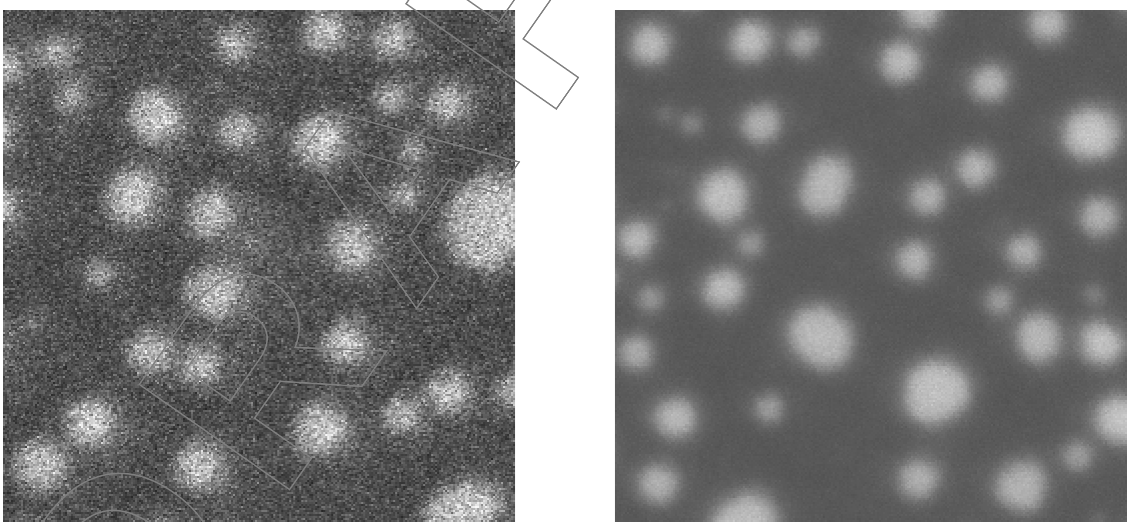


Figure 3 — Intensity profile of an image

(a) *CNR* = 5 (b) *CNR* = 10 (c) *CNR* = 50

Figure 4 — Simulated images with different contrast-to-noise ratios (*CNR*)



(a) Low contrast-to-noise ratio (*CNR* ≈ 4) (b) High contrast-to-noise ratio (*CNR* ≈ 30)

Figure 5 — SEM images with different contrast-to-noise ratios (*CNR*)

4.8 Focus and astigmatism of the image

Focus the electron beam as best as possible. Use an image that is free of astigmatism.

4.9 Interference from external factors

External factors such as mechanical vibrations, distortion by magnetic field and those listed in Annex B of ISO 16700 affect the image sharpness. Ensure, as far as possible, that images used are not affected by these factors.

4.10 Erroneous contrast

Make sure that images do not contain erroneous contrast (e.g. contrast due to charging-up of the specimen).

4.11 SEM Image data file

Image data, which is directly saved from an SEM, shall be in digital format with the greyscale at least 8 bits deep. Data file of the image shall be in an uncompressed graphics file format, e.g. BMP or TIF.

NOTE Do not use the data obtained from a printed SEM image.

5 Acquisition of an SEM image, and selection of an area within the image

The procedures described in this section are common in this standard (see **6**).

a) Use a specimen prepared according to the procedure described in **4.2**. Acquire an image by paying attention to conditions in **4.3** to **4.10**.

b) Select a square area in the SEM image (hereafter referred to as the image) comprising at least 256 x 256 pixels. The area shall not have superimposed extraneous data (e.g. magnification display, scale marker, characters, arrows, etc.).

NOTE Choose an area containing images of preferably non-overlapping particles.

c) Store the selected SEM image in a data file in an un-compressed graphics file format specified in **4.11**.

6 Evaluation methods

6.1 General

Evaluation methods described in **6.3** to **6.5** are based on the assumption that the electron beam has a Gaussian profile. Hence the results obtained by the methods do not represent the actual beam size (see Annex E.4). Figure 6 shows a general flow chart of the evaluation of an SEM image including the common procedure for evaluation of the *CNR.*

Basic procedures for obtaining the image sharpness are as follows:

a) Select an SEM image by following **5**.

b) Determine the *CNR* for the selected SEM image (see **6.2**) and ensure that it is larger than or equal to 10 before proceeding further.

c) Calculate a sharpness factor 2σ of the selected SEM image, in the frequency space or the real space (depending on methods applied). Here, the image sharpness of an SEM image is determined from an equivalent image produced by convolution of a binary SEM image with a two-dimensional Gaussian profile with the sharpness factor 2σ (i.e., a twofold standard deviation).

NOTE The calculation procedures depend on the method.

d) The image sharpness is defined as $k{\cdot}2\sigma$, where $k = 1/\sqrt{2}$.

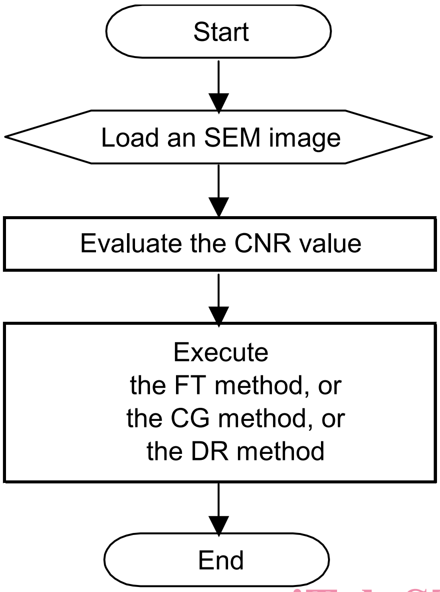


Figure 6 — General flow chart of the evaluation of an SEM image

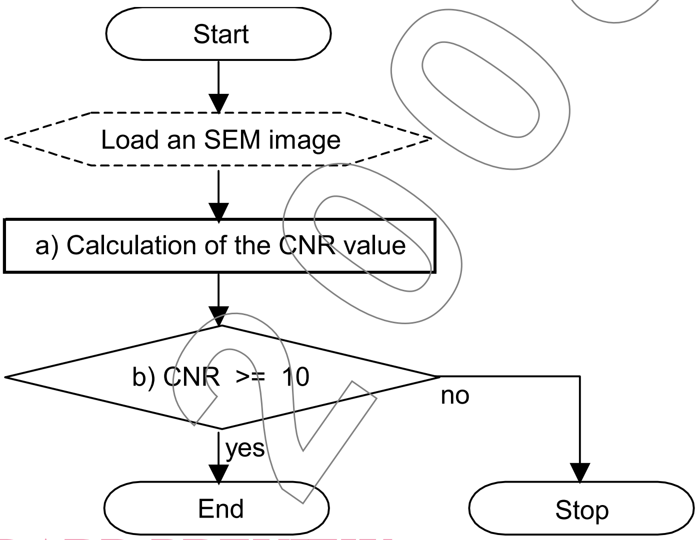


Figure 7 — Flow chart of the evaluation of *CNR*

6.2 Contrast-to-noise ratio (*CNR*)

The basic concept of the contrast-to-noise ratio (*CNR*) was developed in the medical imaging field. Refer to **4.7**. The *CNR* for the selected SEM image of interest shall be evaluated. Only the images with *CNR* = 10 or larger can be passed to the next step for the image sharpness. Figure 7 shows a brief flow chart of the *CNR* evaluation following routines a) and b). Details of the routines are described in Annex A.

NOTE If the value of *CNR* < 10, discard the SEM image. Acquire a new SEM image with lower noise, and carry out the evaluation again.

6.3 Fourier transform (FT) method

For evaluating image sharpness, the Fourier transform (FT) method is used with the spatial frequency components given by the FT of an SEM image. The spatial frequency components of the SEM image are compared with those of the convoluted images obtained by the convolution of the binarized SEM image via Gaussian profiles with various sharpness factors 2σ (see Figures 8 and 9). Details of procedures for the FT method are given in Annex B.

NOTE 1 The signal intensity of an image I_m is expressed as $I_m(i,j)$, and the coordinates i and j are chosen as 0, 1, …, L–1 for an image with x- and y-size L (= 256, 512, …). However, the coordinates i and j are treated as integers ranging from $-L/2$ to $L/2-1$ for the FT pattern.

NOTE 2 The following explanation is applied to the image with L = 256 pixels.

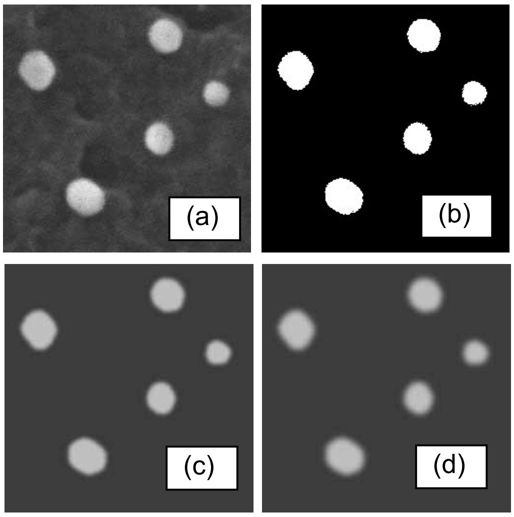


Figure 8 — (a) a selected SEM image $I_O(i,j)$ with image size L = 256, (b) the binarized image $I_B(i,j)$, (c) and (d) the convoluted images $I_C(i,j;2\sigma)$ with 2σ = 4 pixels, and $I_C(i,j;2\sigma)$ with 2σ = 6 pixels, respectively

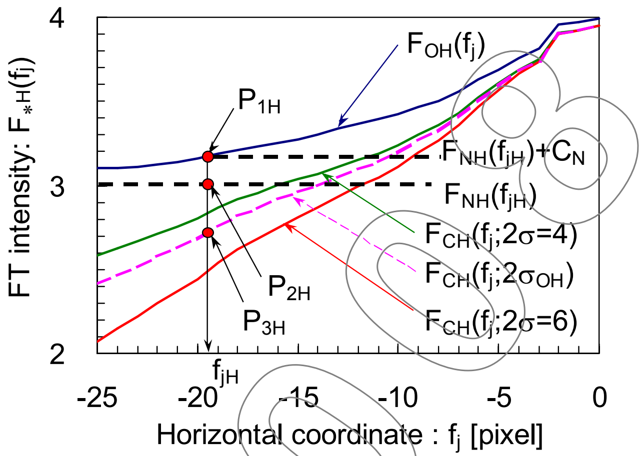


Figure 9 — Averaged and smoothed FT curves taking common logarithm, $F_{OH}(f_j)$ for the selected SEM image $I_O(i,j)$, $F_{CH}(f_j;2\sigma)$ and $F_{CH}(f_j;2\sigma_{OH})$ for the convoluted images $I_C(i,j;2\sigma)$ and $I_C(i,j;2\sigma_{OH})$

a) Generation of convoluted images

1) Generate a filtered image $I_{OF}(i,j)$ processed by the 3x3 median filter, for a selected SEM image $I_O(i,j)$.

2) Produce a histogram $H(S)$ of $I_{OF}(i,j)$, and then obtain a smoothed histogram $H_S(S)$ by using the moving averages of 9 points. Then calculate $h_S(S) = \log_{10}\{H_S(S) + 1\}$.

3) Determine S_L and S_H that correspond to the intensities of the substrate and the particles respectively, and determine a threshold level $(S_L + S_H)/2$ by using $h_S(S)$.

4) Produce a binarized image $I_B(i,j)$ by using $(S_L + S_H)/2$.

5) Add the white noise to the selected image $I_O(i,j)$ by setting $SNRp$ (signal-to-noise ratio for particles) = 30 for the signal intensity S = 192.

6) Generate convoluted images $I_C(i,j;2\sigma)$ by the convolution of the binarized image $I_B(i,j)$ via two dimensional Gaussian profiles with various sharpness factors $2\sigma = 2\sigma(N)$ beginning with $2\sigma(1)$ = 1, where each σ corresponds to the standard deviation of the Gaussian distribution and N (=1, 2, …) is the step number.

7) Adjust the intensity of the various convoluted images $I_C(i,j;2\sigma)$ so that the maximum and the minimum intensities are S_H and S_L, respectively.

b) Generation of curves of FT patterns

1) Carry out the FT for the selected SEM image $I_O(i,j)$ and the various convoluted images $I_C(i,j;2\sigma)$. The $G_O(f_i,f_j)$ and $G_C(f_i,f_j;2\sigma)$ represent the FT patterns corresponding to $I_O(i,j)$ and $I_C(i,j;2\sigma)$, respectively.

2) Obtain the horizontally averaged-and-smoothed value of $|Re[G_O(f_i,f_j)]|$ and the vertically averaged-and-smoothed value of $|Re[G_O(f_i,f_j)]|$, and calculate the curves $F_{OHA}(f_j)$ and $F_{OVA}(f_i)$ by taking common logarithm of them.

NOTE Re [...] denotes the real part, and |...| denotes the absolute value.

3) Obtain the averaged curves of $F_{OH}(f_j)$ and $F_{OV}(f_i)$ by applying the moving averages of 5 points along the horizontal f_j and the vertical f_i directions for the curves $F_{OHA}(f_j)$ and $F_{OVA}(f_i)$, respectively.