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PROCESSING OF SCANNING ELECTRON MICROSCOPE IMAGES ON BASIS OF FAST FOURIER-TRANSFORMATION

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Abstract

The solar cell as a combined substrate and detector was used for automated SEM-image analysis. It was noted that an image processing system was created and its operational features are shown in some typical applications. The step size of the fatigue striations was found. The obtained value of the step corresponds to the formula with an accuracy of about 1 per cent. Quantum-mechanical constant of material fracture for aluminum alloys was found to be $\Delta = 0.22$. Two-dimensional periodic analysis was applied to fracture surfaces and a microchannel plate. The integral characteristics of microstructure was determined quantitatively.

KEY WORDS: Scanning electron microscopy, solar cell, spectrum, Fourier-transformation, two-dimensional, microcomputer, grain boundary, particles, fractals, fracture, striations, quantitative, programs.

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Introduction

The use of digital methods makes it possible to perform a spectral analysis of information obtained by a scanning electron microscope (SEM). The hardware basis of processing facilities of scanning electron microscope images is the ISKRA 226 (USSR) microcomputer with 128 K memory and 16 bit - 10 MHz processor. The interface with the SEM provides the input to the computer of an image with 256 brightness gradations together with digital scanning of up to 1024 x 1024 points. A black-and-white binary display of 256 x 560 pixels and a colour half-tone display with a buffer memory 3 x 256 x 256 pixels by 16 gradations are used which allows more than 4000 colour gradations to be displayed. The recording of results and images is effected by a printer with graphics capabilities. Storage of information, programs and images is realized by flexible discs, 5M hard discs and magnetic tape memory.

The basis of programs of spectral processing of SEM-information is the procedure of one-dimensional and two-dimensional direct and inverse fast discrete Fourier-transformation. Mathematical basis of Fourier-transformation and algorithms of fast Fourier-transforms are described in many publications but it is not our intention to dwell on these problems here. The peculiar features connected with individual objects and methods will be mentioned in each example shown below.

Fourier-study of forms of microobjects

Spectral methods of investigations on the basis of fast Fourier-transformation (FFT) make it possible to obtain a larger scope of information than that of conventional studies of form factors or ratio of maximum and minimum sizes of objects. The purpose of Fourier studies of a form is the separation of information about a form and roughness of the surface of microobjects.

At the first stage a microcomputer is loaded from the SEM with a digital image of a specimen containing the particles to be studied. In a dialogue mode with the operator the discrimination level is selected to separate the studied particles from the background. This procedure is facilitated considerably by a high contrast initial image. For such objects as sand grains a high contrast image may be obtained in the cathodoluminescence mode. High contrast images of objects of any nature are obtained in a transmission mode if the particles are arranged on a formvar film transparent to electrons. A similar effect may be reached if the signal source is a solar cell on which the studied particles are arranged. In the latter two cases the shadow of the boundary of particles provides a high contrast image without additional discrimination.

After formation of a binary image of the studied particles a programmed scanning of the image is carried out line by line in the microcomputer beginning in the upper left corner of a frame. As soon as the boundary of a particle is detected the program stores the coordinates of this boundary point and then traces around the image of the particle while storing the coordinates of all points of the boundary until it comes back to the first encountered point. For the purpose of exclusion of a repeat analysis of the same particle during further examination of the image, the particle is erased from memory by "crossing-out" and simultaneously calculating the area. Then a classical form-factor is determinated from the area and perimeter.

On the basis of coordinates of boundary points the center of gravity of the given particle is found and relative to the centre of gravity a transformation is made to polar coordinates. The function of particle boundary in polar coordinates is subjected to one-dimensional FFT with computation of the energy spectrum out of the first 32 components. The low magnitude components of Fourier-spectrum correspond to coarse forms on the grain boundary and components with larger values correspond to sharp and fine details of the boundary. A zero component corresponds to an average radius of a particle and may serve as a norm to compare the forms of particles of different sizes, for which all Fourier components should be divided by the zero component.

During the study of sand grains (Enrich and Weinberg, 1970; Sokolov et al, 1982) the Fourier spectrum of the boundaries of whole particles contained only low frequency components, while particle fragments were characterized by a wide spectrum containing a considerable amount of high frequency components. Fig. 1 shows the results of the Fourier analysis of the form of different particles. Fig. 1a shows the image on the microcomputer display where in the right section a binary variant of the image of spherical plastic particles is presented and in the left section data about area, perimeter and form-factor of each particle and its Fourier spectrum are shown. The similar results of the analysis of particles of crushed quartz are given in Fig. 1b. From a comparison of these data it is seen that the more complicated profile of the boundary of crushed quartz particles results in a more developed Fourier spectrum. As an intermediate variant, Fig. 1c shows the results of similar treatment for well-rounded grains. In this case low frequency components predominate in the response to the smooth forms of the grain boundaries and high frequency components indicating rough boundaries are absent.

For approximate comparison of particles by Fourier spectra it is convenient to approximate the spectrum by a function of the form:

$$F(n)=(a/n)-b \qquad (1)$$

where n - harmonic number in spectrum F(n). Parameters of this approximation a and b make it possible to separate the studied particles according to form and roughness. In spite of the fact that such approximation carries less information than a full spectrum it allows the objects to be easily classified.

The methods of Fourier analysis of forms of microobjects in the SEM are most effective in cases in which the properties of the material are determined by the surface roughness. This is displayed in the above mentioned study of sand grains where the surface roughness of the particles determines the mechanical properties of the sand. It should be expected that similar methods will be effective for studies of biomedical objects, such as blood components, etc.

Quantitative Fourier fractography

The demand for spectral methods of analysis of the structure of the fracture boundary is determined by the necessity to extract periodical structures from the rest of the information. As a result of a cyclic loading of the material, fatigue striations (Shanyavsky, 1984; Haken, 1983) appear on the fracture boundary. The fatigue striations are characterized by a complex profile which varies as the length of

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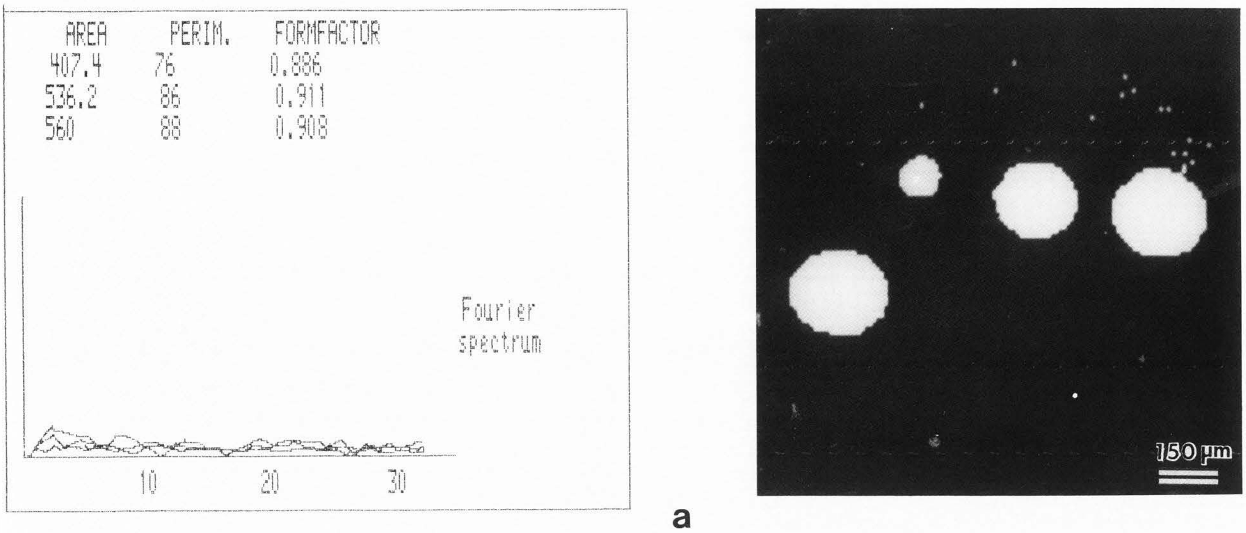
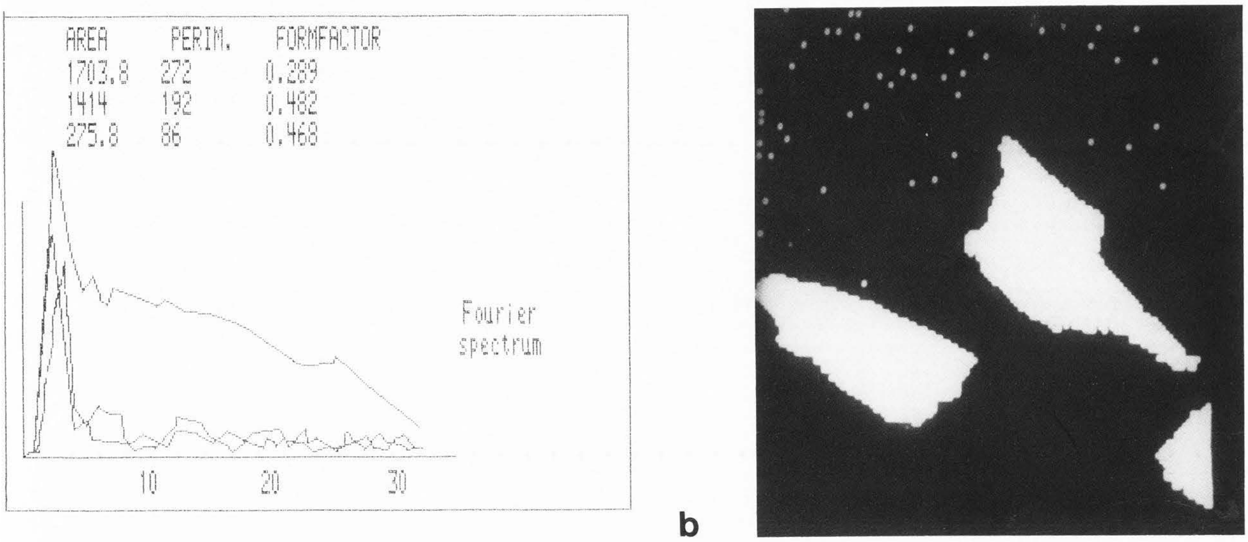
Fig. 1. Results of Fourier analysis of particle form: a - plastic spheres, b - crushed quartz, c - river sand.



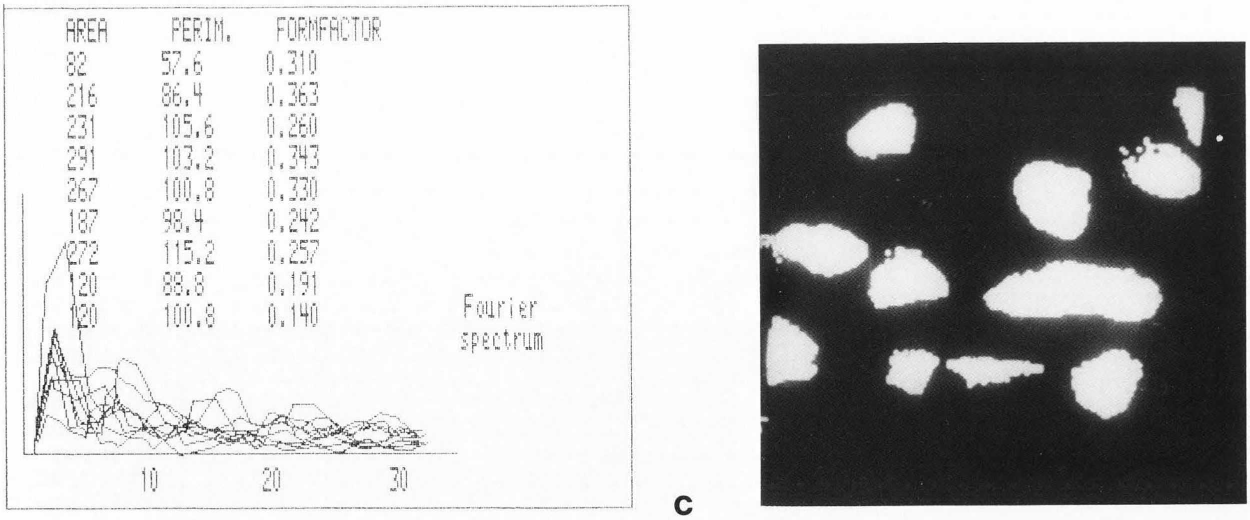
AREA	PERIM.	FORMFACTOR
407.4	76	0.886
536.2	86	0.911
560	88	0.908

a



AREA	PERIM.	FORMFACTOR
1703.8	272	0.289
1414	192	0.482
275.8	86	0.468

b



AREA	PERIM.	FORMFACTOR
82	57.6	0.310
216	86.4	0.363
231	105.6	0.260
291	103.2	0.343
267	100.8	0.330
187	98.4	0.242
272	115.2	0.257
120	88.8	0.191
120	100.8	0.140

c

the crack increases. These striations result from the processes of shear deformation and development of several dislocation cracks before the main crack. The step of a fatigue striation, i.e. its size in the direction of crack growth, is the most important feature of the kinetics of fatigue fractures. By the size of a step one may judge the rate of crack growth in the loading cycle and the intensity of stresses. Therefore a knowledge of the true sizes of a fatigue striation step is of scientific and practical importance. The existence of high levels of self-organization in the process of crack growth determines the sequence of possible values of the step. It is necessary to search for the quantization level of fractals (Mandelbrot, 1983) to reveal the nature of fatigue striation formation. A theoretical analysis of a discrete process of crack growth made it possible to describe a hierarchy of step values δ through the use of a universal fracture constant of the material Δ (Ivanova, 1975) in the form:

$$\delta_i/\delta_{i+1} = \Delta^{1/m} \qquad m=1,2,4...2^n \qquad (2)$$

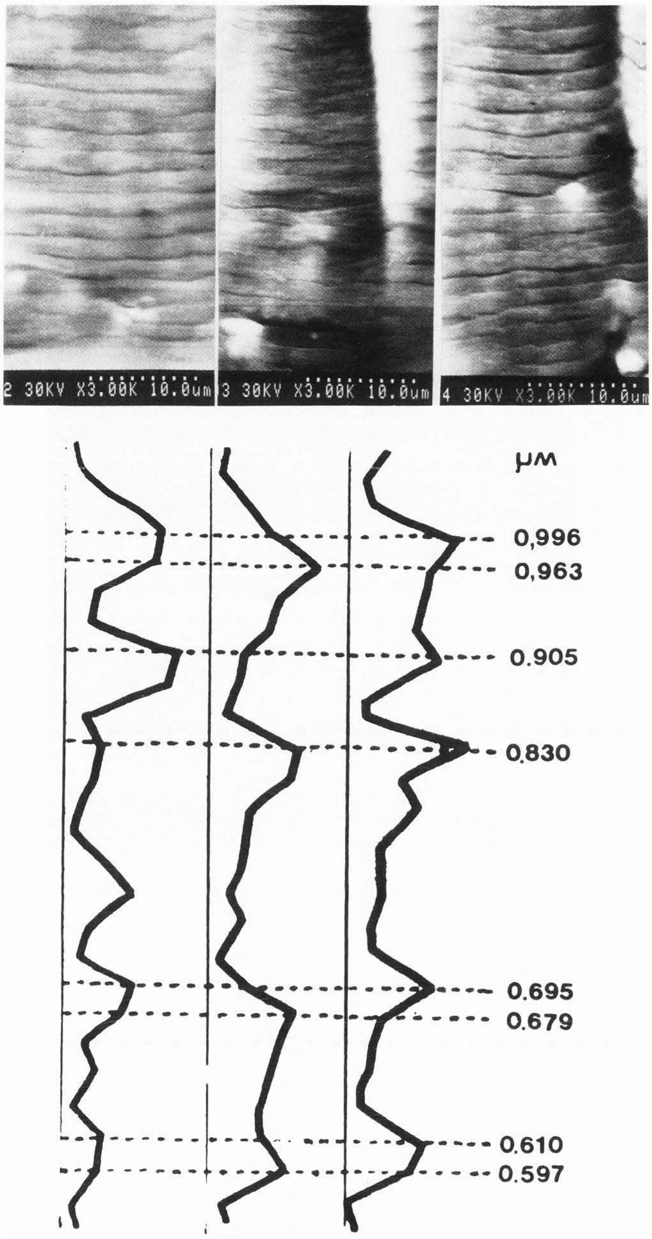
The traditional set of statistical data about a step of fatigue striations obtained by averaging the values measured by the SEM does not make it possible to determine reliably the presence of fractals for the purpose of characterizing the quantum-mechanical nature of crack growth. However, methods of spectral analysis of SEM images on the basis of Fourier-transformation offer greater potential.

Determination of a step of a periodical structure of the boundary of the crack fracture was carried out on the basis of one-dimensional FFT. For this purpose from the SEM to the computer a line of information was read in the direction normal to the striations. By 1024 points of the initial line a Fourier spectrum out of 512 components the striation steps were computed in conformity with an increase of each component to the size of the respective structures on the object. Fig. 2 shows parts of three Fourier spectra and the image of the crack surfaces from which this information was obtained. The peaks in the Fourier spectra indicate the size of the fatigue striations. The analysis of a large number of spectra obtained by images of fatigue striations confirms the presence of a series of discrete sizes corresponding to formula (2) accurate to about 1 per cent. By a series of measurements the quantum-mechanical fracture constant of the material $\Delta = 0.22$ was obtained.

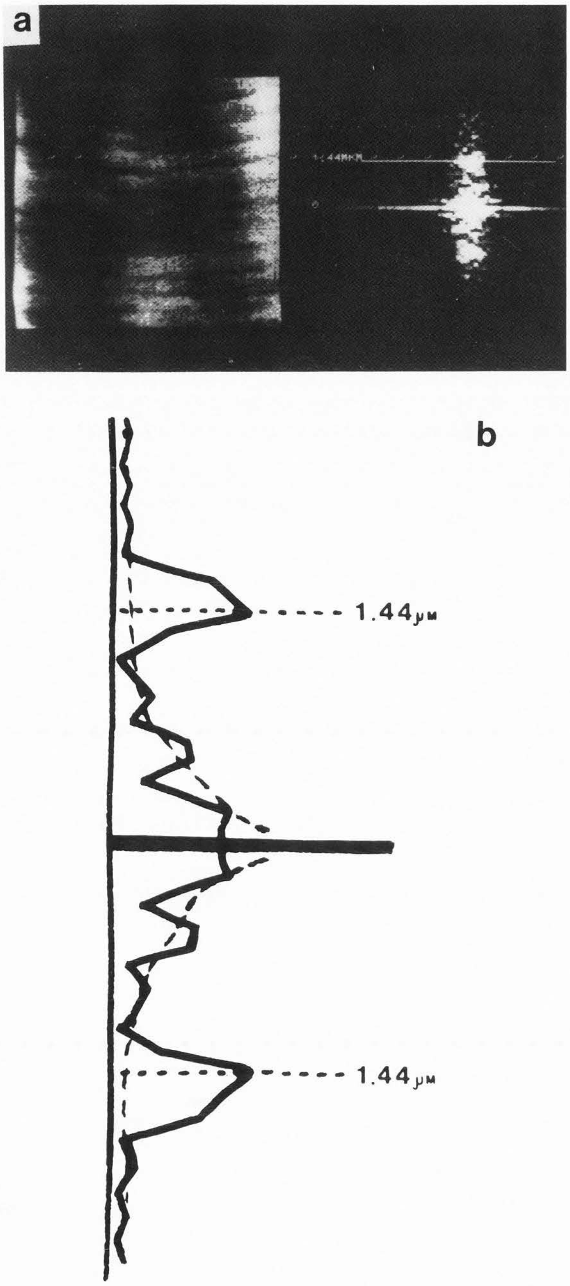
Studies by one-dimensional Fourier spectra allow one to determine accurately enough the step sizes of the periodical structure of the spectrum, even at relatively small differences in these values. At the same time a set of reliable statistics on data of one-dimensional Fourier analysis takes much time and the absolute values of structural periodicity differ from the apparent values due to the local slope of the specimen surface relative to the electron beam of the SEM. Two-dimensional FFT makes it possible in this case to obtain additional useful information. For two-dimensional discrete FFT a halftone image of periodical structure of the fracture in 128 x 128 points format is read into the microcomputer. The result of two-dimensional FFT is brought into a central-symmetrical form (similar to the result of optical diffraction). Fig. 3a shows the computer display of such a transform. To the left there is the initial image of the periodic structure and to the right - its two-dimensional Fourier spectrum. The step size of the fatigue striations was found to be 1.44 μm as determined by the average of 128 image columns. The effects of local surface slope may be determined by section through the centre of this spectrum - Fig. 3b. The slope causes a decrease in the computed size of a step in the image relative to the true one, therefore the peak in the spectrum section corresponding to 1.44 μm has a gentle slope from the side of smaller sizes of striations and a steep slope from the side of larger sizes (a step larger than the true one is never seen). In the section of the Fourier spectrum a dotted line shows the approximate level of noise computed by a normal section where information about fatigue striations is not available. The value obtained for the step corresponds to formula (2) to an accuracy of about 1 per cent at the same value of quantum-mechanical constant of material fracture.

Fourier analysis of two-dimensional periodic structures

During studies of two-dimensional periodic structures usually problems of a metrological nature are to be solved. If the initial specimen has uniform elements in a certain direction and at interval a then it will result in peaks in the two-dimensional Fourier spectrum in components 1/a in the direction normal to periodicity of the initial structure. Number of peaks and their amplitudes depends on accuracy of repeated periods. For two-dimensional periodic structures the result of two-dimensional FFT will be represented by a group of peaks similar in configuration to electron diffraction patterns of crystalline specimens. The background is formed by responses to a nonperiodical portion of the studies specimen. The measured distances from the centre of the Fourier



<u>Fig. 2</u>. One-dimensional Fourier analysis of three surface sections of metal fracture.



<u>Fig. 3</u>. Two-dimensional Fourier spectrum of fracture surface (a) and its section (b).

spectrum to the nearest peak in each direction make it possible to determine accurately an average statistical size of the period of structure of microobjects. Distribution of intensity inside a peak represents the function of distribution of periods of the specimen structure.

As an example Fig. 4 shows the results of two-dimensional FFT the SEM-image of a microchannel plate. To the up there is an initial image and to the down - its two-dimensional Fourier spectrum is shown. For this image the spectrum is represented by groups of mutually hexagonal peaks which allow the statistics of the periodical structure of the specimen to be obtained. This method is used most effectively for analysis of and the determination of defects in fibre optics systems, crystal structures, and other similar objects.

Quantitative determination of integral characteristics of microstructure

For objects whose periodicity is not well-defined, two-dimensional FFT makes it possible to determine integral statistical characteristics. The radial component of the two-dimensional Fourier spectrum is a reflection of the gradient of the original object and the angular component indicates its anisotropy. A two-dimensional Fourier spectrum for pseudorandom structures such as soil cracks, paper fibres, polymeric filters, etc. has a form of a blurred centrally symmetrical spot elongated in the direction normal to the axis of anisotropy of the original structure. For the purpose of separating gradient information and orientation characteristics of objects, integration of a Fourier spectrum by sector and circumferential segments is used as shown in Fig. 5 a,b. A function of the integral of the Fourier spectrum in the sector depending on orientation of this sector reflects anisotropy of the object irrespective of sizes of structural elements. A similar relationship of the integral by the ring depending on sizes of the ring (with regard to normalization on the varying area of the ring mask) reflects the distribution of structural elements of the object irrespective of their orientation. In this case there is no difference in analysis of pores or particles of the object because the Fourier spectrum does not change if the original image is replaced by the negative one.

Transformation of the two-dimensional Fourier spectrum to two relationships (gradient and orientation) allows the body of information to be contracted considerably. This opens up possibility for the correlation of structure with properties. If a critical size is revealed during studies of the object structure in the SEM, this fact may be used for further contraction of information. During studies of soils objects of investigations are usually divided into particles of up to several μm and microobjects of sizes of more than tens of μm. Moreover, anisotropic specimens when studied in the SEM may be orientated in the given direction, e.g., in the horizontal direction. Then anisotropy and grading may be evaluated not by full functional dependences but by numerical coefficients. When integrating by sector segments shown in Fig. 5c anisotropy is expressed as a relationship of the integral of the Fourier spectrum in segments I and III to the integral in segments II and IV. A dotted line shows the boundary corresponding to a critical size of the structure (in the above mentioned case of the study of soils it is the boundary between sizes of separate particles and microaggregates). During studies of the microstructure when particles and pores have a complicated form

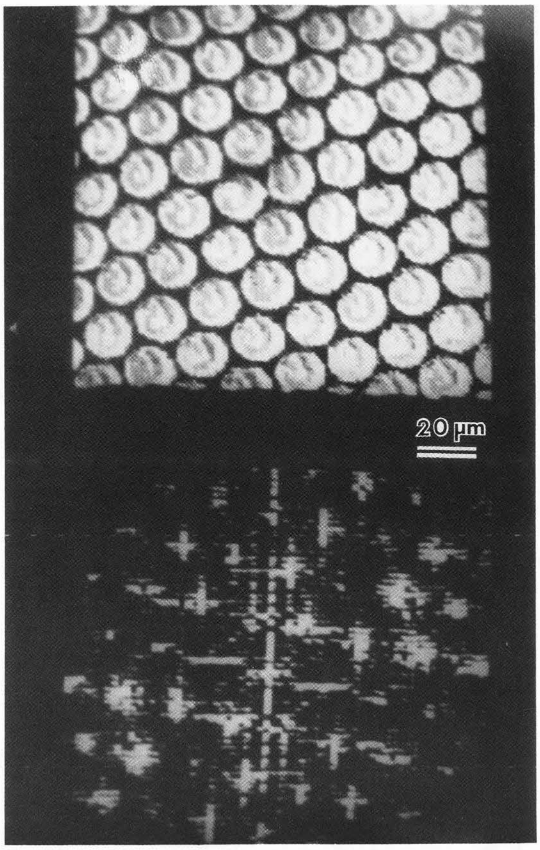


Fig. 4. Two-dimensional Fourier analysis of microchannel plate.

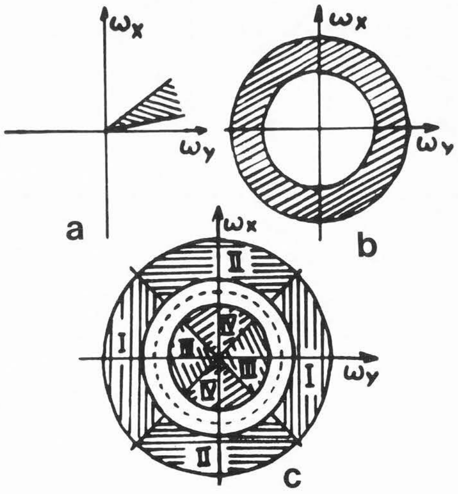


Fig. 5. Segment of integration for analysis of anisotropy (a), orientation (b) and obtaining numerical characteristics (c)

the best results in differentiating the structures with respect to two-dimensional Fourier spectra are obtained if a certain gap is provided between ring segments of the integration. A 1000x magnification of SEM for studies of soils gives the best separation in case segments III and IV include the first 10 Fourier components and segments I and II incorporate components higher than 20. This corresponds approximately to the records in segments III and IV of microaggregates with sizes larger than 10 μm and in segments I and II of separate particles (or pores) with sizes smaller than 5 μm.

As an example let us consider the results of two-dimensional FFT of SEM images of an isotropic structure of polymeric filter (Fig. 6a) and varved clay (Fig. 6b). Two-dimensional Fourier spectra show graphically orientation characteristics of these objects. Anisotropy coefficients computed by the methods shown above are 0.98 for a polymeric filter and 0.29 for varved clay. Grading coefficients are 0.71 for a polymeric filter and 0.33 for clay of a coarse structure.

It might be well to point out the principal difference between the analysis of integral characteristics of structures on the basis of FFT and conventional methods. Usually the analysis of morphology is preceded by the transformation of an image of the object to a binary one in a dialogue mode of the operator with the computer. In this case, on the basis of experience and previous data the operator selects the level of discrimination for the separation of the structure, e.g. by pores and particles and then the analysis by the method of mathematical morphology is carried out. Subjectivism introduced by the operator during discrimination of the image usually does not permit an adequate analysis of structures of different classes to be performed and it cannot even provide reproducible results obtained from one image. The integral analysis of the structure on the basis of Fourier spectrum allows the effect of the operator (prior to the selection of the section of the analysis) on objectivity of the obtained data to be reduced to a minimum because the transformation is performed on the basis of a SEM image.

Conclusion

The above mentioned examples of use of one-dimensional and two-dimensional FFT do not reach the limit of all fields

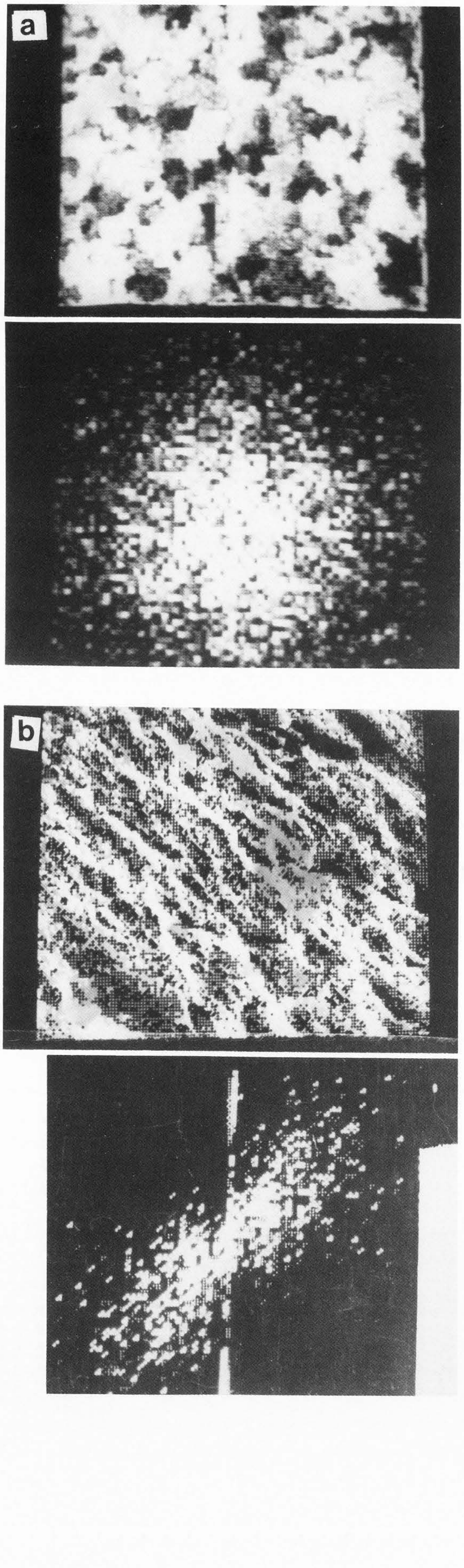


Fig. 6. Results of two-dimensional Fourier analysis of microstructure of polymer filter (a) and varved clay (b).

of application of this powerful technique of analysis of microobject structures in the SEM. The spectral methods are most effective in revealing the general statistic regularities in microstructure of objects and in metrological analysis of periodic structures. The results of most studies by spectral methods may serve as a reliable quantitative basis in revealing correlations of microstructures with object properties.

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Discussion with Reviewers

Reviewer 1: The use of a solar cell as a combined substrate and detector is an interesting idea. Have the details been published? Does one encounter trailing of the signal due to the high capacitance of the P-N junction?

Authors: The solar cells are used exactly in the same way as solid state detectors of back-scattered electrons in production microscopes. In case of slow scanning modes no signal trailing is encountered due to the high capacitance of the P-N junction.

Reviewer 1: In figure 1c to what do you attribute the periodicity in the Fourier transform spectra?

Authors: The periodicity in Fourier spectra appears when a particle projection is similar in its form to a regular polyhedron.

Reviewer 2: The problems examined here have been analysed in the past with the aid of "mathematical morphology" (see e. g. Jeulin: J.Microsc.Spectrosc.Electron. 8, 1983, 1-18 and the book on Image Analysis and Mathematical Morphology by J. Serra). Please compare your approach with that of the mathematical morphologists.

Authors: Practically in all the applications proposed in the present paper Fourier transformation allows to obtain more information on the structure than mathematical morphology methods (cf. J. Serra. Image Analysis and Mathematical Morphology. Academic Press, 1982).

1. When analysing the form of separate grains on the basis of mathematical morphology methods the fullest information is obtained by way of taking into account the erosion and dilatation influence with the help of a circular structural element of various diameters. However, it is easy to imagine two grains of different forms giving indistinguishable information,e.g. two stars, one of them having no two adjacent beams and the other - the first and the third beams. The method of the form analysis by way of one-dimensional Fourier transformation allows to obtain exact information about the form, any difference in object forms being reflected in Fourier spectrum.

2. In mathematical morphology structure periodicity is determined with the help of covariance function (pp.288-290). Page 290 reads: "Although a periodic covariance results from a periodic process, an "almost" periodic covariance may come from a completely aperiodic structure".

The periodicity analysis by way of one- and two-dimensional Fourier transformations allows to determine exactly the periodicity of the structures studied.