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 (λ = 638 nm) and a Si photodiode. Using our setup, we estimated the roughness parameters Rq for two reference surfaces (Al mirrors with flatness λ/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 λ = 638 nm, P = 20 mW and Si photodetector 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 (l2 and l3 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 λ/10) 8 and steel plates 9 (steel surface to be measured, PD – photodetector, d1 = 330 mm, d2 = 35 mm, d3 = 160 mm, d4 = 250 mm, d5 = 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
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 $\lambda$, 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\textsuperscript{10} and circular variable neutral-density filter\textsuperscript{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\textsuperscript{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 $\mu W$ 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.

\begin{equation}
U = f(P) \quad \text{(1)}
\end{equation}

3.2. Surface roughness. Expressions for the relation between surface reflectance and root mean square roughness derived originate by H. Davies\textsuperscript{[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\textsuperscript{[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\textsuperscript{[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\textsuperscript{[15]} . Based on this experience, the TIS (total integrated scatter) method was developed\textsuperscript{[2]} , where the roughness of the sample surface determined from measurement of the light flux scattered, is described by the (2).

\begin{equation}
R_q = \left( \frac{\lambda}{4 \pi \cos \theta_s} \right) \left[ \ln \left( \frac{P_0}{P_{\text{spec}}} \right) \right]^{\frac{1}{2}}, \quad (2)
\end{equation}

where:

- $R_q$ – the root mean square (RMS) roughness of the surface,
- $\lambda$ – wavelength (638 nm),
- $\theta_s$ – specular direction,
- $P_0$ – optical power of the incident beam,
- $P_{\text{spec}}$ – optical power of the reflected light into the specular direction.

\textsuperscript{10} Thorlabs compact power and energy meter PM100D with photodiode power sensor S120C
\textsuperscript{11} Melles Griot 07 HFD 001
\textsuperscript{12} RIGOL DS1052E
A background light was reduced to a minimum by working in the dark. We measured the surface roughness parameters $R_q$ (not due to the measurement resolution) for tested aluminium mirror $M#1$. The decimal numbers are a calculation variability (not due to the measurement resolution)

$$\frac{R_q}{\lambda} \approx 0.3.$$  \hspace{1cm} (3)

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

$$\frac{R_q}{\lambda} = \frac{170}{638} \approx 0.266. $$ \hspace{1cm} (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 measurement, but the approximation limitation is [2]:

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 $R_q$ are correspond 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>
<thead>
<tr>
<th>$\theta$ [°]</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q$ [nm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td>8.60</td>
<td>8.64</td>
<td>8.68</td>
<td>8.74</td>
<td>8.81</td>
<td>10.93</td>
<td>11.05</td>
<td>11.19</td>
<td>11.34</td>
<td>11.51</td>
<td>11.69</td>
<td>11.90</td>
<td>12.14</td>
<td>12.39</td>
<td>12.68</td>
<td>15.06</td>
<td>15.46</td>
<td>15.90</td>
</tr>
<tr>
<td>#5</td>
<td>8.60</td>
<td>8.64</td>
<td>8.68</td>
<td>8.74</td>
<td>8.81</td>
<td>8.90</td>
<td>11.05</td>
<td>11.19</td>
<td>11.34</td>
<td>11.51</td>
<td>11.69</td>
<td>11.90</td>
<td>12.14</td>
<td>12.39</td>
<td>12.68</td>
<td>12.99</td>
<td>13.34</td>
<td>13.72</td>
</tr>
</tbody>
</table>

Table 1

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

<table>
<thead>
<tr>
<th>$\theta$ [°]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q$ [nm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>132.74</td>
<td>139.21</td>
<td>151.16</td>
<td>170.06</td>
</tr>
<tr>
<td>#2</td>
<td>132.74</td>
<td>139.21</td>
<td>151.05</td>
<td>170.06</td>
</tr>
<tr>
<td>#3</td>
<td>132.83</td>
<td>139.11</td>
<td>151.16</td>
<td>169.94</td>
</tr>
<tr>
<td>#4</td>
<td>132.74</td>
<td>139.21</td>
<td>151.16</td>
<td>169.94</td>
</tr>
<tr>
<td>#5</td>
<td>132.74</td>
<td>139.21</td>
<td>151.16</td>
<td>170.06</td>
</tr>
<tr>
<td>#6</td>
<td>132.74</td>
<td>139.21</td>
<td>151.16</td>
<td>170.06</td>
</tr>
<tr>
<td>#7</td>
<td>132.74</td>
<td>139.21</td>
<td>151.16</td>
<td>170.06</td>
</tr>
</tbody>
</table>

Table 2

We checked the relation $R_q = f(\theta)$ for samples. When the specular angle is growing, the average of surface roughness parameter $R_q$ 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)

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

3.3. Uncertainty evaluation. We estimated the measurements uncertainty budget. For the same reflection angle, we calculated the extended uncertainty coefficient $(2\sigma \times t_n)_{15}$ (see e.g.

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

Bull. Pol. Ac.: Tech. 68(3) 2020

487
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 – $R_q$’s and standard deviations in a function of $\theta$ (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.

Table 3
Average surface roughness parameters $R_q$ 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 $n = 7 \Rightarrow t_n = 1.1$

<table>
<thead>
<tr>
<th>$\theta$ [°]</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{R}_q \pm (2\sigma \times t_n)$ [nm]</td>
<td>10.59 ± 4.72</td>
<td>10.64 ± 4.73</td>
<td>10.70 ± 4.77</td>
<td>10.77 ± 4.80</td>
<td>10.85 ± 4.84</td>
<td>11.25 ± 4.46</td>
<td>11.66 ± 3.92</td>
<td>11.81 ± 3.97</td>
<td>12.18 ± 4.92</td>
</tr>
<tr>
<td>$\overline{R}_q \pm (2\sigma \times t_n)$ [nm]</td>
<td>12.36 ± 4.99</td>
<td>12.79 ± 5.51</td>
<td>13.03 ± 5.60</td>
<td>13.28 ± 5.72</td>
<td>13.77 ± 6.76</td>
<td>14.35 ± 7.19</td>
<td>15.00 ± 7.18</td>
<td>15.64 ± 7.86</td>
<td>16.09 ± 8.09</td>
</tr>
</tbody>
</table>

Table 3 and Table 4). We expand the normal standard deviation parameter with the confidence level 68.3% by the Student-Fisher coefficient ($t_n = 7 \Rightarrow 1.1$), 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 $R_q$ 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 $n = 7 \Rightarrow t_n = 1.1$

<table>
<thead>
<tr>
<th>$\theta$ [°]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\overline{R}_q \pm (2\sigma \times t_n)$ [nm]</td>
<td>132.75 ± 0.07</td>
<td>139.20 ± 0.08</td>
<td>151.14 ± 0.09</td>
<td>170.03 ± 0.13</td>
</tr>
</tbody>
</table>

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

![Fig. 4. $\overline{R}_q = f(\theta)$ for the tested mirror ($M\#1$). Line is a $x^2$ approximation](image)

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

![Fig. 6. $R_q = f(\theta)$ for the tested steel plate ($S\#1$). Line is a $x^2$ approximation](image)
3.4. Complex measurement errors. According to (2), roughness parameter $R_q$ is a complex function. Maximum error of individual $R_q$ parameter $\Delta R_q$, can be described as follows (6):

$$
\Delta R_q = \left| \frac{\partial R_q}{\partial \theta} \right| \cdot \Delta \theta + \left| \frac{\partial R_q}{\partial P_0} \right| \cdot \Delta P_0 + \left| \frac{\partial R_q}{\partial \lambda} \right| \cdot \Delta \lambda,
$$

where:

- \( \Delta \theta = 1^\circ \approx 0.01745 \text{ rad} \) – rotation stage accuracy,
- \( \Delta P_0 = \Delta P_{\text{spec}} \approx 0.048 \mu W \) – accuracy of the incident and specular beam power (from a scope resolution),
- \( \Delta \lambda = 10 \text{ nm} \) – wavelength accuracy.

The total maximum roughness parameter error $\Delta R_q$ is given by (7):

$$
\Delta R_q = \left| \frac{\lambda}{4\pi \cos \theta} \ln \left( \frac{P_0}{P_{\text{spec}}} \right) \tan \theta \right| \cdot \Delta \theta + \left| \frac{\lambda}{8\pi \ln \left( \frac{P_0}{P_{\text{spec}}} \right) \cos \theta} \right| \cdot \Delta P_0 + \left| \frac{-\lambda}{8\pi \ln \left( \frac{P_0}{P_{\text{spec}}} \right) \cos \theta} \right| \cdot \Delta P_{\text{spec}} + \left| \frac{\lambda}{4\pi \cos \theta} \right| \cdot \Delta \lambda.
$$

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

$$
\Delta R_q = [0.04 \cdot 0.01745 + 0.17 \cdot 0.048 \cdot 10^{-6} + 0.18 \cdot 0.048 \cdot 10^{-6} + 0.22 \cdot 10 \approx 0.6 \text{ nm},
$$

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 $\bar{R}_q$ 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 $2\sigma$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\bar{R}_q \pm 2\sigma$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M#1$</td>
<td>12.60 \pm 5.94</td>
</tr>
<tr>
<td>$M#2$</td>
<td>15.68 \pm 3.37</td>
</tr>
<tr>
<td>$S#1$</td>
<td>148.28 \pm 28.88</td>
</tr>
<tr>
<td>$S#2$</td>
<td>147.26 \pm 28.80</td>
</tr>
<tr>
<td>$S#3$</td>
<td>150.65 \pm 29.33</td>
</tr>
<tr>
<td>$S#4$</td>
<td>155.03 \pm 30.20</td>
</tr>
<tr>
<td>$S#5$</td>
<td>147.09 \pm 28.61</td>
</tr>
<tr>
<td>$S#6$</td>
<td>142.50 \pm 26.01</td>
</tr>
<tr>
<td>$S#7$</td>
<td>143.40 \pm 27.87</td>
</tr>
</tbody>
</table>

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-\( \mu \)m 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


