The concept of a virtual roughness tester

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1. Introduction

For the calibration of roughness testers various methods are available which are prescribed in international standards [1,2]. However, from a calibration of a roughness tester it is not evident what the uncertainty will be in a measured roughness of a product, with a deliberate roughness profile. On the other hand, international standards require that for a proof of the conformance to specifications, the measurement uncertainty must be taken into account (ISO 14253-1 [3]). In principle it is possible to vary all measurement conditions by experiment (stylus tip diameter, measuring force) to estimate the influence of the uncertainty of these measurement parameters on the calculated roughness parameter [4,5]. This however requires many different measurements for each sample and this cannot be demanded of shop-floor measurements.

To solve this problem, the concept of the virtual roughness tester is proposed, where a measured roughness profile is re-calculated many times with varying measurement conditions so that for each parameter a complete uncertainty evaluation is made which satisfied all requirements of e.g. the GUM or EAL-R2 [6].

2. Traceability in roughness measurements

Traditionally, the traceability of roughness amplitude parameters, such as Ra, is considered to be basically dependent of the calibration of the z-axis (ordinate) of the measured profile. For this calibration, groove standards are considered as the highest level standards as they can be calibrated by interferometry where via the light wavelength the traceability to a primary (laser-wave-) length standard is achieved.

With a calibrated groove-depth standard a roughness tester is calibrated and with this calibrated roughness tester it is considered that calibrated measurements of workpieces can be done. However, in general no answer can be given to the question of what the uncertainty is in any measured product, which is quite contrary to the concept of traceability. This situation is similar in the field of the
metrology of co-ordinate measurement machines (CMM's), where methods exist to 'calibrate' a CMM but the question about the uncertainty in a measurement carried out with this CMM is not easy to answer [7]. This situation is depicted in Table 1 where it is shown that despite all efforts the ultimate goal: to determine the uncertainty in a roughness measurement of a workpiece is not (or seldom) achieved.

Table 1. Traceability chain and typical uncertainties in the field of roughness measurements

<table>
<thead>
<tr>
<th>Typical uncertainty in Ra</th>
<th>National standards laboratory</th>
<th>Accredited laboratory</th>
<th>Workshop laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength calibration of interference microscope</td>
<td>&lt; 0,01%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration of groove-depth standard</td>
<td>2 nm + 1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration of standard-roughness tester</td>
<td>5 nm + 2%</td>
<td>5 nm + 2%</td>
<td></td>
</tr>
<tr>
<td>Calibration of type C or D roughness standard</td>
<td>5 nm + 4%</td>
<td>5 nm + 5%</td>
<td></td>
</tr>
<tr>
<td>Calibration of workshop roughness tester</td>
<td></td>
<td>10 nm + 8 %</td>
<td>10 nm + 8 %</td>
</tr>
<tr>
<td>Measurement of workpiece roughness</td>
<td></td>
<td></td>
<td>??</td>
</tr>
</tbody>
</table>

The reason of the question marks in the last column is that the result of a roughness measurement depends on much more than just the z-axis calibration. These factors are mentioned in the next section.

3. Conditions which influence roughness parameters and their calibration

Where the nominal conditions of the roughness tester and the applied filter are fixed in written standards [2,8], possible deviations in any of these conditions will more or less influence the roughness parameters. For some conditions the influence is obvious: e.g. the amplitude parameter Ra is directly proportional to the calibration factor of the z-axis. Therefore much effort is spent to calibrate the roughness tester for this influence properly, as it is indicated in the previous section. For other conditions, e.g. the probe radius, this relation is less clear and depends on the measured profile. The general procedure is that a parameter is calculated according to the nominal (measured) profile under the nominal measurement/filtering conditions, the parameter is re-calculated according to the nominal conditions plus the uncertainty in the conditions and the difference is taken as a measure of the uncertainty in the parameter.

The conditions which are taken into account in re-calculating the profile and its related parameters are:
• calibration of z-axis (ordinate)
The uncertainty in the calibration factor directly influences any amplitude parameter, but not spacing parameters or dimensionless parameters.

• calibration of x-axis (abcissa)
The uncertainty in the calibration factor directly influences any spacing parameter, but hardly amplitude parameters or dimensionless parameters (only via the filtering).

• cut-off long wavelength $\lambda_c$
May influence any parameter. To determine the actual cut-off wavelength and the actual filtering characteristics a 'moving-table' like apparatus can be used. An alternative is that a profile which contains sharp peaks is measured both filtered and unfiltered and that the amplitude spectra are compared.

• cut-off short wavelength $\lambda_s$
The influence of this condition depends strongly on the fine-roughness of the sample and on the used stylus-tip radius. It can be determined in basically the same way as $\lambda_c$.

• stylus tip
The stylus tip radius can be measured using a microscope or by measuring an uncoated razor blade. Obviously, measurements can not be re-calculated with a smaller stylus tip radius, so for this case the profile is only recalculated for a larger stylus tip.

• measuring force
The measuring force can be calibrated using a balance. A proper tip and a proper measuring force should give a small regular trace in aluminium and certainly no scratch in a steel surface.

• step size
The step-size (or sampling rate) is taken as 0,5 $\mu$m here, like it is prescribed in the standard.

• software
Improper calculation and rounding errors may cause deviations. A useful method to check roughness software is to generate data-files containing signals of which the parameters can be determined analytically, such as sinusoidal, triangular and block-type signals. The filter-function can be checked by Fourier analysis on both the raw and filtered signal, or by considering a peak-response.
4. Example of a measurement and an uncertainty calculation

In this section we give as an example the measurement and the uncertainty calculation for a few parameters of a Rubert-Song type 2 roughness standard [9], carried out with a Mitutoyo type SVC-624-3D roughness tester. This is a rather smooth ISO 5436-1 [10] type D standard with a profile which repeats each 5 cut-off wavelength of 0.25 mm so it becomes homogeneous for many roughness parameters when evaluated over 5 cut-off lengths. In figure 1 are given: the profile, its amplitude spectrum and its autocorrelation function. The peak in the latter at 1.25 mm illustrates the repeating of the profile, which is hard to observe directly.
The profile is re-calculated many times with slightly different measurement conditions. In fact this simulates the measurement of the profile with many different 'virtual' roughness testers. This only takes a fraction of a second and it is no extra effort for the user, once the uncertainties in the measurement conditions are fixed. This enables the on-line determination of the uncertainty of any parameter of any surface without any extra effort for the user.

In the table below the result is given of a measurement of a Rubert-Song type 2 roughness standard, carried out with a Mitutoyo type SVC-624-3D roughness tester. The indicated uncertainties are mostly due to the calibration method, the roughness tester itself is not yet exploited to its full capabilities. Note that the calibration of the z-axis, traditionally taken as the major contributor to the uncertainty of Ra or Rz, is not the dominant influencing factor to the uncertainty.

Table 2: uncertainty budget of a Rubert-Song [9] roughness standard

<table>
<thead>
<tr>
<th></th>
<th>nominal uncertainty</th>
<th>uncertainty Ra 28,3 nm</th>
<th>uncertainty Rz 172 nm</th>
<th>uncertainty RSm 14 µm</th>
<th>uncertainty Rsk 0,411</th>
</tr>
</thead>
<tbody>
<tr>
<td>x-axis</td>
<td>1</td>
<td>1%</td>
<td>0</td>
<td>0,14 µm</td>
<td>0</td>
</tr>
<tr>
<td>z-axis</td>
<td>1</td>
<td>1%</td>
<td>0,28 nm</td>
<td>1,72 nm</td>
<td>0</td>
</tr>
<tr>
<td>λc</td>
<td>0,25 mm</td>
<td>2%</td>
<td>0,05 nm</td>
<td>0,31 nm</td>
<td>0,4 µm</td>
</tr>
<tr>
<td>λs</td>
<td>2,5 µm</td>
<td>20%</td>
<td>0,43 nm</td>
<td>3,1 nm</td>
<td>0,3 µm</td>
</tr>
<tr>
<td>F</td>
<td>1 mN</td>
<td>50%</td>
<td>0,02 nm</td>
<td>0,16 nm</td>
<td>2,3 nm</td>
</tr>
<tr>
<td>radius</td>
<td>2 µm</td>
<td>50%</td>
<td>0,10 nm</td>
<td>0,8 nm</td>
<td>0,1 µm</td>
</tr>
<tr>
<td>stepsize</td>
<td>0,5 µm</td>
<td>100%</td>
<td>0</td>
<td>1,5 nm</td>
<td>0,2 µm</td>
</tr>
<tr>
<td>total</td>
<td>(1s)</td>
<td></td>
<td>0,60 nm</td>
<td>4,4 nm</td>
<td>0,6 µm</td>
</tr>
</tbody>
</table>

So for this specimen the results are, with the uncertainty expressed as two standard deviations:

\[
\begin{align*}
Ra &= 28,3 \pm 1,2 \text{ nm} \\
Rz &= 172 \pm 9 \text{ nm} \\
RSm &= 14,2 \pm 1,2 \text{ nm} \\
Rsk &= 0,411 \pm 0,028
\end{align*}
\]

Not yet incorporated are the effects of noise and the inhomogeneity of the sample.
5 Conclusion

We have shown that the concept of a virtual roughness tester enables the estimation of the uncertainty of any roughness parameter of any profile, and enables traceable shop-floor measurements which were not possible before.

6. Acknowledgement

This research is supported by Mitutoyo Nederland B.V.

7. References

[2] ISO/DIS 12179. ‘Calibration of contact (stylus) instruments’