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Optical filtering technique for surface roughness measurements

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The paper presents a simple model of the correlation between amplitude modulation of a coherent beam reflected by a rough surface and the intensity distribution spatially filtered in the Fourier plane. A method for measurement of roughness correlation length was developed and experimentally investigated.

1. Introduction

The most attractive advantage of an optical data processing system consists in its speedy and simple processing of two dimensional data. Spatial filtering techniques have shown their usefulness for research and industrial purpose [1], [2], when applied to qualitative and quantitative measurements of some properties of metal surfaces.

We present a method for quantitative non-contact measurements of surface correlation length, based on the dependence of light intensity distribution in Fourier plane on the statistical parameters for the surface finish, when the sample is normally illuminated by a coherent laser beam. Spatial filtering techniques used in order to eliminate specular reflection offered us an opportunity to control and modify in the desired manner the correlation between light intensity and roughness parameters.

The relations between output signal and roughness, predicted theoretically on the assumption that the autocorrelation function of the geometrical surface fluctuation is a Gaussian distribution, were in a good agreement with the experimental plots.

2. Theoretical remarks

Consider the reflection of a collimated beam, normally incident on a surface, which will be modulated due to reflecting surface roughness, as follows:

$$E(x, y) = A_0 \exp\left[\frac{2\pi i}{\lambda} 2h(x, y)\right] \tag{1}$$

where $h(x, y)$ is a function which described the geometrical surface fluctuation, $|A_0|^2$ – constant intensity of the illuminating beam, and λ – wavelength of the illumination beam.

We assume that the autocorrelation function of $h(x, y)$ is a Gaussian distribution

$$g(x', y') = \lim_{S \to \infty} \frac{1}{S} \int_{(S)} h(x, y) h^*(x - x', y - y') \, dx \, dy = \sigma^2 \exp\left(-\frac{x'^2}{2\varrho_x^2} + \frac{y'^2}{2\varrho_y^2} \right) \tag{2}$$

where S is the illuminated area, σ is the mean square of the surface fluctuations, ϱ_x, ϱ_y are the correlation lengths of $h(x, y)$ process on x, y axes [3]. The parameters σ, ϱ_x, ϱ_y make the statistical description of the surface fluctuations.

The correlation between amplitude distribution in the two focal planes (x, y) and (x', y') of a Fourier lens is $G(x', y') = \mathscr{F}[E(x, y)]$, where $E(x, y)$ is the amplitude distribution in front focal plane, $\mathscr{F}$ – Fourier transform of $E(x, y)$ and $G(x', y')$ – amplitude distribution in back focal plane [4], [5].

The intensity distribution in the back focal plane is

$$I(x', y') = |G(x', y')^2 = \mathscr{F}[E(x, y) \times E^*(x, y)]. \tag{3}$$

For the industrially machined surfaces dealt with in our experiment the approximation $h(x, y) < \lambda/4\pi$ seems to be reasonable. Thus, the intensity distribution in back focal plane becomes

$$I(x', y') = |A_0|^2 \left\{ [1 - (4\pi/\lambda)^2 \sigma^2] \, \delta_S \left(\frac{2\pi}{\lambda f} x', \frac{2\pi}{\lambda f} y' \right) + (4\pi/\lambda)^2 \sigma^2 \varrho_x^2 \varrho_y^2 \right.$$
$$\left. \times \left[\exp\left(-\frac{\varrho_x^2 \alpha^2 x'^2}{2} - \frac{\varrho_y^2 \alpha^2 y'^2}{2} \right) \right] \right. \tag{4}$$

where f is the focal length of the spherical lens, $\alpha = 2\pi/\lambda f$ and $\delta_S = \mathscr{F}[(1/S) \int_{(S)} dx \, dy]$.

Hence, we have the relation between the diffraction pattern and surface roughness parameters δ, ϱ_x, ϱ_y. The total intensity in (x', y') plane of the diffraction pattern filtered with a circular band-pass filter with the two parameters R, R' $(R < R')$ will be

$$I = \int_0^{2\pi} \int_R^{R'} I(r, \theta) r \, dr \, d\theta. \tag{5}$$

When Equation (4) transformed into polar coordinates in Eq. (5) and assuming that the correlation length of the surface roughness is uniform in every direction, we obtain

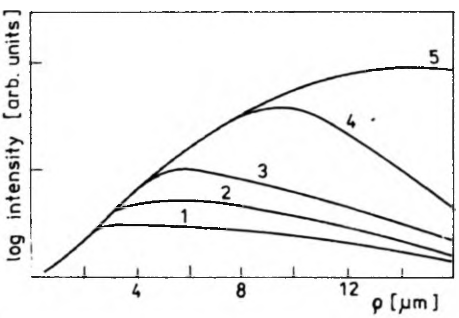
$$I = |A_0|^2 \left\{ \frac{16\pi}{D\alpha^3} [1 - (4\pi/\lambda)^2 \sigma^2] \int_R^{R'} \frac{\cos^2(\alpha S r - 3\pi/4)}{r^2} dr \right.$$
$$\left. + 2\pi\sigma^2 \varrho^2 (4\pi/\lambda)^2 \int_R^{R'} r \exp(-\varrho^2 \alpha^2 r^2/2) dr \right\}. \tag{6}$$

In these conditions, when the root mean square of surface fluctuations is fixed, the global intensity of the filtered diffraction pattern dependence on correlation length becomes

$$I(\varrho) = |A_0|^2 \left\{ \frac{4}{\alpha^2 D}(R^{-1} - R'^{-1})[1-(4\pi/\lambda)^2\sigma^2] + \frac{32\pi^3}{\alpha^2\lambda^2}\sigma^2 \right.$$
$$\left. \times [\exp(-\alpha^2 R^2 \varrho^2/2) - \exp(-\alpha^2 R'^2 \varrho^2/2)] \right\} \tag{7}$$

where D is the collimated incident beam diameter.

The dependence $I(\varrho)$, for different focal lengths was evaluated from Eq. (7). The results are shown in Fig. 1 for $\lambda = 0.633$ μm and $\sigma = 0.02$ μm. A similar set of graphs was made for different parameters $k = R'/R$ and focal length $f = 100$ mm (Fig. 2). The dependence I vs ϱ was determined for $\varrho > 0.1$ μm, which represents a field of values compatible with the purpose of our experiment.



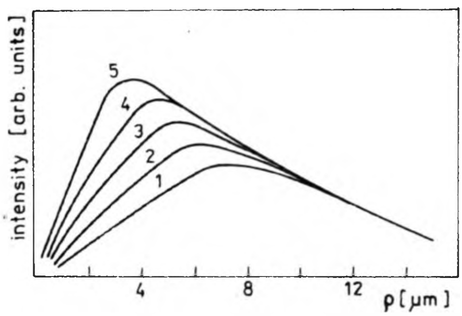


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Fig. 1. Dependence I vs ϱ for $\sigma = 0.02$ μm, $R'/R = 5$, and focal length in order: 50 (1), 70 (2), 100 (3), 200 (4) and 300 (5) mm.

Fig. 2. Dependence I vs ϱ for $\sigma = 0.02$ μm $f = 100$ mm and R'/R factors in order: 3 (1), 4 (2), 5 (3), 6 (4) and 8 (5)

As it can be seen in Figures 1 and 2, if the correlation length grows, the total intensity on the surface of a detector placed in the Fourier plane increases rapidly to a maximum

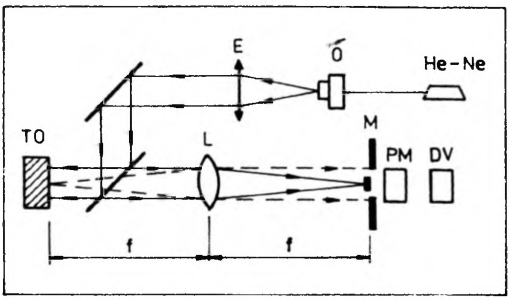
$$\varrho_m = \frac{\lambda f}{\pi R}\sqrt{\frac{\ln K}{K^2-1}}. \tag{8}$$

When the correlation lengths are greater than ϱ_m, the total intensity decreases till its saturation for high enough roughness values. In this region, the light dispersion is so great that the aperture diameter does not influence the amount of light intensity received by the detector. For correlation lengths smaller than ϱ_m, the absolute values of I and the slope of the function $I(\varrho)$ may be optimized in the desired domain correlation length.

3. Experimental setup

We prepared RUL steel samples of correlation lengths ranging from 1 to 10 μm, and roughness ϱ varying from 0.03 to 0.04 μm. They were tested in the experimental setup presented in Fig. 3. The collimated beam from a He-Ne laser was used for a normal illumination of the sample. The integral reflection was collected by a Fourier lens which has the sample, and the mask filter in its front and back focal planes, respectively. The filter was placed just in front of a photomultiplier and its output was measured digitally.

In Figure 4, the output intensity vs correlation length was plotted for a filter with $k = 8$ and focal length $f = 200$ mm (plot A), the output intensity in the same arrangement but without filter was also presented (plot B).



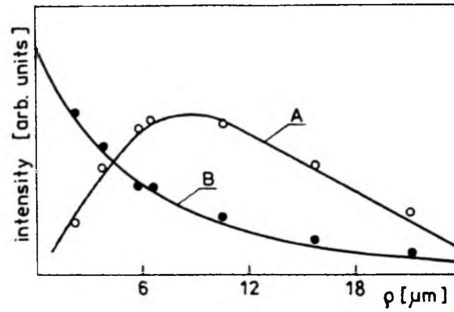


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Fig. 3. Experimental setup: O – objectiv, E – expander, TO – testing object, L – Fourier lens, M – mask, PM – photomultiplier, DV – digital voltmeter

Fig. 4. Experimental dependence I vs ϱ: ● – without filter, o – with $f = 200$ mm, $k = 8$ and σ varying from 0.03 to 0.04 μm

The experimental data were in a good agreement with the theoretical predictions, as it can be seen, thus providing the assumptions concerning the autocorrelation function. It should be noted that the curve A has an increasing linear region which may be used to measure the roughness with a good sensitivity. The curve A is quite different from B, and has a pronounced maximum, the position and magnitude of which depend on the geometry of the experiment and on the correlation length. By varying the filter parameter R'/R and focal length, we modify the measurement sensitivity, and the linear region can be moved in the desired domain of roughness values.

Because of a large testing surface, the proposed method is independent of the direction of measurement, in contrast to the classical reflexometric or contact methods. If the illuminated area increases, the dependence remains unchanged, only the output signal grows. Based on this experiment, it is possible to develop a real-time system in which k and f parameters could be changed for different fields of correlation lengths, if necessary.

4. Conclusions

The paper presents the results of a theoretical model for evaluation of the relation between the light reflected normally by a plane sample and the roughness parameters, when the scattered beam is spatially filtered by using a common technique.

The experimental results are in a good agreement with theoretical predictions based on the assumption that the autocorrelation function of surface fluctuations has a Gaussian distribution around the mean value.

We also present the results concerning the influence of the experiment geometry on the dependence I vs ϱ. We propose a new noncontact real-time method for the measurements of correlation length, based on the dependence $I(\varrho)$.

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Техника оптического фильтрирования в измерениях шероховатости поверхности

Представлена простая модель корреляций между модуляцией амплитудного когерентного пучка, отраженного от шероховатой поверхности, и распределением напряжения пространственно фильтрируемого в плоскости Фурье. Развиты методы измерения длины корреляции для шероховатости и проведены экспериментальные исследования.