STUDY OF DISTRIBUTIONS OF QUASI-PERIODIC NANOSTRUCTURES

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Abstract: Nanorelief on metalic substrates (Ti, Ta, etc.) formed by laser ablation is analyzed by the scanning electron microscopy images. Distribution of the spatial periods of nanorelief (their most probable values and dispersion) is calculated with different methods of image processing (manual calculation, Fourier analysis, image filters, binarization algorithm, and analytic estimation of distribution). It is shown satisfactory correspondence between the characteristics of the distributions determined by various methods of image processing with analytic estimation. Practical suggestions of processing image methods are presented.

Keywords: distributions; most probable value; dispersion; spatial period; nanorelief; nanostructure; laser ablation; spectrum; binarization; Fourier transform

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Figure Captions

Figure 1 An example of manual processing of an electron micrograph showing HSFL (High-Spatial-Frequency LIPSS (Laser-Induced Periodic Surface Structures) and LSFL (Low-Spatial-Frequency LIPSS) on a Ti substrate irradiated in air by laser pulses with a duration of $\tau = 10$ ps and $\lambda = 1064$ nm (authors' experiment [32]). The nearly horizontal marks indicate the averaging series for the MSPS period, corresponding to a single LPSS valley. The vertical marks represent the averaging series for the period of large-scale LPSS

Figure 2 Averaged periods of HSFL and LSFL according to experimental data [4] obtained in various media at different laser wavelengths for substrates made of different materials: *1* — large-scale LSFL (experiment); *2* — HSFL (experiment); and *3* — calculation of HSFL by formula (1). The energy density (fluence) values in J/cm^2 are given in parentheses on the abscissa axis

Figure 3 Local periods of HSFL and LSFL from different zones of the micrograph Ti 1_1 ($\lambda = 1064$ nm, $\tau = 10$ ps, and fluence of 0.33 J/cm^2), without averaging (authors' experiment [32]): *1* — LSFL (experiment); *2* — HSFL (experiment); *3* — calculation of HSFL by formula (1) without correction; and *4* — calculation of HSFL by formula (1) with correction for the number of pulses per spot $N_i = 56$

Figure 4 Linear growth of the thermal spot diameter with the number of pulses per spot in the authors' experiment [32] (data correspond to micrographs Ti 1_1 – Ti 12_1 at $\tau = 10$ ps) (*a*) and comparison of the experimental and calculated spatial periods of HSFL and LSFL averaged for each individual micrograph (taking into account the melt depth correction) at different laser energy densities (*1* — LSFL (experiment); *2* — HSFL (experiment); *3* — HSFL (calculation); and *4* — energy density) (*b*)

Figure 5 Periods of Ti HSFL (*1*) and Ta HSFL (*2*) normalized to their mean series values, shown as a coarse-binned distribution (abscissa error is $\pm 5\%$), and the Ti LSFL distribution (*3*) normalized to the mean λ_L; *4* — curve for formula (3); and *5* — curve for formula (4)

Figure 6 Processing of the original electron micrograph shown in Fig. 1 using a binary structure extraction algorithm: (*a*) image preprocessing using Bradley's algorithm (right — with noise removal); (*b*) and (*c*) size distributions of the nanostructures: LSFL (variance 16.6%) (*b*) and HSFL (variance 39.6%) (*c*); (*d*) and (*e*) image processing of two isolated LSFL ridges ((*d*) variance 22.1% and (*e*) variance 39.8%); *1* — histogram; *2* — smoothed curve; *3* — $1/\sqrt{e}$ level of 62.879 (*b*), 32.672 (*c*), 20.72 (*d*), and 19.122 (*e*); *4* — width at $1/\sqrt{e}$ of 0.331 (*b*), 0.792 (*c*), 0.442 (*d*), and 0.796 (*e*); *5* — mode of 1.0 ($\lambda = 28$ (*b*), 15 (*c*), 9 (*d*), and 19 px (*e*)); and *6* — mean (1.04 (*b*), 1.12 (*c*), 1.2 (*d*), and 1.46 (*e*))

Figure 7 Processing of the electron micrograph shown in Fig. 1 by constructing size distribution spectra using the Fourier transform — averaged plots of columns (variance 7.15%) (*a*) and rows (variance 20.24%) (*b*) after one-dimensional Fourier transform (horizontal/vertical bands): *1* — corrected spectrum; *2* — exact smoothing; *3* — fundamental frequency of 0.0072 (*a*) and 0.0172 (*b*); *4* — $1/\sqrt{e}$ level of 21.2749 (*a*) and 3.7119 (*b*); and *5* — width at $1/\sqrt{e}$ of 0.001035 (*a*) and 0.006956 (*b*)

Figure 8 Artificially synthesized image ((*a*) original and (*b*) processed) of quasi-periodic structures with a 10 percent fluctuation, its structure size distributions, and their Fourier spectra (variance of 2.58% (*c*) and 7.63% (*d*)): *1* — corrected spectrum; *2* — exact smoothing; *3* — fundamental frequency of 0.0703 (*c*) and 0.0488 (*d*); *4* — $1/\sqrt{e}$ level of 30.7374 (*c*) and 4.1780 (*d*); *5* — width at $1/\sqrt{e}$ of 0.003629 (*c*) and 0.007455 (*d*); and correlation dependence of the spectra variances on the specified fluctuations in the artificially synthesized images (blue signs — for the measured column lengths in horizontal bands and red signs — for the measured row lengths in vertical

Table Captions

Table 1 Thermophysical data of liquid metals at melting point [10, 11, 34]

Table 2 Comparison of relative standard deviations (half width at half maximum to most probable value)

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