A Novel Method for Areal Surface Roughness Measurement

Romuald Synak, Wlodzimierz Lipinski, Marcin Pawelczak

Abstract**—**An area-integrating method that uses the technique of total integrated light scatter for evaluating the root mean square height of the surface Sq has been presented in the paper. It is based on the measurement of the scatter power using a flat photodiode integrator rather than an optical sphere or a hemisphere. By this means, one can obtain much less expensive and smaller instruments than traditional ones. Thanks to this, they could find their application for surface control purposes, particularly in small and medium size enterprises. A description of the functioning of the measuring unit as well as the impact caused by different factors on its properties is presented first. Next, results of measurements of the Sq values performed for optical, silicon and metal samples have been shown. It has been also proven that they are in a good agreement with the results obtained using the Ulbricht sphere instrument.

Keywords**—**ISO 25178 Standard, scatterometry, surface metrology, surface roughness

I. Introduction

THE new ISO 25178 surface roughness standard [5] has created a need for making progress in the methods and instrumentation destined for measurement of 3D surface texture parameters. Areal-topography methods such as white light interferometric microscopes [10] or atomic force microscopes [2] have already been put into practice. These instruments enable one to measure a great number of the parameters specified in the ISO 25178 standard, but they are very expensive. However, for many surface control tasks, the root mean square (rms) height of surface Sq could merely be sufficient. This takes place, for instance, in optical or electronic industries, where this parameter (usually marked as σ) has been used for years. To measure it, an area-integrating method (also specified in the standard), known as total integrated scatter, is often used. The light scattered from the surface is collected over a wide range of angles, and the ratio of its power and the power of specularly reflected light (defined as the TIS parameter) is used to calculate the rms roughness. For measuring this parameter, instrumentation, including the Ulbricht sphere or the Coblentz hemisphere, is usually applied [8]. Due to the considerable dimensions of these units as well as their high cost, these methods are mainly applied in laboratories and in measuring devices dedicated to specific tasks, e.g. for control of magnetic disks [7]. It seems, however, that one may also find a possibility to design portable and inexpensive TIS instruments, which may find their application among manufacturers as well as recipients of such items as optical components, length measuring standards (e.g. size blocks), silicon wafers, etc.

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The aforementioned materials are characterised by their Sq values from less than 1 nm to several or more than a dozen nanometres, and their surface structure is isotropic in a majority of cases. Having made such assumptions, one may design a measuring device based on a completely different, much simpler structural principle of the scattered radiation integrating element. We are proposing to realise this idea by using a planar silicon photodiode with a hole through which a laser beam passes to reach the surface being examined. The light scattered from this surface falls on the photodiode active area, causing generation of a current proportional to the incident light power.

However, such an integrating system, here referred to as a photodiode integrator, requires checking whether it meets the requirements applicable to TIS measuring units, and particularly whether the results obtained by using it are similar to those obtained in traditional instruments. The major question is, therefore, whether it ensures detection of the total radiation scattered from a surface. Another property of the new measuring unit is that its bandwidth limit values are mutually interconnected (reduction of the lower angle causes reduction of the upper one), which requires investigating as to whether there are potential conditions under which a satisfactory area of the unit's operation can be established.

An analysis of the functioning of the unit, as well as the impact caused by said factors on its properties, is the main subject of the article. The analysis has been preceded by a description of the measuring unit in question. In the final section of the paper, the results obtained using an experimental measuring unit have been provided.

II. A Principle of TIS Measurements

A light beam incident on a surface is partially diffused from the surface and partially deflected under the angle equal the angle of light incidence. By denoting the incident, specular and diffuse power as P_i, P_r and P_s correspondingly, by definition, the specular reflectance R_r equals:

$$R_r \equiv P_r / P_i \qquad (1)$$

and the diffuse reflectance R_s equals:

$$R_s \equiv P_s / P_i \qquad (2)$$

The reflectance value for the given material mainly depends on how rough its surface is. The correlation between the surface reflectance and the root mean square (rms) roughness – denoted in optical terminology as σ – for a perfectly conductive surface of Gaussian irregularity distribution was provided by Davies [4] and then generalised for a partially light absorbing surface by Bennett and Porteus [1]. In the course of further works, it was proved that the above dependence also applies to surfaces of any irregularity distribution Church [3]. Therefore, with reference to the said works, the ratio of the specular and the total reflectance decreases exponentially along with the ratio of σ and light wavelength λ.

Assuming that surface irregularities are far smaller than the wavelength, i.e. when $\sigma << \lambda$, the exponential function may be substituted with its linear approximation. Additionally entailing that the total reflectance practically equals the specular one in such a case, one obtains the following dependence:

$$\sigma \cong \frac{\lambda}{4\pi \cos \Theta_i} \sqrt{\frac{R_s}{R_r}} , \quad (3)$$

where Θ_i is the angle of light incidence.

The ratio of the diffuse and the specular reflectance is commonly referred to as the TIS parameter [8]:

$$TIS \equiv R_s/R_r = P_s/P_r . \quad (4)$$

Having substituted formula (3) with (4), one obtains the following relation:

$$\sigma \cong \frac{\lambda}{4\pi \cos \Theta_i} \sqrt{TIS} \cong \frac{\lambda}{4\pi \cos \Theta_i} \sqrt{\frac{P_s}{P_r}} . \quad (5)$$

In the case, where Θ_i is close to zero, and changing the symbol of rms roughness from σ into Sq one obtains:

$$Sq \cong \frac{\lambda}{4\pi} \sqrt{TIS} \cong \frac{\lambda}{4\pi} \sqrt{\frac{P_s}{P_r}} . \quad (6)$$

The main function of a measuring unit based on the application of the light scatter phenomenon is separation of the scattered and specularly reflected light, which arises when the light beam strikes the surface, and the measuring of their radiant power. To realise this function, two measurement units are commonly applied [8], namely the Ulbricht sphere (or integrating sphere) and the Coblentz sphere (or a hemispherical mirror). In the first one, the light scattered from a sample surface reflects many times from the diffusely reflected surface coating, and finally an inside photodetector measures the power proportional to the total scatter from the sample. In the second unit, the scattered light is reflected by the hemispherical mirror onto a photodetector. The specular beam in both approaches enters and leaves the spheres through a small circular hole. The diameter of that hole defines the near specular limit of the instrument, e.g. the minimal angle of the scattered light that is measured by the sphere. Typically, its value is 2^{o}. The maximal angle can be close to 85^{o} [6].

For purpose of estimation of the novel measuring unit an Ulbricht sphere unit has been used and therefore it is shown in Fig. 1

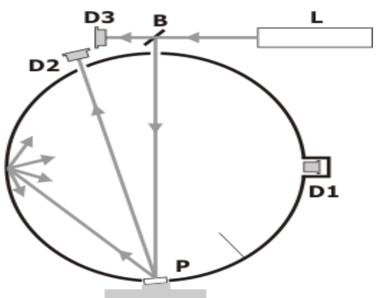

Fig. 1 Unit for measuring TIS parameter with the Ulbricht sphere B – beam splitter, D1, D2, D3 – photodiodes, L – laser, P – surface being examined

As a laser source, a He-Ne 633 nm is most frequently used and a measuring range is from several decimals to some tens nanometres in this case. The sphere diameter is from 150 up to 350 mm, which makes the whole measuring unit has a stationary character and which can mostly be used in laboratory conditions.

III. Measuring Unit

The main components of the new surface roughness and reflectance measuring unit have been depicted in Fig. 2.

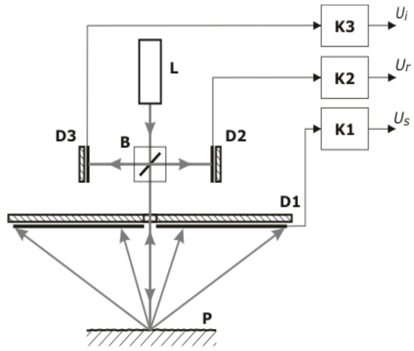

Fig. 2 Diagram of the surface parameters measuring unit. B – beam splitter, D1– photodiode integrator, D2, D3 – photodiodes, K1, K2 and K3 – photodiode loading elements, L – semiconductor laser module, P – surface being examined

The light beam emitted by the laser (L), after passing through the beam splitter (B) and then through the integrator (D1) hole, falls on the surface being examined (P) and is directly reflected and scattered from its. The beam incidence angle is close to normal, owing to which the reflected beam returns through the hole to unit B, from where it is directed to photodiode D2. The scattered beams fall on the active part of photodiode D1 causing emergence of currents corresponding to the radiant power of these beams. The beam splitter also serves another purpose, namely that of generating a reference beam used to determine the power of the incident beam by means of photodiode D3. All detectors operate in the photovoltaic mode, as a result of which their output current is proportional to the power of the incident light. The current is transformed into the voltage, for instance by means of a transimpedance amplifier (K), or on the load resistor. By measuring these voltages (U_i, U_r and U_s), one can calculate the relevant surface parameters by applying the dependences provided below.

The surface parameters can be established based on the following formulae:

$$R_r = K_r U_r \,/\, K_i U_i , \quad (7)$$

$$R_s = K_s U_s \,/\, K_i U_i , \quad (8)$$

$$TIS = K_s U_s \,/ K_r U_r , \quad (9)$$

$$\sigma \cong \frac{\lambda}{4\pi} \sqrt{\frac{K_s U_s}{K_r U_r}} , \quad (10)$$

where quantities K_s, K_r, and K_i are constants of the measuring unit which can be established by way of measurements.

Concluding the above consideration, one may notice that in order to calculate the rms roughness of a surface, it is enough to measure two voltages, or three voltages when the surface reflectance is also to be established.

IV. Results of Experiments

A. Subject of Investigations

In order to conduct a preliminary assessment of the potential measurement applications of the new method, a model of a photodiode integrator as well as an experimental measuring set has been prepared. The integrator model was developed using four planar silicon photodiodes. The integrator active surface diameter is ca. 20 mm, and the internal hole diameter is 2 mm. The measuring set included a semiconductor laser module with an output power of 3 mW and a beam diameter of 1 mm. The samples used in testing comprised manually polished metal size blocks and lapped tungsten carbide plates, mechanically polished silicon wafers, mirrors with a very high reflection coefficient with sputtered layers. In the following, the Sq measurement results obtained for these samples, as well the results the Ulbricht sphere, are presented. They are followed by a showing of the influence of the distance between the integrator and a sample on the unit range of the acceptance angle and measured Sq values.

B. Influence of the Angular Bandwidth on Rms Roughness

Theoretical analysis of the influence of the measuring unit angular bandwidth on the measured roughness values in TIS instruments has been given in the paper [9]. Here we present experimental results concerning the photodiode integrator model. Measuring unit parameters have been defined in Fig. 3.

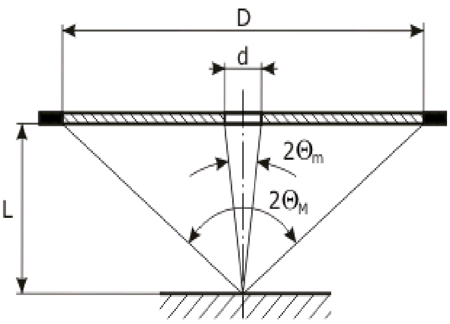

Fig. 3 Geometrical parameters of the measuring unit

The figure implies that the minimum angle θ_m and the maximum angle θ_M, between the scatter is measured, are given by the following formulae:

$$\theta_m = \mathrm{arctg}(d/2L), \quad (11)$$

and

$$\theta_M = \mathrm{arctg}\,(D/2L), \quad (12)$$

where d is the integrator hole diameter, D is the outer diameter of the active integrator surface, L the distance between the sample and the integrator.

The influence of the lower angle θ_m and the upper angle θ_M on surface roughness measurement results has been performed using a variable aperture diaphragm, which was situated close to the integrator.

To measure the influence of the angle θ_m, the distance L has been changed precisely while the diaphragm diameter has been regulated to prove θ_M value approximately constant. To measure the influence of the upper angle, the diaphragm diameter has been changed precisely at L being constant.

Measurement results obtained for some samples are shown in Fig. 4 and Fig. 5.

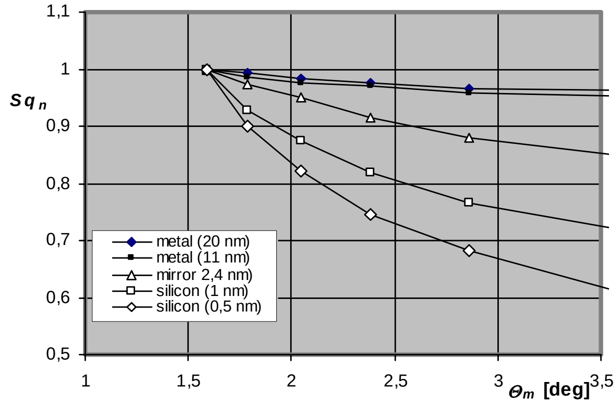

Fig. 4 Influence of the lower angle on normalized *Sq* values for the samples: metal (tungsten carbide), optical mirror and silicon wafer (in brackets *Sq* values of the samplesare given)

The graphs show measured values of *Sq* normalised to their maximum values given in figure captions. As implied by Fig. 4 in the case of very smooth surfaces (silicon wafers) even slight augmentation of the lower angle causes a considerable drop of the measured *Sq* value. The most of standard TIS instruments because of technical regards is characterised by the value of the lower angle even 2^o.

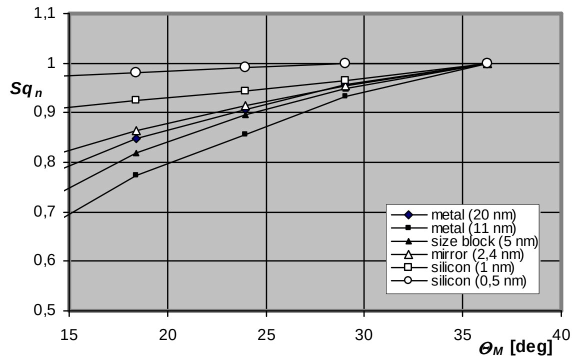

Fig. 5 Influence of the upper angle on normalized *Sq* values for the samples: metal (tungsten carbide), size block, optical mirror and silicon wafer (in brackets *Sq* values of the samples are given)

As implied by Fig. 5 in the case of smooth surfaces a satisfactory value of *Sq* in function of the upper angle is achieved already at 20 – 30^o. For metal surface the values of θ_M should be greater than 30^o.

Based on Fig. 3 one can notice that angular bandwidth limit values are mutually interconnected. Reduction of the lower angle by increasing the distance L causes also reduction of the upper one what can restrict measurement range of an instrument.

As a solution one can choose another parameter of the measuring unit, e.g. the integrator diameter. It results from Fig. 6, which according to equations (11) and (12), shows change of the θ_m and the θ_M as a function of L.

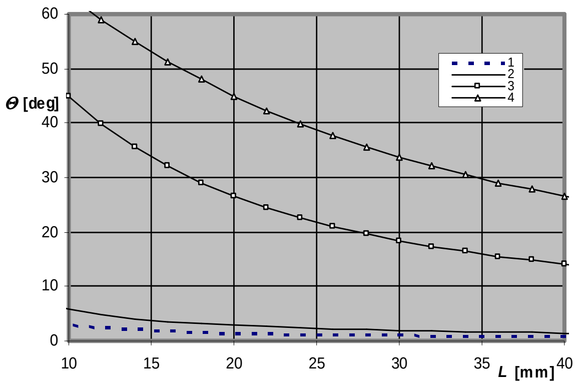

Fig. 6 Angular bandwidth of the measuring unit in function of the distance L: (1) θ_m for d = 1 mm, (2) θ_m for d = 2 mm, (3) θ_M for D = 20 mm and (4) θ_M for D = 40 mm

As may be noticed, considerable changes of angle Θ_m occur on distances L below 10 – 15 mm. The working range of L should exceed this threshold, and its more precise determination is conditional to the assumed lower threshold of the angle bandwidth and the assumed laser beam diameter as well as the related hole diameter. Assuming, for instance, that angle Θ_m is 2°, at the hole diameter is 2 mm, distance L should come to ca. 30 mm. Then, as one may notice in the graph, the maximum angle of Θ_M will come to 20 – 30° depending of the integrator outer diameter. Still broader bandwidth can be achieved for a smaller hole diameter. These results indicate that there are conditions under which a satisfactory compromise can be established while designing a photodiode integrator destined for measurement roughness of smooth surfaces.

C. Comparison of Measurement Results Obtained Using the Photodiode Integrator and the Ulbricht Sphere

For purpose of estimation of the new method destined for surface roughness evaluation, a measurement set equipped with an Ulbricht sphere has been developed. Its main elements are shown in Fig. 1. As a diffusing material of the sphere, barium sulfate is used. The sphere diameter is 20 cm and its lower acceptance angle is $1{,}43^{\circ}$. The upper angle is about 80°. To establish the same conditions for measuring surface roughness of samples using the integrating sphere and the photodiode integrator, the same laser source and other parts of the measuring units have been used. The sphere was calibrated using standards of diffuse reflectance made by firm Labsphere.

Because of the large influence of the lower angular limit of TIS instruments on results of *Sq* measurements, investigations of very smooth surfaces using the photodiode integrator have been provided at the similar lower angle like that of the sphere. A comparison between results obtained for a lot of silicon wafers and optical mirrors is presented in Fig. 7.

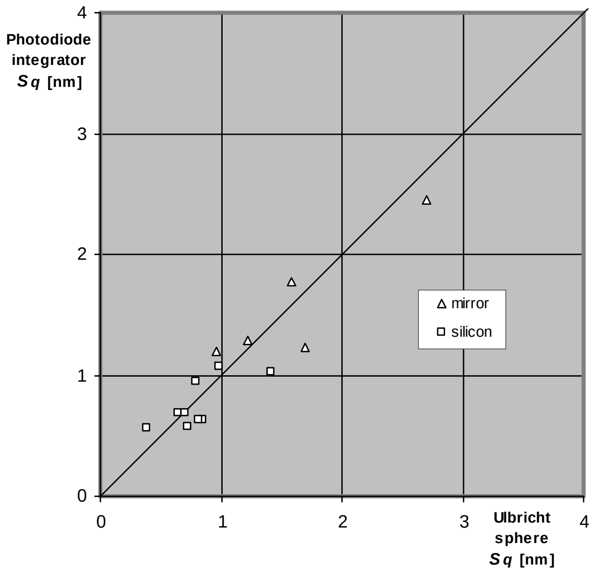

Fig. 7 Comparison of *Sq* measurement results for very smooth surfaces using the photodiode integrator and the Ulbricht sphere

Measurements of metallic surfaces, that are rougher than the previous ones, have to be performed at a greater integrator outer diameter to cover total scatter. In Fig. 8 comparison is presented for such surfaces Sq together with preceding results.

To establish measuring the same part of the sample, it was located in a special holder and carefully positioned to laser beam. Nevertheless, because of surface non-homogeneity or other factors occur spread of the results.

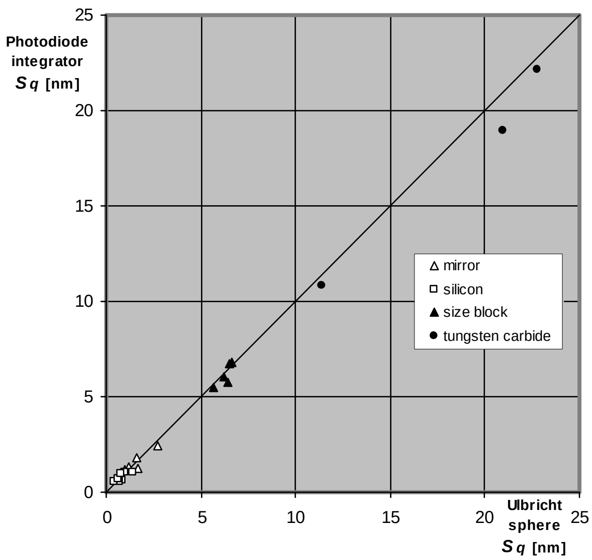

Fig. 8 Comparison of Sq measurement results using the photodiode integrator and the Ulbricht sphere

One can notice, however, that a general distribution of results indicate on a good correlation between both issues.

V. Conclusions

The measurement results of the Sq parameter using a model of the photodiode integrator obtained for smooth isotropic surfaces are in a good agreement with the results measured with the aid of the Ulbricht sphere. The integrator in its actual version enables to measure Sq in the range from 0.5 nm up to 10 – 20 nm. By duplicating its diameter or diminishing a laser beam, it is possible to considerably increase the upper range even to the natural limit of TIS application (about 40 nm at the wavelength 633 nm). Because of the influence of the distance between the integrator and a sample on the unit range of the acceptance angle, the parameters of the measuring unit should be adapted to the expected rms measurement range.

Total integrated scatter method, in contrary to other methods listed in the ISO 25178 Standard, e.g. 3D profilometers, is functioning on the basis of light integration and thanks to that enables to get measurement results faster and at lower costs. Compared to traditional TIS methods, the new unit is characterised by significantly reduced dimensions, which allows for TIS instrument fabrication in the form of a small and compact measuring head. These features enable the range of its potential applications to be considerably extended. Specifically, it can find application in small and medium enterprises acting in the field of precision mechanics or optics, both for production process monitoring and for end quality control.

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