How reliable are surface roughness measurements of micro-features?
- Experiences of a Round Robin test within nine 4M laboratories

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Abstract
Surface roughness of tiny micro machined features is not easy to verify. The statistical variation of the surface itself can be the limiting factor that hampers tolerance verification. In this paper we have studied this effect and we also test the performance of 10 different surface profilers over a very well specified surface area. For this area 6 profilers yielded the same result within a standard deviation window of ±6%. For other areas, on top of narrow bars and in narrow and deep channels, a much larger spread in the Round Robin results was found.

Keywords: Surface roughness, Micro metrology, Round robin, Surface profiler, Ra, Pa

1. Introduction
The 4 M Multi Material Micro Manufacture Network of Excellence has proven to be an excellent forum for testing procedures and throwing light on non-standardised metrology issues of micro components. In a first test round we found that large variations in surface roughness measurements existed among the partners in the Polymer and Metrology divisions. Also, the dimensional measurements of the micro ridges of four metal inserts were far from a complete overlap when the results were analysed. This first test was quite open and gave no detailed instructions to the instrument operator on how to perform the measurements, as the intention was to get an idea of the measurement praxis at the different laboratories and if it is good enough to provide reliable and accurate data. The result was negative. Even on a simple ground metal surface the spread in surface roughness values was astonishing, and the width and height measures of the micro structures departed significantly depending on what lab did the measurement.

As already pointed out in the review paper on micro metrology challenges\cite{1} severe problems arise when surface roughness is to be assessed on tiny surfaces, as the entire concept of ISO standardised line profile based Ra, Rz, Rq, Rp, Rv parameters rely on long traces - by default seven times the sampling length including a start and a stop length. For a surface roughness of about 1 µm the standardised sampling length is 0.8 mm, which means a need to access a default line profile of 5.6 mm. This is far from acceptable and contradictory to the reality of many micro components. The updated ISO standards 4287 [2] and 4288 [3] give the opportunity to specify primary profile based parameters Pa, Pz, Pq, Pp, Pv – values instead, where sampling length, i.e. the measured length along the surface, can be set to an arbitrarily determined length adapted to the surface feature being measured, as long as it is stated with the measured values. The primary profile is by default only filtered by the short wavelength cut off at 2.5 µm, i.e. it is not suitable for sub-micron feature roughness determination like measurements with atomic force microscopes.

If a non-skilled operator just put the sample on the measurement table and pressed the Ra measurement button the risk is obvious that totally wrong results will come out of the instrument. It is therefore absolutely necessary to have well educated instrument operators when micrometer sized features are to be measured.

After the initial metrology Round Robin on several injection mold inserts, it was obvious that a much more strict measurement description was needed and only one insert, milled at MEC Cardiff, was chosen for the Metrology Round Robin presented in this paper.

2. Equipment and artefact
2.1. Equipment
The instruments used for roughness
measurements in the Round Robin were all commercial instruments; four optical profilers based on white light interferometry (WLI), two confocal microscopes, one autofocusing profiler, one chromatic focusing profiler and two stylus profilers. Each instruments have its own calibration gauge delivered with the instrument for traceable verification of its performance. Nine different laboratories participated in the surface roughness Round Robin, while only five managed to fulfil the dimensional measurements.

2.2. Artefact

For the Round Robin testing of surface roughness on true 3D micro-features we have to rely on our own artefact, as ISO certified roughness gauges are meant to yield the same value all over the surface, and would not reveal the lateral micro feature size influence that might exist. The artefact, shown in Fig. 1, is a steel insert made by mechanical micro milling. The structure contains three 100 µm high Ø 3 mm plateaus connected with 100 µm high ridges of nominally 20, 50 and 75 µm widths. The ground surface of the middle plateau was selected as test area (2a – 2c) for as-good-as-possible surface roughness inter-comparison measurement. Pos 3 and 4 reveal the roughness reproducibility on top of the 75 µm ridge and at the bottom of the 150 µm wide and 100 µm deep channel respectively. Six alignment holes were laser drilled 300 µm apart as shown in Fig.2 for x,y localization of measurement traces. The arrows in Fig. 1 show the profiling directions.

At position 2a, 2b and 2c the surface profile was recorded from hole to hole and the 250 µm sampling length centred between the holes is used for calculating the P-parameter values for each profile. At position 3, five consecutive 250 µm long profiles were recorded along the nominally 75 µm wide ridge starting at the laser drilled hole pair to the left. The same procedure was done at position 4, at the nominally 150 µm wide bottom level surrounded by the two 100 µm high ridges. For the stylus profilers this structure was critical as the cone angle of the stylus limits the positioning tolerances to some ten microns sideways. It was also evident that there were some burrs left at the bottom from the milling operation, as seen in Fig.3.

3. Measurement procedure

3.1. Parameter selection

As discussed in the introduction the surface roughness parameters to be preferred in micro-metrology are the P-parameters based on primary profile data introduced in ISO 4287:1997[2] By default P parameters are evaluated over the feature size, but P-values can just as well be stated with a clearly defined measurement length that can be set in accordance with the feature to be measured.

Based on these facts the Round Robin parameters to be measured were stated as Pa – arithmetic mean deviation of the assessed profile, Pq – root mean square deviation of the assessed profile (equivalent to the standard deviation of the surface structure), Pv – maximum profile valley depth, Pp – maximum profile peak height and Pz – maximum height of profile.

However, in order to compare the output of instruments having the options of both P and R parameters, Ra, Rq, Rv, Rp and Rz were also requested, but just for one single sampling length of 250 µm. In most figures to follow Pa is used as it corresponds to the common Ra values. Pq which measures the standard deviation of the surface structure is a bit more sensitive than Pa to larger pits and bumps.

3.2. Round Robin Measurement instruction

A thorough checklist and measurement protocol was provided with the metal insert sample for the
measurements. The checklist, from which excerpts are given here, was aimed to standardise the Round Robin measurements between the different metrology labs, and to eliminate possible mistakes.

**General sample handling remarks:**
Keep the sample in the delivery container as long as possible to prevent particle contamination. Do not touch the insert with your fingers!! Wear clean dust free gloves! After measurement secure the insert safely in the delivery container, for transportation to next partner.

**Sampling length and filtering:**
For the analysis we make use of a single sampling length of 250 µm. The measured and stored profile length might be larger, e.g. to cover the laser drilled holes. For terminology and parameters refer to EN ISO Standard 4287:1998.

If possible operate the instrument with minimum filtering in the measurements, and perform the analysis of the 250 µm sampling lengths for the P-parameters and R-parameters as advised in the table.

**Roughness measurement at position 2**
Alignment marks have been laser drilled into the surface of the flat at the pos. 2 area according to figures 1 and 2. They are positioned in pairs, referred to as 2a, 2b and 2c, with a centre-centre distance of approximately 300 µm. Surface profiles must be measured between these indentations from left to right approximately 300 µm. Surface profiles must be surface of the flat at the pos. 2 area according to and R-parameters as advised in the table.

**Analysis of measurements at position 2**
Load the measured profile, 2a_1FL, and locate the centre point between the two indentations. Go 125 µm towards the beginning of the profile from the center point and select that as the start point of your analysis. From this point let the instrument make a calculation of primary profile parameters Pa, Pq, Pz, Pp for 250 µm (try also Ra1, Rq1, Rz1, Rv1, Rp1 for a single cut off length of 250 µm). Note the values in the enclosed table. Repeat the analysis process for the other measurement positions.

**4. Measurement results and discussion**

4.1. Surface roughness at Position 2
A typical surface profile, recorded at position 2b by the KTH Talystep stylus profiler [4] is shown in Fig. 4. The entire profile length is 500 µm and the two laser drilled holes appear well in the ± 3 µm height scale. From the profile in Fig. 4 the mid point between the laser drilled holes is determined and a 250 µm long profile centred at this midpoint is saved for parameter evaluation. By repeating the trace three times with a side-shift of ± 8 µm, i.e. perpendicular to the trace of the stylus, the variation in Pa and Pq were found to be about ±1% at position 2a and 2b, while 2c was close to 4%. The reason for the latter was a pit at the beginning of the profile and a shift of just a few micrometers in and out of this pit changed the Pa and Pq values by 24 nm and 33 nm respectively. For the Pz values measuring the maximum peak to valley height over the entire 250 µm the variations in 2c were up to 9% while 2a and 2b were less than 4%.

In Fig. 5 the Pa results are shown with the standard deviations of 0.9 - 3.8 % obtained at position 2a-2c. This is the variation we can expect in a very well localised area, in this case within 16 µm x 250 µm. By taking all profiles obtained from the three positions 2a, 2b and 2c we get a standard deviation of 14% (see Fig 5) over the area 600 µm x 250 µm, i.e. almost one order of magnitude larger variation than when measurements were kept within a width of 8 µm.

![Fig. 4. Surface profile at pos. 2b. Scale in µm.](image)

By making the measurement more random but still aligned with the measurement direction of 2a -2c at five different places within the 3mm feature size, the standard deviation is increased by a factor of two to 29%. Still, the average Pa values for the random (0.39 µm) and 600 µm x 250 µm areas (0.39 µm) agree very well. This shows the strong influence of surface structure variation when different areas of a surface are measured within short sampling lengths and it is the reason for the ISO-standard recommendation [3] of measuring over 800 µm sampling length for the Ra roughness interval of 0.1 – 2 µm. This exercise shows in a nutshell that inter-comparison measurements for short sampling lengths on rough surfaces are bound to be very uncertain due to the statistical nature of the roughness. That is also to say that a roughness specification on a rough but laterally tiny surface is almost impossible to verify with a reasonable uncertainty.

In Fig. 6 we present the Pa roughness values over 250 µm obtained with ten different profilers at position 2a. The spread of the measurements for each instrument represents the repeatability and is indicated by the line marks at the top of each bar. They are quite small, in agreement with what was obtained in Fig. 5 for the 2.7 µm stylus radius. The variation among the different instruments can not be attributed to the surface variation, but has to be related to the differences of profile interpretation among the different
producers used in the 4M laboratories. To achieve this surface roughness values $p_a$ were found for 60% of the
In conclusion we have found that good agreement of
5. Conclusion
60° cone angle will inevitable hit it.

The Round Robin results obtained at position 3 and 4 are shown in Figs. 7 and 8. At position 3, on top of the nominally 75 $\mu$m bar the most striking features are the outliers of the chromatic and the first WLI profilers in addition to the autofocus and the 4th WLI. No obvious explanation has been found so far for the two new outliers. The $p_a$ measurements at position 4 between the two 20 $\mu$m wide and 100 $\mu$m high bars separated by nominally 150 $\mu$m challenged the profilers as seen in Fig. 8. The 5 $\mu$m radius stylus and the chromatic profiler did not work it out, and the variation from one 250 $\mu$m profile to the other were very large. The reason has already been shown in Fig. 3 and is caused by remaining burrs in the deep channel. Some operators of the WLI and confocal microscope profilers have been able to avoid the burrs while e.g. the 2.7 $\mu$m stylus with 60° cone angle will inevitable hit it.

5. Conclusion
In conclusion we have found that good agreement of surface roughness values $p_a$ were found for 60% of the profilers used in the 4M laboratories. To achieve this level of conformity the measured area had to be well localized and positioned to micrometer accuracy. Some instrument results deviate by large amounts and needs further investigations and probably interaction with the instrument manufacturers to sort out the problems.

Acknowledgements
This paper was compiled with support from EC FP6 NoE on 4M, Metrology and Polymer Divisions.

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