Roughness measurement using optical profiler with self-reference laser and stylus instrument — A comparative study

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Roughness is measured by two techniques namely optical profiler with self reference laser and stylus type instrument on roughness samples of nominal roughness average \( R_a \) values 0.174, 0.610 and 1.77 \( \mu m \) have been reported. Roughness parameters \( R_a \) and \( R_z \) are measured by these two techniques. It has been observed that the results obtained by them are in good agreement within the uncertainty of measurement for roughness standards of nominal values 0.610 and 1.77 \( \mu m \). However for a nominal roughness 0.174 \( \mu m \), there is a disagreement between the results of optical and stylus measurements and is much beyond the uncertainty. Comparison and analysis of measurements carried out by these two methods reveal that this may be attributed to stylus radius.

Keywords: Surface texture, Optical profiler, Stylus profiler, Nanometrology

1 Introduction

Surface texture is a key factor affecting the functionality and reliability of components. Surface measurement can be a diagnostic tool for monitoring the processes that produced the component. For example, the effectiveness of a grinding process can be gauged by the surface texture of the ground part.

The surface roughness is an important parameter for evaluating the material surfaces since it directly affects the optical/mechanical properties of the materials. Surface roughness determines the friction and amount of lubricant a surface can hold and thus is a quality determining factor in mechanical parts and components. It is also important in determining the amount of scattering from optical parts. Surface roughness characterization is also of much interest in the magnetic storage area where the roughness of magnetic tape, floppy disks, hard disks, and magnetic heads is very important.

Characterization of surface topography is important in applications involving friction, lubrication and wear. In general, it has been found that friction increases with average roughness. Roughness parameters are, therefore, important in applications such as automobile brake linings and floor surfaces. A wide range of methods have been developed for measuring surface texture to the extent that it is difficult to sort out their various strengths and limitations to ascertain which methods are suitable for which measurement applications. There are many diverse techniques that can be employed to relate the surface profile to the physical effect used in their measurement. The techniques used can be generalized into two categories; contact and non-contact methods.

The contact or stylus methods involve dragging a measurement tip across the surface whereas non-contact methods are based on imaging and microscopy principle. Stylus profilers are more commonly used by the industries and are calibrated with the help of calibration standards. Non-contact methods are based on optical techniques and are fast and offer aerial measurement of surface. Traceability in such methods is achieved through interferometry.

In the recent years, there have been several reports on comparative studies between optical and contact method. Vorburger et al. have studied roughness samples in range of 50 to 300 nm using these two methods. Under optical method they used vertical scanning white light interferometry (WLI) and phase shift interferometry (PSI). They reported that there are discrepancies between WLI and the stylus method. In some cases the reported discrepancy was as large as about 75% of the value obtained with the stylus method. By contrast, results of PSI over its expected range of application (nominal roughness 14 to 103 nm) are in good agreement with those of the stylus method.

Thus it is important to understand the correspondence of roughness measurement by optical
and stylus methods. In this paper, we present and compare the results of roughness measurement on roughness standards of nominal \( R_a \) values 0.174, 0.610, and 1.77 \( \mu \)m using optical and stylus profilers and effort has been made to understand the difference between these two methods.

2 Experimental Procedure

2.1 Instruments used and their traceability

Roughness samples 1, 2 and 3 of nominal \( R_a \) 0.174 \( \mu \)m, 0.610 \( \mu \)m, 1.77 \( \mu \)m, respectively and a gold coated mirror were measured by a 3D optical profiler (Wyko NT9800) using vertical scanning interferometry (VSI) mode and stylus profiler (Perthometer S6P). The traceability hierarchy of optical and stylus profilers is shown in Figs 1(a) and 1(b), respectively.

The 3D optical profiler is equipped with a He-Ne (633 nm) laser interferometer for calibration of \( z \)-scan with traceability to SI unit meter. In VSI, white light LED along with interferometric objective is used to form interference fringes, for this reason VSI is also sometimes called WLI. The interferometric objective moves vertically to scan the surface at varying heights. The system scans through focus as the camera capture the frame of interference data at evenly spaced intervals. The system uses series of advanced computer algorithms to demodulate the interference data. Finally the vertical position corresponding to the best focus i.e. peak of the interference signal is extracted for each point on the surface. This gives the information in the form of pixel by pixel data. This information is processed to obtain a three-dimensional picture of the test sample for further analysis. Software that accompanies the profiler calculates roughness parameters for the measured samples from this data. The vertical resolution of this instrument is 0.1 nm however the lateral resolution is a function of the magnification objective and for 10X magnification objective it is 635 nm.

Contact method measurements were taken by stylus profiler having tip radius of 5 \( \mu \)m. The stylus profiler senses the surface height through mechanical contact where a stylus traverses the peaks and valleys of the surface with a small contacting force. The stylus position depends mainly on repulsive mechanical contact with the surface. The stylus method is directly sensitive to surface height with little interference. The vertical motion of the stylus is converted to an electrical signal by a transducer, which represents the surface profile \( Z(X) \). The vertical resolution of this profiler is 10 nm. The lateral resolution is limited by the size of the stylus tip. Traceability of stylus measurements is achieved by calibrating the instrument using calibrated artifacts. In our case a groove depth, calibrated with traceability to SI unit metre, was used to calibrate vertical movement of the stylus. The measured value is compared with the certified value and correction factor is applied.

2.2 Measurement details

For contact method the measurements were taken by stylus profiler (Perthometer S6P) having tip radius of 5 \( \mu \)m. The traced length was set at 5.6 mm with a cut off length 0.8 mm. The surface was evaluated by averaging ordinates over a length of 4 mm. Five profiles were recorded and \( R_a \) value was estimated from average \( R_a \) of line profile using the following formula:

\[
R_a = \frac{1}{N} \left( \sum_{i=1}^{N} |Z_i| \right) \quad \text{(1)}
\]

where \( N \) is the number of data points of the array in horizontal direction and \( Z \) is the surface height relative to the reference mean plane.

The average of five profiles is taken to represent roughness of surface. The measurements were also taken using optical profiler at magnification objective 10X having field of view 0.860×0.650 mm\(^2\) with pixel size 635 nm and 4 mm×4 mm area was covered using stitching algorithm. The optical profiler’s software processes the data of surface image to calculate roughness. This three-dimensional roughness calculated from image is given by\(^7\):

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Fig. 1 — Traceability of (a) stylus and (b) optical profiler measurement
\[ S_a = \frac{1}{NM} \sum_{i=1}^{N} \sum_{j=1}^{M} |Z_{ij}| \]  \hspace{1cm} \ldots (2)

where \( Z_{ij} \) is array of \( N \times M \) points in a topographic image. However, line by line profiles can also be processed using stylus option in software of optical profiler. In this option Eq. (1) is used for \( R_a \). We used this option to calculate \( R_a \) and \( R_z \) parameters.

The parameter \( R_z \), average maximum height of the profile, is calculated from the average of ten highest and ten lowest point in the data set for both the methods and calculated using the following equation:

\[ R_z = \frac{1}{10} \left[ \sum_{j=1}^{10} H_j - \sum_{j=1}^{10} L_j \right] \]  \hspace{1cm} \ldots (3)

where \( H_j \) are the highest points and \( L_j \) are the lowest points found in the dataset.

### 3 Results and Discussion

Figures 2(a,b), 3(a,b), 4(a,b) and 5(a,b) show the 2d profiles of roughness standard sample 1, sample 2, sample 3 and gold coated optical flat as recorded by optical and stylus profilers. It can be seen from these profiles that these are very similar in profile. Figures 6(a, b, c) show the 3D view of roughness standards sample 1, sample 2 and sample 3, respectively. Tables 1 and 2 present the values for roughness parameters \( R_a \) and \( R_z \) for roughness samples as observed by optical profiler and stylus profiler and Table 3 shows the deviation (stylus value-optical value) of the results. Table 4 shows the...
measurement taken on gold coated mirror by both methods. Uncertainty in measurement given in Tables 1 and 2 is expanded uncertainty calculated as per ISO GUM at coverage factor $k=2$, which for a normal distribution corresponds to confidence interval of approximately 95%.

It can be seen from Table 3 that the deviation between the results, obtained by optical (VSI) and stylus measurements, is within the 6% uncertainty of stylus instrument for roughness standard samples 2 and 3 of nominal values 0.61 and 1.77 μm, respectively. However, for sample 1 of nominal roughness 0.174 μm, there is a significant discrepancy between the results of optical and stylus measurements (up to 27% approx). Vorburger et al. also reported a discrepancy in roughness $S_a$ measured by WLI and $R_a$ measured by stylus profiler. This discrepancy may be attributed approximation of profile by finite size of stylus. In case of stylus profiler a tip is moving on the surface. Stylus profiler will show lower value for valleys as it cannot reach the bottom of narrow valleys. This may be the one of the reasons of the difference for lower roughness. If surface is very smooth, there are no valleys that can be missed by stylus, and this discrepancy will diminish. To confirm this we took measurement on
smooth surface (gold coated optical flat) using stylus and optical (VSI) methods. As seen from Table 4, in this case the values of $R_a$ are 9.3 and 10 nm using optical profiler and stylus profiler, respectively. Thus there is a good agreement between $R_a$ measured by VSI and stylus method.

### Table 3 — Deviation (stylus – optical) from values obtained by stylus method

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Deviation $R_a$ (µm)</th>
<th>% Deviation</th>
<th>Deviation $R_z$ (µm)</th>
<th>% Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>-0.017</td>
<td>10</td>
<td>-0.376</td>
<td>26.67</td>
</tr>
<tr>
<td>Sample 2</td>
<td>-0.014</td>
<td>2.37</td>
<td>-0.12</td>
<td>4.33</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.094</td>
<td>5.44</td>
<td>0.5</td>
<td>5.40</td>
</tr>
</tbody>
</table>

### Table 4 — Measurements taken on gold coated optical flat by optical and stylus profilers

<table>
<thead>
<tr>
<th>Method Parameter</th>
<th>Using optical profiler</th>
<th>Using stylus profiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average of 5 runs</td>
<td>9.30 µm</td>
<td>1.49 µm</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.096</td>
<td>0.050</td>
</tr>
</tbody>
</table>

4 Conclusions

Roughness samples of nominal roughness average $R_a$ values 0.174, 0.610 and 1.77 µm have been measured by two techniques optical profiler with self reference laser and stylus type instrument. The comparative study reveals that results of roughness measurements by stylus and VSI agree within the uncertainty limit for higher roughness. As the roughness becomes lower, valleys and peaks become narrower and spacing between these is lesser than the stylus tip radius, the stylus cannot probe the valley fully. This leads to the significant discrepancy between the stylus and optical measurement results. However, when surface is very smooth the values obtained by optical (VSI/PSI) and stylus measurements are very close.

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#### References