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WRINGING DEFORMATION AND ROUGHNESS ASPECTS IN OPTICAL LENGTH MEASUREMENTS

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Abstract − Texture deformations of gauge block surfaces arising in the wringing contact between similar structures have been determined for the first time using atomic force microscopy and optical interferometry. The level of deformations is shown to be dependent on the surface structure, and for modern gauge blocks is about 3 nm, only. Using new parallax-free methods of interferometric length measurements, roughness contribution to the measurement result by optical interferometry have been measured with a few nanometer uncertainty level.

Keywords: Interferometry, deformation, metrology

1. INTRODUCTION

Roughness of the gauging surface of a gauge block has an important effect on the result of an interferometric length measurement [1,2]. The contribution of the surface roughness to the interferometric length measurement [1], and the relation between the roughness values for a free surface and under the condition of a wringing contact to a reference plate of the "same surface texture" [2] have been intensively studied. At first, it was considered that the position of the wringing contact is shifted from the mean value of the roughness contour by the value of approximately one standard deviation of the corresponding roughness texture [3]. But gradually, it became clear that the position of the contact lies closer to the maximum heights of the surface texture, slightly shifted inside by the value of the surface texture deformations [4]. As a result of relatively large uncertainties resulting both from the interferometric method and from the stylus roughness measurement, it was not possible to detect the wringing surface texture deformations [4]. In the present studies, we have used parallax-free methods of optical interferometry [5-8] to measure new length specifying parameters of a gauge block: its mechanical (L_M) [6] and optical (L_{OPT}) [5] lengths. Atomic force microscopy (AFM) has been used to find the surface roughness of a free gauge block surface, and optical ellipsometry to measure the optical constants [4] of the gauge block material. As a result of these studies, wringing deformations of the surface texture have been determined for the first time, and in typical cases, the value of these deformations is found to be about 3 nm.

2. THEORETICAL BACKGROUND

A possibility of measurements of the wringing texture deformations stems from the relation between the mechanical length L_M and the peak-to-peak value of the physical length L^{PP}_{PH} [9]. The mechanical length is defined under the condition of the tight wringing contact (TWC), when the excessive wringing film thickness Δ is approaching zero [5,6]. The L_M value corresponds to the highest level of texture deformations observed in the wringing contact between the surfaces with the same textures and materials. The L_M value is obtained as a result of the measurement by the slave-block method with reproducible wringing of both: the measured block to the reference plate, and the slave block to the measured block [7]. Its relation to the optical length L_{OPT}, obtained by the double-sided measurements on quartz plate [5], is given by equation:

$$L_M = L_{OPT} + 2\delta_S + \delta_{R,1}^* + \delta_{R,2}^* \qquad (1).$$

Here, δ_S denotes the skin depth value in the gauge block material [4,9], and quantities $\delta_{R,1}^*$ and $\delta_{R,2}^*$ describe the roughness contributions for the two gauging surfaces of the block under the condition of the TWC.

In contrast to L_M, the physical length of a block corresponds to a free, unperturbed artefact. The peak-to-peak value of the physical length, L^{PP}_{PH} , is related to the optical length of the block L_{OPT}, to the skin depth value δ_S, and to the roughness values $\delta_{R,1}$ and $\delta_{R,2}$ corresponding to free gauging surfaces of the block. This relation is given by the expression:

$$L^{PP}_{PH} = L_{OPT} + 2\delta_S + \delta_{R,1} + \delta_{R,2} \qquad (2).$$

Here, $\delta_{R,1}$ and $\delta_{R,2}$ denote the maximum heights of the roughness structures of the two gauging surfaces, that are measured from the corresponding mean plains of the roughness structures. In order to determine experimentally the value of L^{PP}_{PH}, besides the measurements of roughness textures by AFM, we are to measure the optical length of a gauge block [5], and also to find the skin depth value from optical ellipsometry measurements [4,10]. By definition, the wringing texture deformations D are considered to be equal to the quantity $(\delta_{R,1} - \delta_{R,1}^* + \delta_{R,2} - \delta_{R,2}^*)/2$. That is:

$$D = (\delta_{R,1} - \delta_{R,1}^{*} + \delta_{R,2} - \delta_{R,2}^{*})/2 = (L^{PP}_{PH} - L_M)/2 \qquad (3).$$

So, to find the surface texture deformations resulting from the wringing procedure, we are to measure L^{PP}_{PH} and L_M.

It is also useful to introduce the mean value of the physical length L^{MN}_{PH} by equation:

$$L^{MN}_{PH} = L_{OPT} + 2\delta_S \qquad (4)$$

If we move from the centre of the block O (Fig.1) half of the L^{MN}_{PH} value, in accordance with [4], we shall reach the position of the mean plain of the roughness structure.

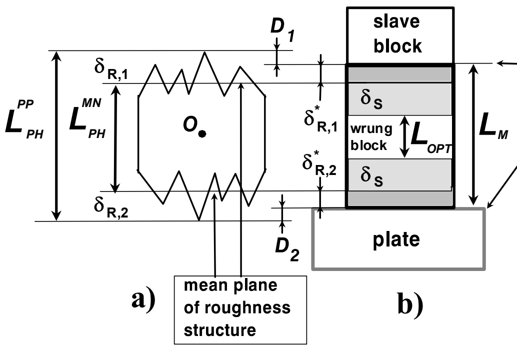

Fig.1. Schematic drawing of the block with roughness textures of the gauging surfaces in a free state **a)** and under the condition of the wringing contact **b)**. (See text for other details.)

When moving further by the value of $\delta_{R,1}^{*}$ and $\delta_{R,1}$, we shall come to the positions of the TWC and the highest peaks of the roughness structure, respectively. So, expression (3) has a simple physical meaning, and shows the perpendicular distance between the plain touching the highest peaks of the roughness texture and the position of the TWC. Correspondingly, L_M shows the perpendicular distance between the positions of the two tight wringing contacts (Fig.1), when the surface textures of the wringing partners are the same.

3. EXPERIMENT

High-precision measurements of the wringing texture has become possible after the spectacular improvement of the accuracy of interferometric length measurements reported in [5-8]. As it follows from equations (2) and (3), there are only two large-value quantities, *i.e.* the length values L_M and L_{OPT}. But both of them can be measured to within 0.8 nm using the corresponding parallax-free methods [6,8] for high-quality gauge blocks with nominal lengths of a few mm. The two other quantities presented in the equation (2), that is the skin depth value (δ_S) and the maximum roughness value of free surface texture (δ_R), have typical values below 20 nm. For example, for tungsten carbide (TC) gauge blocks (Fig.2) the δ_R value is about 14 nm. For this small value the second order term in the calibration of the displacement transducers of the AFM [11] becomes negligible, and the linear term (if once calibrated) gives the corresponding uncertainty level below (3-4) % [11]. So, the uncertainty associated with the roughness measurements by AFM is below 0.4 nm. For tungsten carbide gauge blocks, the skin depth value is about 12.8 nm [4,10], and the corresponding uncertainty in its measurements can be about 5%.

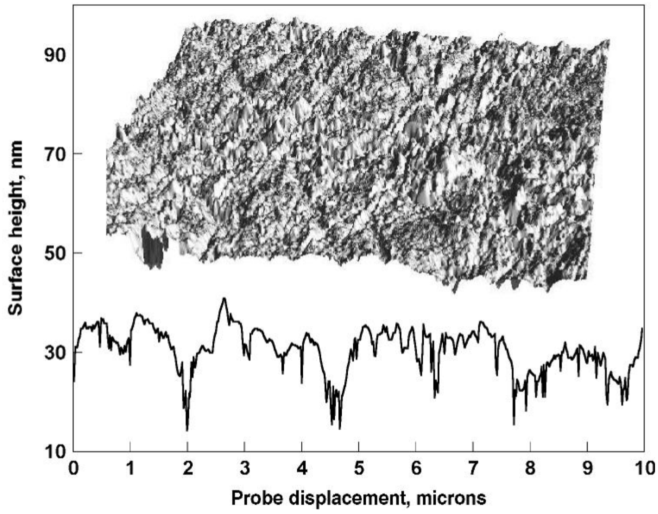

Fig.2a. Topogram of a tungsten carbide TESA gauge block obtained with atomic force microscope and a typical contour of the roughness texture of the block gauging surface.

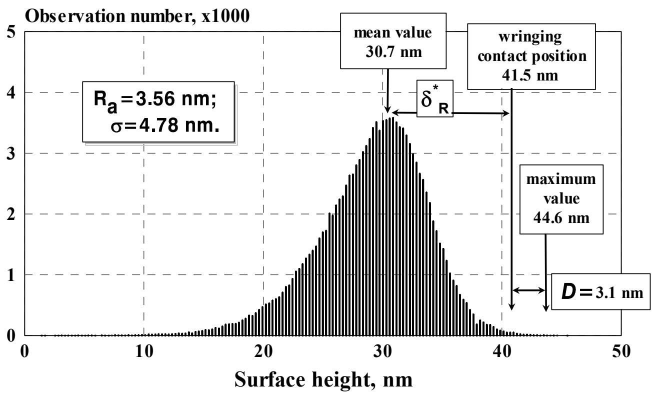

Fig.2b. Histogram of a tungsten carbide surface obtained with atomic force microscope. Here, R_a and σ are the mean absolute value of the deviations of the roughness texture and its corresponding standard deviation. D is the wringing texture deformation value.

This can be achieved, as for the optical constants n_2 and k_2 [10] of tungsten carbide holds a relation $n_2^2 \gg k_2^2$, and by its optical properties this material is closer to dielectrics than to metals. The corresponding uncertainty contribution resulting from the skin depth of the TC blocks is below 0.7 nm. Summing all these contributions as uncorrelated ones, we obtain the total uncertainty of the deformation measurement of about 0.75 nm, in accordance with equations (2),(3), and the uncertainty of 1.5 nm for the measurements of the difference ($L_{PH} - L_M$).

Measurement results of one of the basic parameters in optical interferometry - the roughness contribution to the to the length measurement result is illustrated by Table 1. The measured values of the roughness components $2\delta^*_R = (\delta_{R,1}^* + \delta_{R,2}^*)$ for the gauge block surfaces 1 and 2 are presented by 5-th row of Table 1. Measurements of δ^*_R correspond to the condition of the TWC. For determination of the optical phase change value ($\delta^*_R + \delta_S$), in accordance with (1), we need only the values of L_M and L_{OPT} . The corresponding results for steel and TC blocks are presented in the first two rows of Table 1. Measurements of L_{OPT}, using the double-sided method of [5,8], are performed with a thick oil film (~250 nm). Under these conditions the gauge block can be considered in a free, unperturbed state [8,9]. For steel and TC blocks we use different oils with refraction indexes of 1.403 and 1.507, respectively. The skin depth values, presented in the fourth row, are calculated using (8) in [9], and correspond to the front-side and back-side measurements [5] of the double-sided method. The values of optical constants of the gauge block materials are borrowed from literature [10,13]. For TC blocks we use the values of n_2=3.7; k_2=2.4 [10], and for steel Mitutoyu (Japan) blocks the values of n_2=2.14; k_2=2.955 [13]. The optical constant values reported in [13] give a relatively good agreement with the measured values of the light reflection coefficients [10,13] from the gauge block surfaces. The combination of optical ellipsometry with the reflection measurements by optical radiometry permits to improve considerably the accuracy of determination of the skin depth values in steel gauge blocks.

Table 1. Measurements of the roughness contribution for TC and steel blocks.

	TC 2-mm TESA Block	**TC 3-mm TESA Block**	**TC 6-mm TESA Block**	**TC 2-mm SELECT Block**	**Steel 5-mm Mitotoyo block**
L_M nm	11.07	73.87	-23.17	-25.62	30.03
L_{OPT} nm	-36.39	25.77	-71.1	-65.7	-27.5
Φ, nm	47.46	48.10	47.93	40.08	57.53
δ_S nm	12.82; 13.32	12.82; 13.32	12.82; 13.32	12.82; 13.32	22.54; 22.65
δ^*_R nm	**10.66**	**10.98**	**10.89**	**6.97**	**6.17**

Where $\Phi=2(\delta^*_R + \delta_S)$ is doubled phase change.

As it follows from Table 1, standard deviation for the measurement of the optical phase change value of TESA TC blocks (Switzerland) is 0.13 nm, only. This means that the wringing texture deformations are highly reproducible, and without any tangible loss of accuracy, they can be included into the definition of the mechanical length L_M.

It also follows from Table 1, that the contribution of the surface texture roughness to the result obtained by optical interferometry δ^*_R is in the range of 7-11 nm for TC blocks of different manufacturers. This illustrates the dependence of δ^*_R on the polishing procedure of gauging surfaces. For highly polished steel Mitutoyo blocks the δ^*_R value is even less and is equal to 6.2 nm.

The idea about the uncertainty of the optical length measurements is given by the uncertainty budget of Table 2.

Table 2. Uncertainty budget of the double-sided method for a 5-mm steel block.

Influence factor	**Uncertainty interval for physical quantity**	**Contribution to length; 2σ value in nm**
Laser frequency	500 kHz	0.005
Block temperature	±1 mK	0.06
Dilatation coefficient	$\delta\alpha = 1\ 10^{-7}$ / °C; $\Delta T = \pm 0.1$ K	0.05
Air pressure	±0.066 hPa	0.088
Air temperature	±1 mK	0.005
Air humidity	±1%	0.05
Edlén equation	$3.2\ 10^{-8}$	0.16
Aperture correction	0.09 nm	0.06
Fringe fraction determination		0.21
Optical path perturbations in Quartz resulting from wringing procedure		0.21
Block position determination for the front-side measurement	±0.02 mm; at inclinations of the block surface 6.7 nm/mm and 3.2 nm/mm in X,Y directions	0.15
Block position determination for the back-side measurement	±0.02 mm	0.15
Displacement of the plate in the interferometer for the front side measurement	±0.2 mm	0.12
Displacement of the plate in the interferometer for the front side measurement	±0.2 mm	0.12
Uncertainty, associated with the refractive index of oil	Relative uncertainty in the refractive index measurements of $3\ 10^{-4}$. Maximum oil film thickness in the experiments was 100nm.	0.045
Expanded uncertainty value (K=2)		**0.46**

So, the expanded uncertainty [12] of the double-sided method [8] for measurement of the optical length of a 5-mm steel block is ~0.46 nm, when calculated using the recommended procedure of [12]. This procedure is known as an optimistic way of the uncertainty evaluation, that is valid only for uncorrelated influence factors. For the pessimistic way of evaluation of the total uncertainty, when the absolute values of the contributing uncertainties are summed, we get the value of ~1.45 nm. The real uncertainty value is expected to be somewhere between these two estimations.

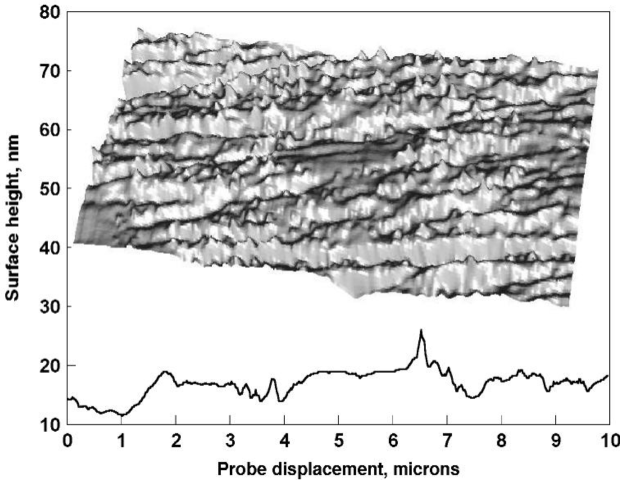

Fig.3a. Topogram of a steel gauging surface of a Mitutoyo block obtained with atomic force microscope, and a typical contour of the roughness texture of the block gauging surface.

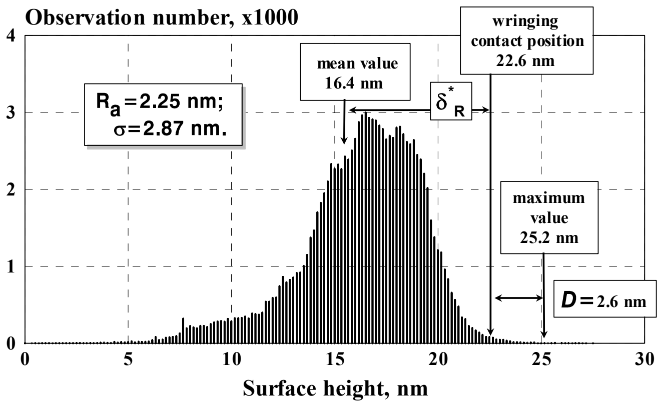

Fig.3b. Histogram of a steel surface of a Mitutoyo block obtained with atomic force microscope. Here, R_a and σ are the mean absolute value of the deviations of the roughness texture and its corresponding standard deviation. D is the wringing texture deformation value.

The results of AFM measurements are presented in Fig.2 and 3. Here we show the 3D profiles for TC TESA block (Fig.2a) and steel Mitutoyo block (Fig.3a). To see more clearly the form of individual peaks and dents of the surface structures, one-dimensional roughness contours of the blocks are also presented. The general quantitative information the surface structure is shown by the histograms of Figs. 2b and 3b. The main parameters, which are measured by AFM and are important for our study, are the mean value of the histogram, the value of the highest peaks and the standard deviation σ of the roughness structure. The values shown in Figs.2b and 3b correspond to some averaged data obtained by measuring several surface areas, having the dimensions of 100x100 microns, on both faces of the blocks. The mean value of the surface texture detected by AFM corresponds to the position of the $L^{MN}{}_{PH}$, which is also determined by optical methods. As it follows from Fig.1, when adding to it the mean roughness component δ^*_R from Table 1, we come to the position of the tight wringing contact, which is also shown in the histograms. So in agreement with (3), the mean texture deformation D is found as a separation of the maximum peak heights in the histogram relative to the position of the tight wringing contact. For both: the steel and TC blocks, the measured surface texture deformations are below the σ value of the roughness contour and are in the range of 2.6-3.1 nm. The position of the tight wringing contact is quite close to the highest peaks of the roughness structure, and this difference cannot be detected by the standard method of optical interferometry [1], having the uncertainty above 10 nm [14]. The separation of the position of the tight wringing contact from the mean plain of the roughness structure is about (2.2-2.3) σ-values for both types of the measured blocks.

3. CONCLUSIONS

Using new high-precision methods of optical interferometry and atomic force microscopy, wringing deformations of the surface texture have been determined for the first time. For steel and tungsten carbide blocks, having the roughness σ-values of 2.9 nm and 4.8 nm, the roughness contribution to the interferometric length measurement has been found to be equal to 6.2 nm and 10.8 nm, respectively. The wringing surface deformations are measured to be about 2.6 nm and 3.1 nm, thus being below the corresponding σ-value of the roughness texture. So, wringing texture deformations are much smaller than typical deviations from flatness for gauging surfaces of the blocks, even for the blocks of the highest grade. With the increase of accuracy of the length measurements, it is necessary to discriminate between the mechanical length of the block, which is defined under the condition of the wringing contact, and the peak-to-peak value of the physical length of the artifact, which is defined in a free, unperturbed condition.

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