Measurement uncertainty of surface roughness measurement

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Abstract. There are several measurement methods to microgeometric examination of the surfaces machined by different cutting processes. At Department of Manufacturing Technology, Institute of Materials and Manufacturing Sciences, Óbuda University it has a traditional contact (stylus) instrument with related software which is widely used in the industrial practice. All measurements such as the surface roughness are characterized by uncertainties which are essential for accurate measurement of the result since the surface quality is characterized by the obtained roughness measurements. The measurement and the characterization of surface roughness and the method of determining measurement uncertainty are standardized. This article describes the determination and analysis of measurement uncertainty for 2D roughness parameters on surfaces prepared with different cutting methods.

1. Introduction

Characterization of surface irregularities is described by a number of measurement methods which examine the surface from different points of view and provide different information. There are three measuring techniques distinguished divided into two types according to the result such as quantitative and visualization. There are the contact (stylus) measurements, optical measurements and the other technical solutions. Typical measurement methods are to compare with standards, the contact stylus and the optical methods. Laser surface test equipment is used especially for cases where the touch probe would cause surface deformation. [1] The tactile measuring technique plays a central role in technical practice where the surface roughness can be detected with a properly configured touch probe. [2]

Other division for methods of examining surface roughness can be the subjective and the objective method. In the subjective comparison the test surface is compared to the standard one with naked eye, touch, or microscope. This method has only a subordinate role because of its subjectivity. During the comparison it was necessary to ensure that the roughness standard has produced by the same machining method as the surface of the test. Nowadays primarily the profiling testers are used for the objective method which are capable of supplying the characteristics used to determine the surface quality and is also capable of computer data processing. It can be distinguished from the point of view of operation: the fine mechanics, optical, pneumatic roughness measuring instruments.

1.1. The contact stylus measurement
The contact measuring technology plays a central role in technical practice. In this process, the properly
calibrated probe slides over the surface and the signal generated by its motion transformed into an
electric signal. For profilometric surface roughness gauges (in case of profiling), the diamond tip with a
very small (about 1 to 10 µm) round radius is moving at a uniform speed and thus smoothes the
unevenness of the surface. The mechanical design of measuring probes has several types. Manufacturers
offer a plurality of probes (whole series) for a roughness measurement, which can be used to measure
the widest range of surfaces. The selection of the most appropriate touch probe for the specific task
requires a great deal of experience and theoretical knowledge of the person performing the measurement.
The probes are mostly conical or spherical with a few micrometers of rounded end. Preferably selected
enlarged image graphs reflect the nature of the surface and, with sufficient experience and practice, can
be the source of much important information. Advanced surface roughness tools allow you to draw
roughness and ripple profiles as well as unfiltered, undistorted profile views. The so-called diagrams are
almost indispensable for providing a comprehensive microgeometric evaluation. When evaluating,
however, it is important to note that due to the significant difference between vertical and horizontal
magnifications, the representation is distorted.

Like all measurement techniques, this also has its own sources of error that are needed to properly
evaluate the results of the instrument, such as rounding the tip of the probe head, the applied load force,
the touch probe slipping [3].

The rounding radius of the probe tip is given (0.5, 2, 5, 10 µm). This small value also means that the
touch probe is unable to detect smaller openings, gaps and faults, so overwhelm them. Thus, the resulting
surface does not exactly match the original. This error is negligible if the unevenness of the surface
texture is significantly greater than the peak punctuation of the touch probe, but it may be remarkable
to use a high-peak circumferential touch probe for a very fine surface. This can smooth out the surface
to such an extent that our result

For probes that are rigidly attached to the drive structure, the fault may occur - especially for soft
surfaces, under the touch probe. Small load on a small surface can also result in high surface pressure.
Touch probes that are free to move only by self-weight cannot have the same effect [5].

A possible slipping of the touch probe from the test surface may occur as a malfunction. This means
that the non-perfectly rigid probe slides out of the large protrusions, steep edges, and is not perfectly
aligned but is different from that. Thus, the highest measured peaks will be smaller than in reality [6].

These errors are mechanical in nature and only refer to the uncertainties of scanning.

1.2. Microgeometric parameters

The task of roughness metrics is to characterize the surface. The requirement is that if the two
measurements are the same, the "quality" of the two surfaces is the same. Separately, the roughness
measurements are analysed, none of which is appropriate to determine the surface and its operating
conditions. It follows that two, or three, separate metrics describing different characteristics are
necessary to allow the two surfaces to be considered as identical.

The microgeometric characterization of working surfaces is practically measured in two-dimensional
measurement techniques. The concept definitions and characteristics associated with plane (2D)
microgeometric parameters have been standardized at international level. [7] The rules for drawing
specifications for machine parts are contained in ISO 1302 [8]. Although there are national standards,
these are identical to the ISO 4287 [9] and ISO 4288 [10] standards with insignificant technical
differences. Based on these standards, the characteristics can be divided into following main categories:

- amplitude parameters (Ra, Rt, Rz, Rq, Rsk, Rku Rq, Rp, Rv, Re)
- spacing parameters (RSm)
- hybrid parameters (RΔq)
- curves and related parameters (Rmr(c), Abbott Firestone curve, RΔc, Rmr, profile height
amplitude curve)

The determination of 2D parameters is the most widely used in technical practice, and mainly the
elevation parameters are used to determine the surface quality. [11]
Roughness average (Ra) according to the ISO 4287 [9] “is the arithmetic average of the absolute values of the roughness profile ordinates”. It contains low information since the value of Ra is not particularly sensitive to the peaks and recesses of the profile. It does not allow the definition of surface characteristics and provides the least amount of grounding for surface performance. For finely machined surfaces, Ra is unusable as it only shows the average of surface roughness as if the surface roughness of peaks and regular variations of recesses would shape that length. In contrast, this is often used in industrial practice to characterize technical surfaces. [9]

Maximum height of profile (Rz) according to the ISO 4287 [9] “is sum of height of the largest peak height and the largest profile valley depth within a sampling length”. The value of the maximum height of the Rz profile is used to evaluate the homogeneity of the surface but still does not allow the detection of surface characteristics and working conditions.

Mean width of the profile elements (RSm) is spacing parameter. It means according to the ISO 4287 [9] “value of the profile element widths Xs within a sampling length”. This parameter is more closely related to the functional nature of the surface. It shows the specify of the surface from the aspect of adhesion and surface treatment. The kurtosis of the assessed profile (Rku) is amplitude parameter. It is according to the ISO 4287 [9] “quotient of the mean quartic value of the ordinate values and the fourth power of Rq respectively within a sampling length”. This parameter expresses good the pointing of the height distribution. Rku = 3 means normal distribution, if Rku > 3 means the height distribution is sharp and if Rku < 3 the height distribution isn’t sharp.

1.3. Measurement uncertainty
The measurement uncertainty is the quantitative value of the quality of the measurement result, allowing comparability of the measurement result with other results, references, technical characteristics or standards. Moreover, each measurement is charged with error, the measurement result differs from the true value of the measured characteristic. The goal of each measurement is to determine the value of the quantity to be measured. The measurement result is the estimate of the quantity to be measured. This will only be complete if the uncertainty of the measurement is also estimated. Measurement error and measurement uncertainty are not the same definitions. According to the [13] the measurement error is “measured quantity value minus a reference quantity value” and the measurement uncertainty is a “non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used”. Measurement uncertainty contains in general many components. There are two type of the calculation in the GUM [14]:

- Type A evaluation of measurement uncertainty from the statistical distribution of the quantity values from series of measurements and can be characterized by standard deviations.
- Type B evaluation of measurement uncertainty can also be characterized by standard deviations, evaluated from probability density functions based on experience or other information.

The steps of the determination of measurement uncertainty in generally shows the figure 1. The purpose of the calculation is to determine the expanded measurement uncertainty, \( U \). The value of the \( k \) coverage factor is usually 2 which refers to the approximately 95% probability range.
Figure 1. Steps of the determination of measurement uncertainty.

The VDI/VDE 2602 [15] describes the method for calculating measurement uncertainty of contact stylus instruments. The evaluations are consists of two parts:

- Measurement uncertainty of the vertical parameters.
- Measurement uncertainty of the horizontal parameters.

In this study several surface roughness parameters were analysed based on their measurement uncertainties. Turned and milled surfaces with the same nominal Ra values were compared with each other based on the measured Ra, Rz, RS\text{m} and Rku parameters and their associated expanded measurement uncertainty values ($U$). The $U$ of the surfaces turned and milled having different surface quality is determined and compared in pair. The aim of this study it to describe the properties of the uncertainty in case of surface roughness measurements for several manufacturing processes having different cutting parameters.

2. Materials and methods

Comparative standards were chosen for the studies obtained by cutting processes (table 1). Measurements were carried out on milling and turning surfaces, where measurements can be repeated several times. Surfaces had a specific Ra value.

| Sign of surface | Ra (\(\mu\)m) |
|----------------|--------------|
| N5             | 0.4          |
| N6             | 0.8          |
| N7             | 1.6          |
| N8             | 3.2          |
| N9             | 6.3          |

2D-la roughness examinations of surfaces machined with Mahr Perhometer-Concept feeler type instrument have been carried out in the Topography Laboratory of the Department. MFB-250 type feeler
was used, which parameter is 90°/2 μm. The setup used at the evaluation of surfaces according to ISO 4288:1996 standard [10]:

- evaluation length, lm = 4 mm but in case of N9 lm = 12.5 mm
- the prescribed filter, lc = 0.8 mm but in case of N9 lc = 2.5 mm

The measurements were repeated twelve times for each surface under the same conditions and settings. In this study the examined microgeometric parameters were: Ra, Rz, RSm, Rku.

3. Measurement results and evaluation of data

The results of the examinations are presented for each microgeometric characteristic. The mean and the standard deviation of the measured Ra, Rz, RSm and Rku values for turned and milled surfaces can be found in table 2.

Table 2. Mean and standard deviation values of the 12 measurements for each sample (the Ra Diff. data show the difference values from the nominated value of each sample).

| Cutting type | Part | Ra [μm] | Rz [μm] | RSm [μm] | Rku [-] |
|--------------|------|---------|---------|----------|---------|
|              |      | Mean    | StDev   | Mean     | StDev   | Mean    | StDev   |
| Turned       | N5   | 0.3242  | 0.00097 | 1.6633   | 0.0273  | 45.1238 | 0.4670  | 2.1632  | 0.0201  |
| Milled       | N5   | 0.3468  | 0.00083 | 2.1804   | 0.0154  | 123.4524| 11.9323 | 2.8171  | 0.0161  |
| Turned       | N6   | 0.8625  | 0.00174 | 4.4334   | 0.0718  | 66.5180 | 0.9619  | 2.1091  | 0.0062  |
| Milled       | N6   | 0.7658  | 0.00117 | 4.8271   | 0.0197  | 196.0958| 10.4236 | 3.0574  | 0.0102  |
| Turned       | N7   | 1.6240  | 0.00097 | 6.1956   | 0.0342  | 126.7379| 0.0201  | 1.6994  | 0.0010  |
| Milled       | N7   | 1.6576  | 0.00148 | 8.0157   | 0.0155  | 177.4028| 0.0245  | 2.3729  | 0.0015  |
| Turned       | N8   | 2.9751  | 0.00106 | 13.8532  | 0.0397  | 264.2753| 0.1070  | 2.6757  | 0.0024  |
| Milled       | N8   | 3.4848  | 0.00157 | 15.3823  | 0.0349  | 537.7273| 0.0000  | 1.8322  | 0.0007  |
| Turned       | N9   | 7.1840  | 0.00132 | 29.0472  | 0.0241  | 307.5000| 0.0000  | 2.1042  | 0.0007  |
| Milled       | N9   | 5.9220  | 0.01551 | 32.2546  | 0.4966  | 674.1176| 0.0000  | 2.5343  | 0.0157  |

In case of Ra it is seen that the standard deviation is quite low for N5-N8 surfaces for both turned and milled process output. The standard deviation is quite large in case N9 comparing with the previous ones. This is because the Ra values continuously increase during the repeated measurements in case of N9 sample, ranging between 5.9033-5.9301 μm (figure 2).

![Figure 2. Measured Ra values on surface N9.](image-url)
The mean values of the measured surface roughness in case of Ra can be examined comparing with the reference or nominal values of the samples, standards (see table 1). There are differences related to the manufacturing type i.e. the surface was produced by turning or milling machine. The largest differences are in case of N8 and N9 samples which have the largest roughness as well (figure 3).

\[ \text{Figure 3. Measured Ra values minus the nominal Ra values on the examined surfaces.} \]

In case of Rz it is seen that the standard deviation is quite low for N5-N8 surfaces for both turned and milled process output. The standard deviation is quite large in case N9 comparing with the previous ones. The StDev value on the N9 surface increased because that the Rz values continuously increased during the repeated measurements, ranging between 31.6486-32.4661 μm (figure 4).

\[ \text{Figure 4. Measured Rz values on surface N9.} \]

In the case of turning surfaces (N5-N9) the RSm ranged from 45 to 307 μm and the deviation of repeated measurements was rather small. The values of Rku parameter were between 1.7-2.1 on the turning surfaces. The average deviation of repeat measurements was small (0.003).
3.1. Measurement uncertainty calculations

The measurement uncertainty calculation is based on the GUM [14]. In case of this study the Type A uncertainty was taken into account. It is supposed that the Type B uncertainty components such as calibration uncertainty, temperature effect, effects on the environment, measurement set and measurement process have small impact on the data of combined uncertainty. Therefore the standard uncertainty of the measurement is calculated by the statistical analysis of repeated measurements. The standard uncertainty is as follows:

\[ u_c = u_A = \frac{\text{StDev}}{\sqrt{n}} \] (1)

where \( \text{StDev} \) is the standard deviation of the repeated measurement, \( n \) is the number of repetition. In the investigated cases \( n=12 \), therefore it has not to take into account the Student \( t \)-factor.

The expanded measurement uncertainty (\( U \)) is as follows:

\[ U = 2 \cdot u_A \] (2)

Figure 5 shows the calculated extended measurement uncertainty of \( \text{Ra} \) on the examined surfaces. For turning surfaces, the \( U \) value was broadly constant (\( U = 0.0004 \mu m \)) as the standard deviation of repeated measurements were low. In the case of milling surfaces, the \( U \) value showed a roughly constant value on the N5-N8 surfaces and the standard deviation of repeated measurements was small. It can be seen in figure 6 the calculated extended measurement uncertainty of \( \text{Rz} \) on the examined surfaces. For turning surfaces, the \( U \) value was broadly constant (\( U = 0.0045 \mu m \)) as the standard deviation of repeated measurements were low. It can be observed that on the milling surfaces the \( U \) value showed a roughly constant value on the N5-N8 surfaces and the standard deviation of repeated measurements was also small.

![Figure 5. Measurement uncertainty values of Ra.](image1)

![Figure 6. Measurement uncertainty values of Rz.](image2)

The calculated extended measurement uncertainty of \( \text{RSm} \) didn’t change on the examined turning surfaces. For the milling surfaces the \( U \) value was broadly constant (\( U = 0.015 \mu m \)) only the N7-N9 as the standard deviation of repeated measurements were small. The \( U \) value on the N5-N6 surfaces increased (3.0-3.5 \( \mu m \)) the reason being that the \( \text{RSm} \) values definitely changed during the repeated measurements (figure 7).

It can be seen in the diagram (figure 8) that the extended measurement uncertainty is almost constant (0.0007-0.005). In the case of milling surfaces (N5-N9) the Rku ranged from 1.8 to 3 and the deviation
of repeated measurements was rather small (0.0003-0.008) accordingly the value of extended measurement uncertainty has only slightly changed (0.0007-0.005).

3.2. Statistical comparison of roughness values and uncertainties

There are significant differences between the samples (N5…N9) milled and turned. The results of the two sample t-probe show this deviations for all the investigated Ra, Rz, RSm and Rku values. It is seen in figure 9 (for Ra) and in figure 12 (for Rku) that the direction of the deviation is not the same for the each sample. On the N6 and N9 surfaces, due to the difference in the cutting marks, the result of the two roughness parameters differs from that seen on the other surfaces. Since weights repeated the same measurement length twelve times the measurement results didn’t qualify the surface. The reason for this discrepancy is rather to find that the selected line was a surface error that gave this result. In case of Rz (figure 10) and RSm (figure 11) the direction is the same, therefore the value of the roughness parameter is larger significantly in case of milled surfaces.
The Wilcoxon test can show whether there are differences between U values regarding the different manufacturing processes. This test is a nonparametric test therefore could be used for the comparison of these data. The results show that there is no significant difference at 95% level between the cutting processes (figure 13).

**Table 3.** The results of the Wilcoxon test for the expanded measurement uncertainty values in case of Ra, Rz, RSm, Rku between milled and turned surfaces.

| Test of median = 0,000000 versus median ≠ 0,000000 | N for Wilcoxon | Estimated | N | Test | Statistic | P | Median |
|-------------------------------------------------|---------------|-----------|---|------|-----------|---|--------|
| Diff Ra_U 5 5 5,0 0,590 -0,0001465             |               |           |   |      |           |   |        |
| Diff Rz_U 5 5 10,0 0,590 0,003391              |               |           |   |      |           |   |        |
| Diff Rsm_U 5 4 2,0 0,361 -1,366                |               |           |   |      |           |   |        |
| Diff Rku_U 5 5 5,0 0,590 -0,0003416            |               |           |   |      |           |   |        |
4. Conclusion
The aim of the study was to investigate measurement uncertainty in surface roughness, which also shows tangible results for practice. The available probing roughness tester, which is commonly used in industrial practice, is typically used in research tasks. Therefore, it was important to examine the exact reproducibility of the metrics supplied by the weighing machine. Previously, such tests were not performed on this equipment. Two cutting surfaces (turning, milling) were examined on the selected comparative standards. From the processing of the measurement results, we can conclude that the values of extended measurement uncertainty have characterized the individual roughness parameters in a very narrow range. This means that during repeated measurements the measured roughness characteristics are precisely provided.

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