BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 68, No. 3, 2020
DOI: 10.24425/bpasts.2020.133364

THERMODYNAMICS, MECHANICAL AND AERONAUTICAL ENGINEERING

A low-cost, simple optical setup for a fast scatterometry surface roughness measurements with nanometric precision

D. KUCHARSKI* and H. ZDUNEK

Division of Metrology and Measurement Systems, Institute of Mechanical Technology, Faculty of Mechanical Engineering, Poznan University of Technology, Jana Pawla II 24 Street, 60-965 Poznan

Abstract. We present a prototype of a simple, low-cost setup for a fast scatterometric surface texture measurements. We used a total integrated scatter method (TIS) with a semiconductor laser ($\lambda = 638$ nm) and a Si photodiode. Using our setup, we estimated the roughness parameters *Rq* for two reference surfaces (Al mirrors with flatness $\lambda/10$) and seven equal steel plates to compare. The setup is easily adaptable for a fast, preliminary manufacturing quality control. We show is possible to construct a low-cost measurement system with nanometric precision.

Key words: scatterometry, surface texture, optical measurement systems, surface metrology, surface roughness.

1. Introduction

We live in the Industry 4.0 age, and surface metrology plays a key role in it. Fast and highly accurate quality control techniques are a clue of it. According to the new redefinition of the SI units [1], optical surface metrology is going to be a game-changer in the manufacturing. Optical measurement techniques are widely developed [2]. Except highly precise interferometry for displacement measurements [3, 4], laser light scatterometry is also successful for surface texture measurements [5–9]. By measuring light scattered (or diffracted) from a sample, the surface texture of the sample itself can be measured. Scatterometry measurements are non-destructive, rapid and highly repeatable, but at the same time, belongs to statistical surface analysing techniques. This state-of-art hopefully will change together with the potential outputs from many ground-breaking research activities like the project of MMT Group[1] from the Nottingham University under the EPSRC[2] grant [10]. We are also on the right research track.

The scattering light from a rough surface is a wave optics effect, well described in the literature [2, 11–13]. The physics of coherent light scatterometry is simple, but surface-light interaction can be complex and not predictable [14]. Rough surfaces scatter more light than smooth ones, and this can be used in manufacturing for a very simple, rapid surface type selection.

We built a simple optomechanical, off-the-shelf components setup for TIS (total integrated scatter) method to test the surface texture of the sample. We used a low-cost components: laser diode module[3] with $\lambda = 638$ nm, $P = 20$ mW and Si phodetector[4] (see Fig. 1).

2. Setup

The optical layout of the setup is shown in Fig. 1.

The laser beam is sent through a multimode optical fibre[5] and a fibre output collimator[6] to collimate the beam. The fibre is used for spatial beam shaping, to compensate well known effect of diode laser beam (the beam emitted from a semiconductor laser typically has an elliptical spatial profile, caused by diffraction). After fibre, beam is round and two lenses (l_2 and l_3 in Fig. 1) as an optical telescope, makes a parallel beam (Ø3 mm). We used a high-precision rotation mount[7] to vary the angular position of the tested object.

We tested two kinds of objects; a reference object (aluminium mirror with flatness $\lambda/10$)[8] and steel plates[9] (steel sur-

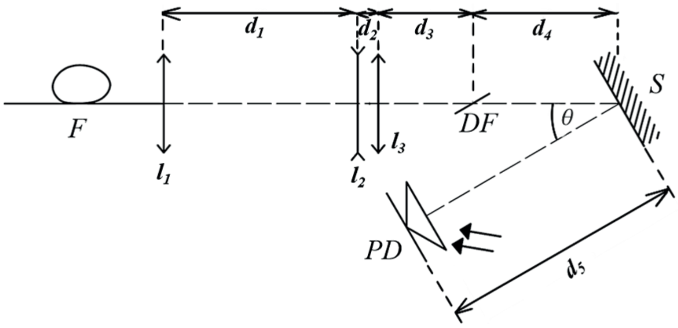

Fig. 1. Optical layout: F – optical fibre, l_1 – fibre collimator, l_2 – lens ($f = -50$ mm), l_3 – lens ($f = 75$ mm), DF – density filter (2.0), S – surface to be measured, PD – photodetector, $d_1 = 330$ mm, $d_2 = 35$ mm, $d_3 = 160$ mm, $d_4 = 250$ mm, $d_5 = 380$ mm, θ – reflection angle [°]

* e-mail: dawid.kucharski@put.poznan.pl
[1] MMT – Manufacturing Metrology Team
[2] The Engineering and Physical Sciences Research Council (EPSRC) is the main funding body for engineering and physical sciences research in the UK
[3] Laser Coherent SNF-xxx-635-30-KB
[4] Thorlabs DET36A/M
[5] Thorlabs GIF625-1000
[6] Schäfter + Kirchhoff 60FC
[7] Thorlabs PR01/M
[8] Thorlabs Ø1" Protected Aluminum Mirror PF10-03-G01
[9] Dimensions: 120×25×2

Manuscript submitted 2019-11-20, revised 2020-02-14, initially accepted for publication 2020-03-14, published in June 2020

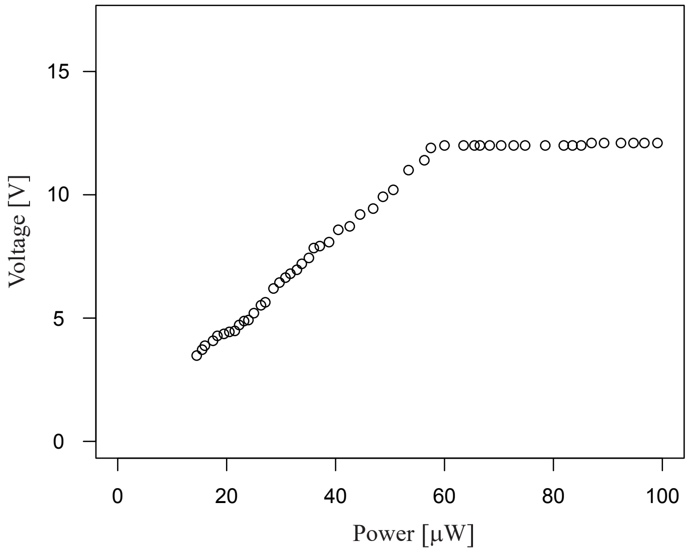

Fig. 2. $U = f(P)$ characteristic of the photodiode

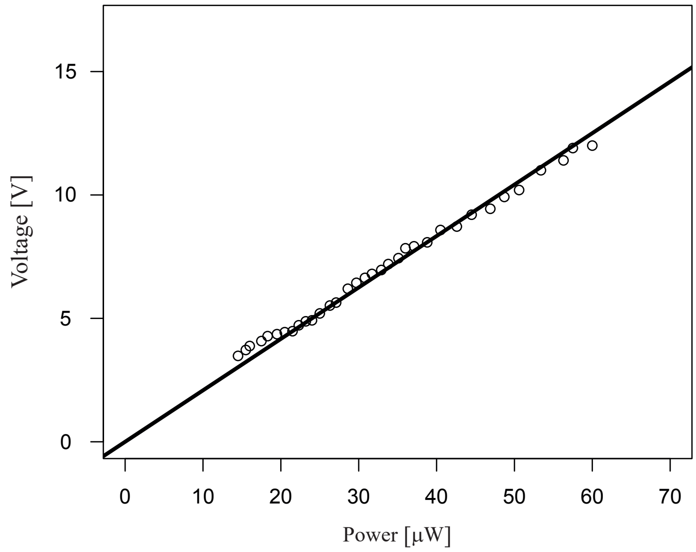

Fig. 3. Linear part of the $U = f(P)$ of the photodiode characteristic from Fig. 2. Line is a linear fit with $(0,0)$ incident

faces with no special preparation). According to the spot size, we evaluated always a surface of 3 mm size (Ø3 mm), which corresponded, together with the total size of the samples and wavelength λ, to the local irregularities of the surface.

3. Results

3.1. A photodiode characteristic. To use a final system with a low-cost photodiode as a light detector instead of an expensive one, a photodiode calibration is needed. We used an optical power meter[10] and circular variable neutral-density filter[11] (instead of *DF* in Fig. 1), without the sample, to find the light saturation limit of the photodiode. This procedure is important to calculate the power of reflected/scattered light from the voltage of the diode.

We registered the photodiode voltage on the scope[12] as a light power changing by the circular neutral-density filter position adjusting (see Fig. 2 and Fig. 3). We found the saturation limit of the diode ($U = 12$ V), corresponds to the optical power $P = 60\ \mu W$. From the linear fit of the $U = f(P)$ relation (see Fig. 3), we found the function to calculate the power of the light P from the voltage U (see (1)). For all measurements, we used 30 μW of the power laser, which is the optimum place in the $U = f(P)$ relation graph. By using, the linear part of the $U = f(P)$ relation, during the final surface texture measurements, we registered the power of the incident light and scattered one by a photodiode voltage changes on the scope.

$$P = \frac{U}{0.21}. \tag{1}$$

3.2. Surface roughness. Expressions for the relation between surface reflectance and root mean square roughness derived originate by H. Davies [12]. This statistical treatment of the reflection of electromagnetic radiation from a rough surface for non-perfect conducting materials was corrected later by H.E. Bennet and J.O. Porteus [13]. Experimentally, determination of standardized roughness values directly from the intensity distribution of the scattered light is not possible. In measurements of a surface, in the first approximation, we get the optical roughness value S_N as the statistical moment of the radiation distribution [15]. But for the surfaces with a Gaussian distribution of the roughness amplitude (e.g. fine surfaces of mirrors, Al plates, etc.), comparative measurements have shown a close correlation between S_N and the standardized roughness values obtained by the stylus profilometry [15]. Based on this experience, the TIS (total integrated scatter) method was developed [2], where the roughness of the sample surface determined from measurement of the light flux scattered, is described by the (2).

$$Rq = (\lambda / 4\pi\cos\theta_i)\left[\ln\left(\frac{P_0}{P_{spec}}\right)\right]^{\frac{1}{2}}, \tag{2}$$

where:

Rq – the root mean square (RMS) roughness of the surface,
λ – wavelength (638 nm),
θ_i – specular direction,
P_0 – optical power of the incident beam,
P_{spec} – optical power of the reflected light into the specular direction.

[10] Thorlabs compact power and energy meter PM100D with photodiode power sensor S120C
[11] Melles Griot 07 HFD 001
[12] RIGOL DS1052E

Table 1
The *Rq* surface roughness parameters for tested aluminium mirror *M*#1. The decimal numbers are a calculation variability (not due to the measurement resolution

		θ [°]																	
		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Rq [nm]	#1	13.75	13.80	13.88	13.98	14.09	14.22	14.37	14.55	16.21	16.45	16.72	17.02	17.36	19.22	19.66	20.14	20.68	21.27
	#2	12.25	12.30	12.37	12.45	12.55	12.67	12.81	12.96	13.14	13.33	15.21	15.48	15.78	16.12	16.49	16.90	19.07	19.62
	#3	8.60	8.64	8.68	8.74	8.81	10.93	11.05	11.19	11.34	11.51	11.69	11.90	12.14	12.39	12.68	15.06	15.46	15.90
	#4	12.25	12.30	12.37	12.45	12.55	12.67	12.81	12.96	13.14	13.33	13.55	13.80	14.07	14.36	16.49	16.90	17.35	17.84
	#5	8.60	8.64	8.68	8.74	8.81	8.90	11.05	11.19	11.34	11.51	11.69	11.90	12.14	12.39	12.68	12.99	13.34	13.72
	#6	8.60	8.64	8.68	8.74	8.81	8.90	8.99	9.10	9.22	9.36	9.51	9.69	9.87	10.08	10.32	10.57	10.85	11.16
	#7	10.11	10.15	10.21	10.28	10.36	10.46	10.57	10.70	10.84	11.01	11.19	11.39	11.61	11.86	12.13	12.43	12.76	13.13

In general profilometry, the parameter *Rq* is defined for a single profile. Is extracted from a surface topography by filtering out the form, and waviness. In the optical surface scatterometry, the *Rq* can still be directly calculated as long as there is a measurable specular spot (the surface still reflecting the light), but the approximation limitation is [2]:

$$\frac{Rq}{\lambda} \approx 0.3. \tag{3}$$

For example, when the surface roughness of a metal plate is $Rq = 170$ nm (see e.g. in Table 4) from the (3) we have got:

$$\frac{Rq}{\lambda} = \frac{170}{638} \approx 0.266. \tag{4}$$

The RMS (root mean square) surface slope can be determined from the RMS width of the scattered light. For more smooth surfaces like Al mirrors with flatness $\lambda/10$, waviness or form are strongly reduced, especially when we measure the surface of 3 mm size without scanning it. Any surface slope can affect an angle of the specular direction and that we did not investigate. The mirror flatness can be taken into account for a complex measurement errors evaluation in the rotation angle error, but it is negligible smaller than the rotation stage accuracy (see Section 3.4).

We obtained roughness in a one-shot of the scattered light from a spot size corresponds to the profile of 3 mm length.

In surface metrology, temperature influence can be significant [16]. We control the temperature in a lab during the measurements 20 ± 1°C, which is enough for short-time detections. A background light was reduced to a minimum by working in the dark. We measured the surface roughness parameters *Rq* of mirrors and steel plates. Due to the different scale of the surfaces roughness (optical vs. mechanical), we chose bigger steps for light reflection angle from steel surfaces (from 5° to 20° with $\Delta\theta = 5°$), than for mirror ones (from 3° to 20° with $\Delta\theta = 1°$). We did not see any changes in light scattering from steel surfaces with smaller angle steps.

We repeated the measurements seven times for every sample (two Al mirrors and seven steel plates). We proved, the average values of all measured surface roughness parameters *Rq* are corresponds to the surface type (see Table 1, and Table 2). The differences between the roughness of the aluminium coated surface and metal one are in the order of magnitude (see Table 5).

Table 2
The *Rq* surface roughness parameters for tested steel plate (*S*#1). The decimal numbers are a calculation variability (not due to the measurement resolution)

		θ [°]			
		5	10	15	20
Rq [nm]	#1	132.74	139.21	151.16	170.06
	#2	132.74	139.21	151.05	170.06
	#3	132.83	139.11	151.16	169.94
	#4	132.74	139.21	151.16	169.94
	#5	132.74	139.21	151.16	170.06
	#6	132.74	139.21	151.16	170.06
	#7	132.74	139.21	151.16	170.06

We checked the relation $Rq = f(\theta)$ for samples. When the specular angle θ is growing, the average of surface roughness parameter $\overline{Rq}$ follows roughly as x^2 function. The same for both type of surfaces (see Fig. 4 and Fig. 6). This corresponds to (2), which means the correct setup construction. The math relation between (2) and x^2 function is explained in (5)

$$\frac{1}{\cos\theta} = \sec\theta \xrightarrow{\theta \in \left(0, \frac{\pi}{2}\right)} x^2. \tag{5}$$

3.3. Uncertainty evaluation. We estimated the measurements uncertainty budget. For the same reflection angle, we calculated the extended uncertainty coefficient $(2\sigma \times t_n)$[13] (see e.g.

[13] t_n – Student-Fisher coefficient; for $n = 7 \Rightarrow t_7 = 1.1$

Table 3
Average surface roughness parameters $\overline{R_q}$ and extended standard deviation $(2\sigma \times t_n)$ parameters of tested mirror $M\#1$ for repeated scattering angles; t_n – Student-Fisher coefficient; for $n = 7 \Rightarrow t_7 = 1.1$

	θ [°]								
	3	4	5	6	7	8	9	10	11
$\overline{R_q} \pm (2\sigma \times t_7)$ [nm]	10.59 ± 4.72	10.64 ± 4.73	10.70 ± 4.77	10.77 ± 4.80	10.85 ± 4.84	11.25 ± 4.46	11.66 ± 3.92	11.81 ± 3.97	12.18 ± 4.92
	12	13	14	15	16	17	18	19	20
$\overline{R_q} \pm (2\sigma \times t_7)$ [nm]	12.36 ± 4.99	12.79 ± 5.51	13.03 ± 5.60	13.28 ± 5.72	13.77 ± 6.76	14.35 ± 7.19	15.00 ± 7.18	15.64 ± 7.86	16.09 ± 8.09

Table 3 and Table 4). We expand the normal standard deviation parameter with the confidence level 68,3% by the Student-Fisher coefficient $(t_{n=7} = 1.1)$, due to the limited number of repeated measurements $(n = 7)$. We estimated in this way, the repeatability of the measurements.

Table 4
Average surface roughness parameters $\overline{R_q}$ and extended standard deviation $(2\sigma \times t_n)$ parameters of tested steel plate $S\#1$ for repeated scattering angles; t_n – Student-Fisher coefficient; for $n = 7 \Rightarrow t_7 = 1.1$

	θ [°]			
	5	10	15	20
$\overline{R_q} \pm (2\sigma \times t_n)$ [nm]	132.75 ± 0.07	139.20 ± 0.08	151.14 ± 0.09	170.03 ± 0.13

The extended standard deviations for steel plates are clearly smaller than for Al mirrors (see e.g. in Table 3 and Table 4). This is caused by the spatial resolution limitation. The average effect is so substantial from the steel surface, that we observed no significant repeatability error. Opposite to the mirror, where surface quality is decisive. To do the comparative measurements, we varied the reflection angle. When the reflection angle of a circular beam is going up, light is hit the target as an elliptical beam. This angle effect is typical when a spot size is big enough to average the texture from a rough surface (again – limited spatial resolution). This causes the roughness and deviation parameters changes. We observe a growing tendency of $\overline{Rq}$'s and standard deviations in a function of θ (see e.g. Fig. 4–7). This comparative correlation of uncertainties between two different surfaces can also be useful for a rapid, non-absolute surface roughness determination. The method is not traceable, but low-cost and very fast.

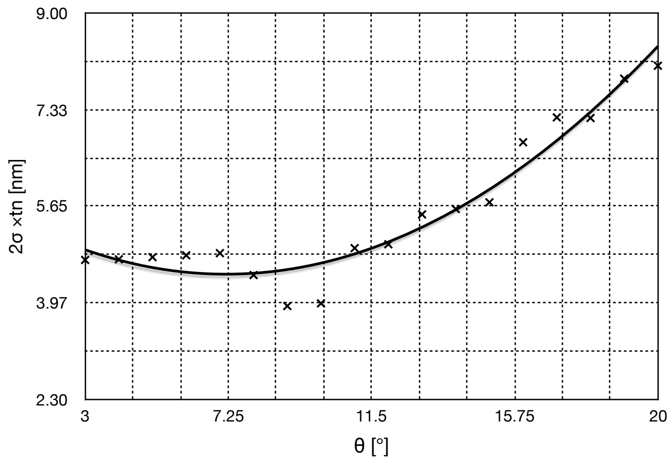

Fig. 5. $2\sigma \times t_n = f(\theta)$ for the tested mirror $(M\#1)$. Line is a x^2 approximation

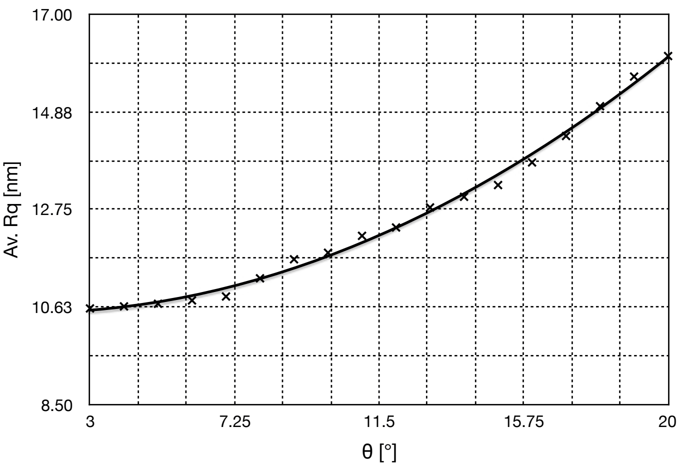

Fig. 4. $\overline{Rq} = f(\theta)$ for the tested mirror $(M\#1)$. Line is a x^2 approximation

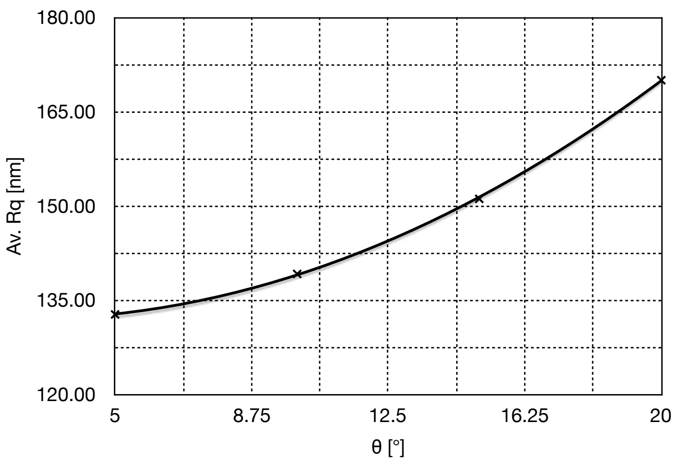

Fig. 6. $Rq = f(\theta)$ for the tested steel plate $(S\#1)$. Line is a x^2 approximation

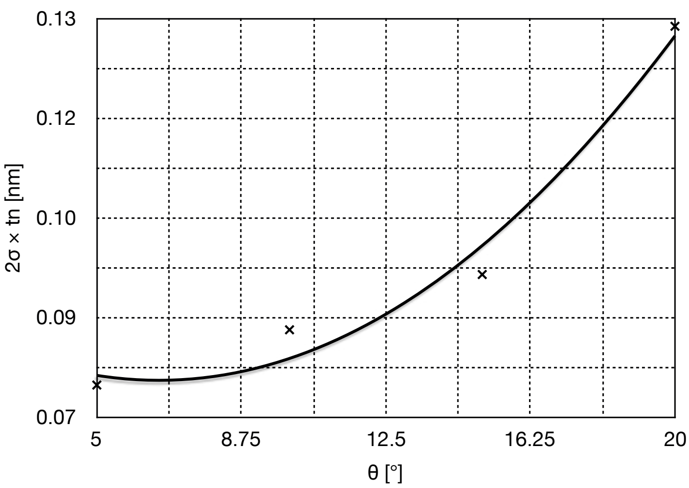

Fig. 7. $2\sigma \times t_n = f(\theta)$ for the tested steel plate ($S\#1$). Line is a x^2 approximation

3.4. Complex measurement errors. According to (2), roughness parameter Rq is a complex function. Maximum error of individual Rq parameter ΔRq, can be described as follows (6):

$$\Delta Rq = \left|\frac{\delta Rq}{\delta\theta}\right| \cdot \Delta\theta + \left|\frac{\delta Rq}{\delta P_0}\right| \cdot \Delta P_0 + \\ + \left|\frac{\delta Rq}{\delta P_{spec}}\right| \cdot \Delta P_{spec} + \left|\frac{\delta Rq}{\delta\lambda}\right| \cdot \Delta\lambda, \tag{6}$$

where:

$\Delta\theta = 1° \approx 0.01745\ rad$ – rotation stage accuracy,

$\Delta P_0 = \Delta P_{spec} \approx 0.048\ \mu W$ – accuracy of the incident and specular beam power (from a scope resolution),

$\Delta\lambda = 10$ nm – wavelength accuracy.

The total maximum roughness parameter error ΔRq is given by (7).

$$\Delta Rq = \left|\frac{\lambda\sqrt{\ln\left[\frac{P_0}{P_{sec}}\right]} \cdot \tan\theta}{4\pi\cos\theta}\right| \cdot \Delta\theta + \\ + \left|\frac{\lambda}{8\pi\sqrt{\ln\left[\frac{P_0}{P_{sec}}\right]}P_0\cos\theta}\right| \cdot \Delta P_0 + \\ + \left|\frac{-\lambda}{8\pi\sqrt{\ln\left[\frac{P_0}{P_{sec}}\right]}P_{sec}\cos\theta}\right| \cdot \Delta P_{sec} + \left|\frac{\sqrt{\ln\left[\frac{P_0}{P_{sec}}\right]}}{4\pi\cos\theta}\right| \cdot \Delta\lambda. \tag{7}$$

For the mirror $M\#1$ as the example, we get (8):

$$\Delta Rq = |0.04| \cdot 0.01745 + |0.17| \cdot 0.048 \cdot 10^{-6} + \\ + |0.18| \cdot 0.048 \cdot 10^{-6} + |0.22| \cdot 10 \approx 0.6\ nm, \tag{8}$$

which shows a negligible level of the individual error and at the same time, the importance of precision, previously estimated by the standard deviation parameters (see Table 3 and Table 4).

In Table 5 all of the average roughness parameters $\overline{Rq}$ are shown, calculated for all numbers of measurements (126 measurements per every mirror and 28 per every steel sample). The differences are clear to be seen as well as the precision described by the standard deviation parameters 2σ.

Table 5
Average surface roughness values $\overline{Rq}$ (total) for measured samples and its uncertainties (2σ). $M\#i$ – mirrors, $S\#i$ – steel samples

Sample	$\overline{Rq} \pm 2\sigma$ [nm]
$M\#1$	12.60 ± 5.94
$M\#2$	15.68 ± 3.37
$S\#1$	148.28 ± 28.88
$S\#2$	147.26 ± 28.80
$S\#3$	150.65 ± 29.33
$S\#4$	155.03 ± 30.20
$S\#5$	147.09 ± 28.61
$S\#6$	142.50 ± 26.01
$S\#7$	143.40 ± 27.87

4. Discussion

We report the progress in the development of the simple scatterometric system for surface texture measurements. We aim to construct a low-cost, easy-to-use system for fast, non-tactile measurements. We show with different samples is possible to construct this type of a system, with pretty high measurement precision, by using simple, off-the-shelf optomechanical components. We postulate, the optical measurement system with sub-μm resolution, does not have to be highly expensive and high innovative, when used for a rapid preliminary surface testing.

To improve the setup and compare the results obtained by the scatterometry and profilometry, research using other stylus and optical measurement systems will begin presently.

Funding: This work was supported by grant 02/22/SBAD/1501.

References

[1] The International Bureau of Weights and Measures (BIPM), The International System of Units (SI), 9th edition, 2019.

[2] R. Leach, *Optical Measurement of Surface Topography*, Springer Science & Business Media, Berlin, Heidelberg, 2011.

[3] P. de Groot, "Phase Shifting Interferometry". In *Optical Measurement of Surface Topography*, pp. 167–186, ed. Leach, R.K., Springer Berlin Heidelberg, Berlin, Heidelberg, 2011.

[4] F. Meijer, D. Kucharski, and E. Stachowska, "Determination of the phase in the center of a circular two-beam interference pattern to determine the displacement of a rough surface", *Opt. Eng*. 57(10) (2018).

[5] M. Calaon, M.H. Madsen, and R. Leach, "Scatterometry", in *CIRP Encycl. Prod. Eng.*, 2019.

[6] J.W. Baumgart and H. Truckenbrodt, "Scatterometry of honed surfaces", *Opt. Eng*. 37, 1435–1441 (1998).

[7] C.J. Raymond, S.W. Farrer, and S. Sucher, "Scatterometry for the measurement of metal features", *Proceedings of the SPIE. BioRad CD Systems*, USA, pp. 135–146, 2000.

[8] M.H. Madsen, and P.-E. Hansen, "Scatterometry – fast and robust measurements of nano-textured surfaces", *Surf. Topogr. Metrol. Prop*. 4, 023003 (2016).

[9] R. Leach, "Surface topography measurement instrumentation", in *Fundam. Princ. Eng. Nanometrology*, Elsevier, pp. 133–204, 2014.

[10] R. Leach, Y. Tzimiropoulos, N. Senin, M. Liu, and J. Coupland, "Revisiting optical scattering with machine learning (SPARKLE)", Grant: EP/R028826/1. (2018–2021). https://gow.epsrc.ukri.org/NGBOViewGrant.aspx? GrantRef=EP/R028826/1, (accessed November 8, 2019).

[11] M. Born and E. Wolf, *Principles of optics: electromagnetic theory of propagation*, *interference and diffraction of light*; 7th ed., Cambridge Univ. Press, Cambridge, 1999.

[12] H. Davies, "The reflection of electromagnetic waves from a rough surface", *Proc. IEE – Part IV Inst. Monogr.* 101, 209–214 (1954).

[13] H.E. Bennett and J.O. Porteus, "Relation Between Surface Roughness and Specular Reflectance at Normal Incidence", *J. Opt. Soc. Am.* 51, 123–129 (1961).

[14] C. Lukianowicz, "Direct and inverse problem in scatterometry of rough surfaces", in *Proc. SPIE 4517*, *Lightmetry: Metrology*, *Spectroscopy*, *and Testing Techniques Using Light*, Poland, pp. 120–125 (2001).

[15] R. Brodmann, "Roughness form and waviness measurement by means of light-scattering", *Precis Eng* 8, 221–226 (1986).

[16] T. Miller, S. Adamczak, J. Swiderski, M. Wieczorowski, A. Łętocha, and B. Gapinski, "Influence of temperature gradient on surface texture measurements with the use of profilometry", *Bull. Pol. Ac.:Tech.* 65(1), 53–61 (2017)