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ESTIMATION OF ERRORS IN DETERMINING CORROSION GRAIN SIZES BY ANALYSIS OF DIFFUSE LIGHT REFLECTION SIGNAL

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The approaches to estimation of lower boundary of the inverse problem solution error concerning the sizing the corrosion microdefects inside the submillimeter corrosion spots are proposed. It is assumed that mentioned error depends on random location of the corrosion spots. The method based on comparison of two estimations of light diffusion reflectance sensor signal discrepancy is proposed. The first estimation is based on the standard deviation for the discrepancy caused by randomly located corrosion spots. The second one is based on corrosion grains size deviation. Also, it is found that the discrepancy based on deviations of the signal peaks positions provides a more stable solution for the corrosion micro defects sizes.

Keywords: *corrosion spots, corrosion microdefects, corrosion grains, diffuse light reflectance, sizing, inverse problem, solution errors, signal discrepancy, metrics.*

ОЦІНЮВАННЯ ПОХИБОК ВИЗНАЧЕННЯ РОЗМІРІВ КОРОЗІЙНИХ ЗЕРЕН НА ОСНОВІ АНАЛІЗУ ДИФУЗНОГО ВІДБИВАННЯ СВІТЛА

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Запропоновано підходи для оцінки нижньої межі похибки розв’язку оберненої задачі оцінки середнього розміру корозійних мікроушкоджень, що мають вигляд зерен продуктів корозії, зосереджених у субміліметрових корозійних плям. Вважали, що вказана похибка повністю зумовлена випадковим характером розміщення корозійних плям. Запропоновано методику оцінювання цієї похибки, що базується на порівнянні оцінок відхилів сигналу сенсора дифузного відбивання світла, зумовлених, з одного боку, випадковим розташуванням корозійних плям, а з іншого – відхиленням розміру зерен корозії від номінального значення. Найменше значення відхилення розміру, для якого відхил сигналу переважає статистичну оцінку відхилу, зумовленого випадковим розміщенням корозійних плям, і буде шуканою нижньою оцінкою похибки розв’язку. Для оцінювання статистичних характеристик розкиду сигналів сенсора, зумовленого випадковим розташуванням корозійних плям, використовували експериментальні дані, отримані на імітаторах поверхні з гетерогенними корозійними плямами, де як зерна корозії використано часточки порошку міді. Різні реалізації випадкового розташування корозійних плям забезпечували різними положеннями імітатора щодо центра зондувального пучка світла на робочій поверхні сенсора. Характеристики розкиду сигналів сенсора, зумовлені різним розміром зерен корозії, моделювали для сферичних мідних розсіювачів субмікронних розмірів, зосереджених у випадково розташованих корозійних плямах із розмірами та концентрацією, що відповідали імітатору. Модельовані та експериментальні сигнали порівнювали на основі двох метрик. Перша з них є звичайною евклідовою метрикою вектора значень сигналу на чутливих елементах фотолінійки. Друга метрика базувалась на різниці положень екстремумів обвідної сигналу. Виявлено, що метрика сигналу, пов’язана з положенням екстремумів його обвідної, дає стійкіші оцінки розміру зерен порівняно зі звиклою евклідовою метрикою вектора амплітудних значень сигналу.

Ключові слова: *корозійні плямки, корозійні мікродефекти, корозійні зерна, дифузне відбивання світла, оцінювання розмірів, обернена задача, похибки розв'язку, відхил сигналу, метрики.*

The problem of estimating the characteristics of corrosion damage of metal surface in the form of submillimetre corrosion spots formed by agglomeration of corrosion products on the elements of the surface microstructure [1–4] is considered (Fig. 1). With time, such spots can develop to pitting corrosion. Therefore, it is important not only to know the total surface concentration of corrosion spots, but also the average grain size of corrosion products within these spots, which allows a more accurate evaluation of the nature of corrosion defects and prediction of their development. It is proposed to evaluate these characteristics on the base of signal of the developed sensor of diffuse light reflection [5]. A detailed analysis of the benefits and principles of the mentioned sensor are given in [5]. In particular, the average grain sizes of corrosion products are estimated by on-the-photodiode-linear-array distribution of the light intensity reflected diffusely by the mentioned corrosion defects of the metal surface [5].

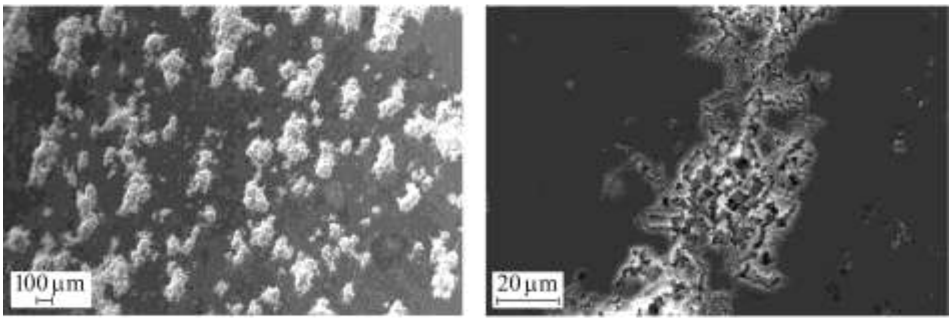

Fig. 1. Images of corrosion spots on the surface of the aluminum alloy for different magnification.

However, evaluation of the corrosion products' grain sizes by the signal of diffuse light reflection is a complex inverse problem [5] which solution depends significantly on both the choice of informative signal parameters as well as the measurement errors. In particular, the absolute values of the signal intensity on the elements of the photodiode linear array (or rather the difference between the values of signals from the surface without defects and the surface with corrosion defects) [6] were chosen as the informative parameters for building the metric and subsequent solving the inverse problem. Other informative parameters for inverse problem solving were the smoothness of the signal envelop function, calculated by the given criteria, and also the positions of the intensity distribution peaks for the diffusely reflected light on the photodiode linear array (hereafter, PhDLA) [7]. Signal measurement errors can be caused, among other, by accidental location of corrosion spots on the area of the investigated surface illuminated by the probing light beam [5]. As a result, we get the significant sizing errors for the grains of corrosion products (hereafter, corrosion grains).

Thus, the estimation of the influence of corrosion spots random location on the errors of the corrosion grains sizing due to sensor signal deviations as well as determination of the optimal metric for this signal are the important scientific and practical tasks.

Stability of estimates of the average grain size of corrosion products in regard to a random location of corrosion spots on the investigated surface. The signal $I_r(q)$ of the sensor of diffuse reflected light by the surface of the construction with randomly located submillimeter corrosion spot-kind defects formed by agglomeration of corrosion products on the elements of the material microstructure is described by expression [5]:

$$I_r(q \neq q_0) = \frac{N}{s_c} \iint\limits_{\sum S_i \subset S_{ilum}} f_r\left(\theta^i, \theta^s; \sigma_s(\gamma, d), n(d), g_{jk}(r); x, y\right) K_s(x, y, q)\,dxdy + \\ + \frac{N_u}{s_c} \iint\limits_{S_{ilum} - \sum S_i} f_r\left(\theta^i, \theta^s; \sigma_{u,s}(\gamma, d_u), n_u(d_u), g_{u,jk}(r); x, y\right) K_s(x, y, q)\,dxdy\,, \qquad (1)$$

where q is the linear coordinate of a PhDLA element, q_0 is coordinate (number of the element of PhDLA) for the focal point of the probing beam, s_c is the area of a single element of PhDLA, N is the counting concentration of light scatterers (corrosion grains) on the investigated surface, S_i is the area of the i-th corrosion spot, S_{ilum} is the illuminated area of the investigated surface, $f_r\left(\theta^i, \theta^s; \sigma_s(\gamma, d), n(d), g_{jk}\right)$ is bidirectional reflectance distribution function for corrosion spots, $\theta^i = \theta^i(x, y, q)$, $\theta^s = \theta^s(x, y, q)$ are directions for the incident and diffusely reflected rays, $\sigma_s(\gamma, d)$ is differential scattering cross-section for angle γ and size of the scatterer (corrosion grain) d , $n(d)$ is disperse composition (distribution of the scatterers' counting concentrations by diameters), $g_{jk}(r)$ are partial radial distribution functions, x, y are the coordinates of a point on the investigated surface, $K_s(x, y, q)$ is the full instrument function of the sensor. The second term of expression (1) is caused by scattering on the microstructural inhomogeneities of the basic (undamaged) material. For it, the N_u is the counting concentration of light scatterers for the undamaged surface, $\sigma_{u,s}(\gamma, d_u)$, $n_u(d_u)$, $g_{u,jk}(r)$ are the differential scattering cross-section for the size of the scatterer (inhomogeneity) d_u, disperse composition, and partial radial distribution functions, respectively.

Since both the bidirectional reflectance distribution function and the sensor instrument function depend on the coordinates on the illuminated area of the investigated surface, it is obvious that the integrals in expression (1) depend on the location of corrosion spots.

The influence of the random location of corrosion spots was investigated in [5] by simulating the sensor signal according to formula (1) for 6 random realizations. The result is shown in Fig. 2 [5].

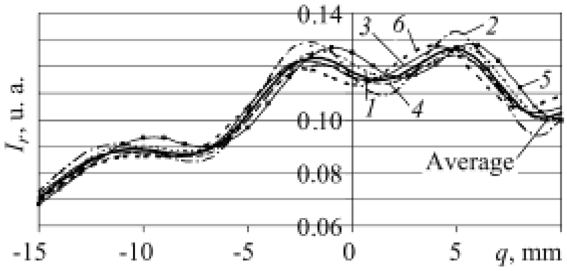

Fig. 2. The sensor signal of light diffuse reflection for 6 implementations of 0.1 mm randomly distributed heterogeneous spots (surface concentration 0.02) filled with 2 μm copper particles [5].

The purpose of this work was to find a way to estimate how much scattering of the sensor signals caused by the random location of corrosion spots can affect the estimates of the average size of corrosion grains in these spots, to select such signal informative features that would provide the effective reproducing of the average size of corrosion grains as well as providing high resistance to interference and fluctuations.

To achieve this goal, we propose an algorithm based on an assumption that if the statistical estimate of the upper limit of the sensor signal informative parameters deviation caused by the random location of corrosion spots does not exceed the deviation of the signal informative parameters caused by some deviation of the average corrosion grain size, this size deviation can be chosen as the estimate of *the lower limit of the solution error* caused by random location of corrosion spots [8–10] in the inverse problem of grain sizing. The given upper limit of the corrosion grains' sizing error is provided by the choice of the regularization method for the mentioned inverse problem [8, 11] and depends on the found lower limit. Also, these errors significantly depend on the choice of informative features of the sensor signal with the corresponding metrics for calculation of the discrepancies in the regularized algorithms of inverse problems solving [11].

Research technique.

The general research technique was as follows:

1. Sensor signals $I_j(q)$ were determined for different realizations j of the random location of corrosion spots on the illuminated area of the investigated surface (by modeling or measurements). The baseline (average) signal was found for the obtained set of signals. With respect to the baseline signal, the discrepancy $D_L(I_j(q))$ was determined for each signal according to the chosen metric. The standard deviation $\sigma(D_L)$ for the obtained set of deviations as well as the estimate of the maximum deviation $2\sigma(D_L)$ were determined.
2. The sensor signal $I_{d0}(q)$ was determined for a given average size of corrosion grains d_0. The signals for the deviations of the mean size $\Delta_i d$, which could take both positive and negative values, were also determined. For those signals, the discrepancy $D_S(I_{(d0+\Delta id)}(q))$ relative to the baseline signal $I_{d0}(q)$ was calculated.
3. The deviation of the average size of corrosion grains $\Delta_{i*}d$ which corresponded to the smallest discrepancy satisfying the condition $D_S(I_{(d0+\Delta i*d)}(q)) \geq 2\sigma(D_L)$ was determined.

In this case, the results were compared for two types of informative features of the sensor signal:

1) Amplitude deviations (see Fig. 3).

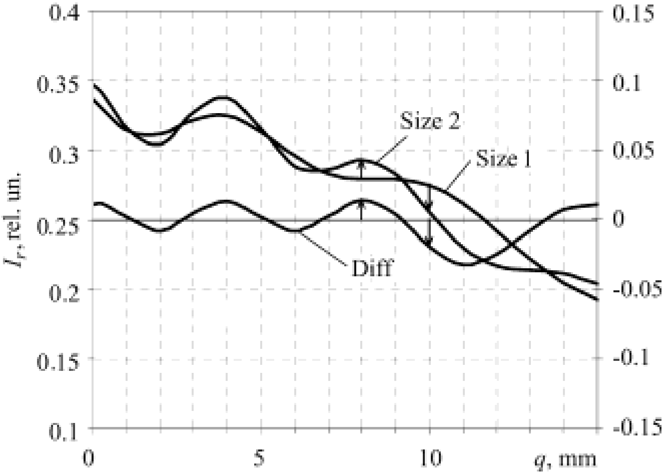

Fig. 3. Comparison of signals based on the vector of amplitude values deviations.

For this set of informative features, the difference between two signals (discrepancy) corresponding to different grain sizes is determined by the following metric:

$$D_S = \left\| (I_r)_{Size2} - (I_r)_{Size1} \right\|_{R^N}, \tag{2}$$

which is the Euclidean discrepancy in N-dimensional vector space of N-channel sensor signal values, where Sise1, Sise2 are the different average diameters d_0 of corrosion grains.

2) The difference between the vectors of the signal extrema positions (see Fig. 4).

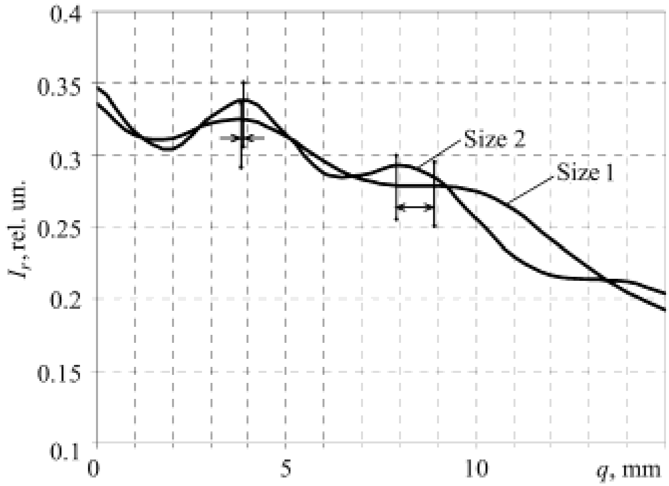

Fig. 4. Comparison of signals based on the difference of the vectors of the signal extrema positions.

For this set of informative features, the difference between two signals corresponding to different grain sizes is determined by the following metric:

$$D_S = \max_{(k=1,K)} \left((X_k)_{Size2} - (X_k)_{Size1} \right), \tag{3}$$

which is the distance in a K-dimensional (K<<N) vector space of signal characteristics (extrema positions X_k of the signal envelop function).

In particular, earlier in [7, 12] several popular algorithms for determining the subpixel positions of the signal peaks were described. And in this paper, it is proposed to apply the algorithm of a 3-element centroid.

Also, to increase the informativeness of the signal $I_r(q)$ during measurements, the useful signal was calculated as the difference between the baseline values $I_{rBL}(q)$ of the diffuse reflected signal for the surface without corrosion defects and the measured values $I_{rM}(q)$ for the surface with corrosion defects

$$I_r(q) = I_{rBL}(q) - I_{rM}(q) \tag{4}$$

Accordingly, instead of expression (1), we use the following expression for modelling:

$$\begin{aligned} I_r(q \neq q_0) = {} & \frac{N}{s_c} \iint\limits_{\sum S_i \subset S_{ilum}} f_r\left(\theta^i, \theta^s; \sigma_s(\gamma, d), n(d), g_{jk}(r); x, y\right) K_s(x, y, q)\,dxdy \, - \\ & - \frac{N_u}{s_c} \iint\limits_{\sum S_i \subset S_{ilum}} f_r\left(\theta^i, \theta^s; \sigma_{u,s}(\gamma, d_u), n_u(d_u), g_{u,jk}(r); x, y\right) K_s(x, y, q)\,dxdy\,, \end{aligned} \tag{5}$$

Research and its results. The set of signals of the diffuse light reflection sensor for the realizations of the random location of corrosion spots was obtained by performing measurements on surface simulators with "spot" corrosion [5]. In particular, simulators No.0 (for the baseline signal) and No.3 were used (Fig. 5).

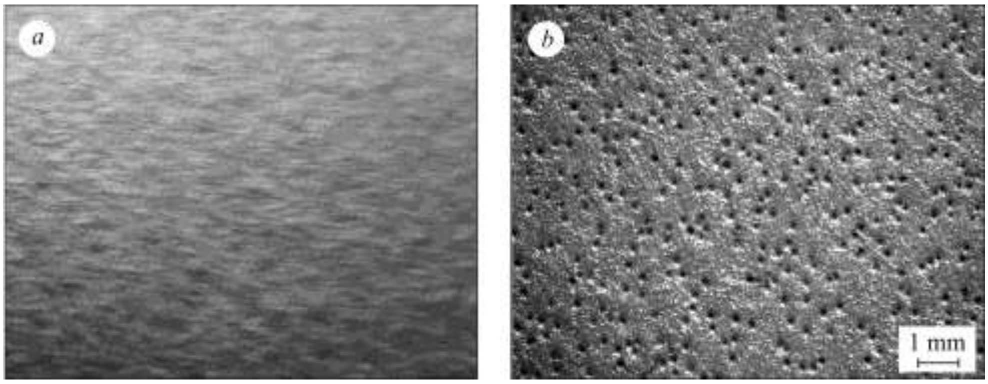

Fig. 5. Model of submillimeter (diameter 0.15 mm) corrosion spots filled with the grains of corrosion products, where n is the counting concentration, $s^{(2)}$ is the cover factor: a – simulator No.0: $n = 0\ \text{cm}^{-2}$, $s^{(2)} = 0$; b – simulator No.3: $n = 326\ \text{cm}^{-2}$, $s^{(2)} = 0.0576$.

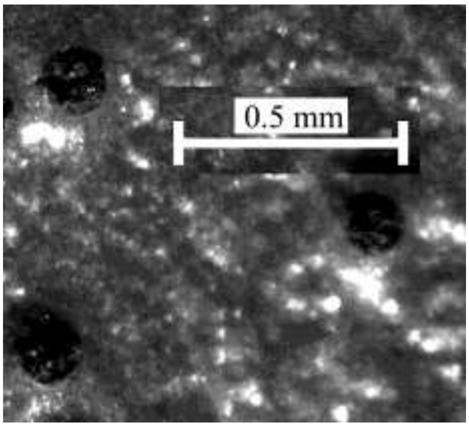

Fig. 6. Microstructure of "corrosion spots".

Particles of copper powder provided the granular microstructure of such "corrosion spots" (Fig. 6).

The random location of the spots was provided by small (±3 mm with 1 mm step) displacements of the simulator No.3 along the X, Y axes relative to the standard position. Since the spots on the surface of the simulator were placed chaotically, such displacements led to significant changes in the spatial configuration of the spots within the illuminated area with a diameter of 4–5 mm. This corresponds to real situations of measurements in field conditions.

All signals obtained for the simulator No.3 were subtracted from the baseline signal obtained for the simulator No.0.

The second group of data corresponding to the set of sensor signals for different grain sizes in corrosion spots was obtained by simulation according to (5). The area of corrosion spots S_i was chosen equal to $\pi\cdot(0,15)^2 \approx 0,07\ \text{mm}^2$, and their concentration was $326\ \text{cm}^{-2}$. It corresponds to the parameters of the simulator No.3. Corrosion grains were modelled as spherical copper particles with a base radius of 1 μm (or a base diameter $d_0 = 2$ μm). Modelling for grain radii of 0.7 μm, 0.8 μm, 0.9 μm, as well as 1.1 μm, 1.2 μm, and 1.3 μm was also performed. That is, the maximum deviation from the base size made 30%.

Before comparison, the amplitudes of the signals obtained by measurement and by simulation were normalized by the difference between the largest and the smallest values and shifted so that they have only positive values.

In addition, so long as the dimensions of the vectors (number of points) of the signal for measurement and modelling were different, the discrepancies (2) obtained for them were reduced to one sensor channel.

For the first type of informative features, the comparison of the discrepancies (2) (see Fig. 7) caused, on the one hand, by the random placement of the corrosion spots (experiment on the simulator) (*a*), and, on the other hand, by grain size differences in the corrosion spots (modelling) (*b*), gave the following results:

a) the double standard deviation (for 49 implementations) $2\sigma(D_L)/15$ reduced to one channel made 0.041 relative units;

b) the maximum discrepancy $D_S(I_{(d0+\Delta i*d)}(q))/26$ reduced to one channel made 0.038 relative units. Thus, it approached the discrepancy estimate specified in the previous paragraph only for a 30% deviation of the grain size.

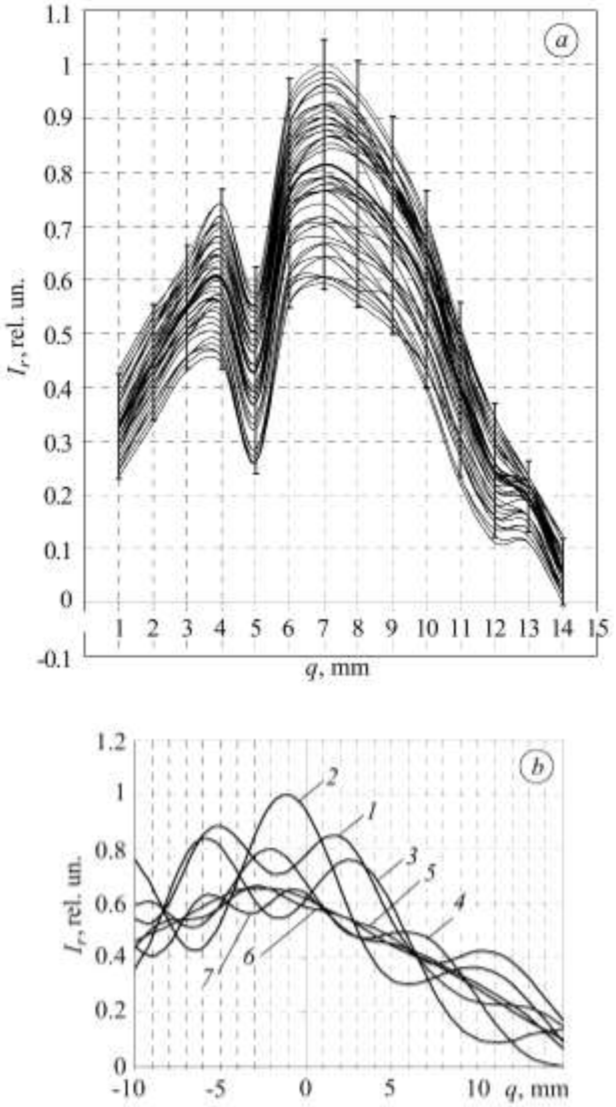

Fig. 7. Comparison of the discrepancies of normalized signal amplitudes reduced to one channel for: random location of corrosion spots (experiment on a simulator) (*a*); differences of grain sizes in corrosion spots (modelling) (*b*): *1* – 1.0 μm; *2* – 0.7 μm; *3* – 0.8 μm; *4* – 0.9 μm; *5* – 1.1 μm; *6* – 1.2 μm; *7* – 1.3 μm.

Thus, the utilization of the amplitude characteristic of the signal in case of chaotic location of corrosion spots gives the lower limit of the corrosion grains sizing error greater than 30%.

For the second type of informative features, which corresponds to the discrepancy (3), the comparison of the differences in the positions of the signal extrema (see Fig. 8) caused, on the one hand, by the random location of corrosion spots (experiment on the simulator) (*a*), and, on the other hand, by grain size differences in the corrosion spots (modelling) (*b*), gave the following results:

a) the maximum deviation of the estimate of the signal extremum position caused by the chaotic location of the corrosion spots, made 0.08 mm;

b) the minimum estimate of the normalized difference between the positions of the signal extrema caused by the 10% deviation of the grain sizes made 0.7 mm for this study.

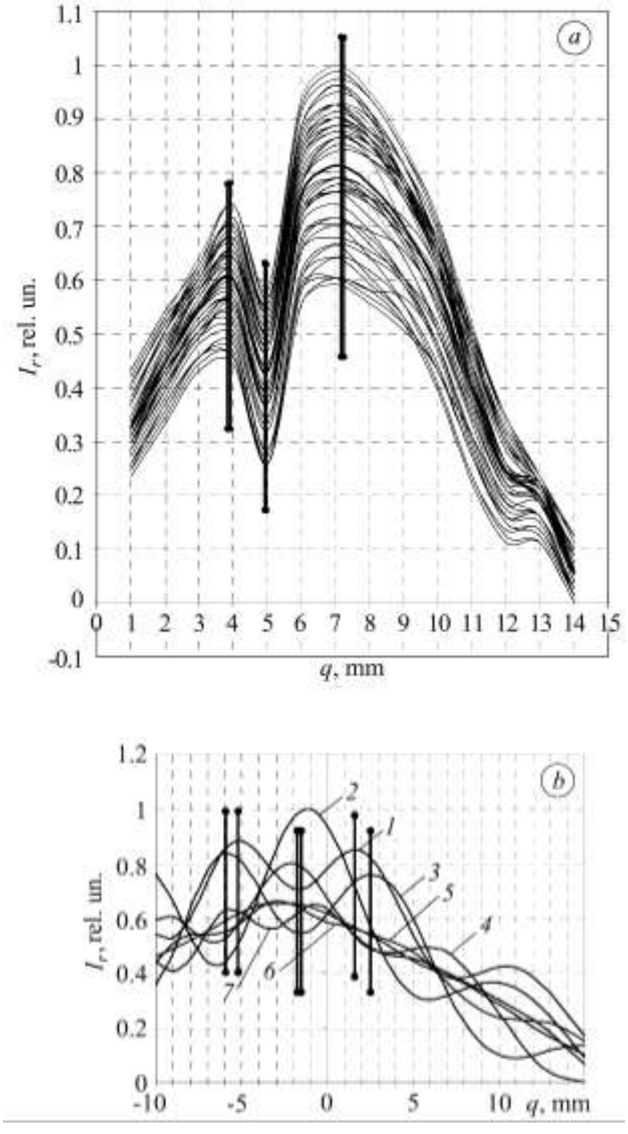

Fig. 8. Comparison of differences in the positions of the signal extrema for: random location of corrosion spots (experiment on the simulator) (*a*); differences of grain sizes in corrosion spots (modelling) (*b*): *1* – 1.0 μm; *2* – 0.7 μm; *3* – 0.8 μm; *4* – 0.9 μm; *5* – 1.1 μm; *6* – 1.2 μm; *7* – 1.3 μm.

Thus, the scatter of the extrema positions caused by random location of the corrosion spots is much smaller than the scatter of positions caused by 10%-deviation of grain sizes in the corrosion spots and, consequently, allows us to achieve higher stability of sizing the corrosion products grains.

CONCLUSIONS

For the problem of sizing of the surface corrosion microdefects by the signal of the diffuse light reflection sensor, the implementation of the algorithms that utilize the metrics based on the signal extrema positions has significant advantage in comparison with implementation which utilizes the metrics based solely on the signal amplitude in terms of tolerance to fluctuations of microdefects location.

However, it is reasonable to investigate the tolerance of these metrics to electrical noise and other interferences as well as to investigate the tolerance of the metrics based on the signal smoothness functional.

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