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Analysis of geometrical errors in measurement data of ultraprecise-turned standards for roughness measurements

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Abstract
At the Physikalisch-Technische Bundesanstalt (PTB), ultraprecision machining has been used for the production of standards needed for the calibration of tactile and non-contact measuring instruments for more than two decades. At the physical limits of manufacturing and measuring capabilities, it is sometimes difficult to find the source of an evident geometrical aberration in a measurement result because the sum of the errors of manufacturing and measurement is considered. In this study, the measurement results of a stylus instrument on a diamond turned roughness standard are discussed. Computer generated profiles, which are used for trajectories for ultraprecise turning, are corrected and then compared to the measurement data of a nickel-phosphorus-plated surface. The modelling of the geometrical errors with a morphological operator is a sensible analysis tool. In this study, submicron geometrical errors of the tool are detected in the profile measured by the stylus instrument. Various results are shown to visualize the difficulties in separating the corresponding geometrical errors in the nanometre range. In particular, lateral distortion must be taken into account.

ultraprecision manufacturing, roughness standard, measurement, modelling

1. Introduction

Ultraprecision machining is a powerful instrument for the generation of deterministic roughness artefacts. Nickel-phosphorus-plated discs are diamond turned and cut into pieces by means of wire-electro-discharge machining (W-EDM) and are then finally marked for the correct orientation for the measurements and an ID by means of laser machining, see figure 1. First introduced at PTB in the 1990s, it is a common process chain for calibration standards, e.g. for roughness, depth-setting or resolution, in the way that they have to be transferred into industry by PTB, the German National Metrology Institute. This process chain is also used for numerous investigations for scientific research at PTB [1,2,3].

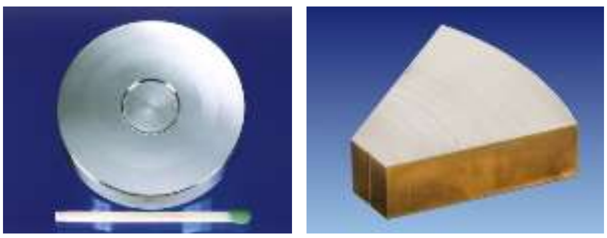

Figure 1. Typical roughness standards manufactured at PTB. Left: turned disc. Right: cut and marked roughness standard.

In a typical process chain, the geometry of the turning tool is taken into account for the generation of the tool path prior to the turning process. In addition to this, after a measurement, a tip correction has to be applied to the measurement data to correct the influence of the tip radius of the stylus instrument. Besides these calculations, both steps are not free of geometrical and random errors and should thus be investigated together.

Figure 2 shows typical simulated data obtained with an ideally circular cutting edge (r_C, tool radius 5 µm) as a black solid curve and a measured line profile as a blue dashed curve (r_t, tip radius 2 µm) in comparison.

In this magnification, the regular repeated pattern can be seen, but no significant difference between the generated and the measured profile is obvious. Enlarging the magnification, several differences can be detected up to more than 200 nm in height, see figure 3. Depending on the targeted roughness data and their mathematical processing, such singular geometrical aberrations may be not significant. This however is important for the understanding of the task and must be interpreted.

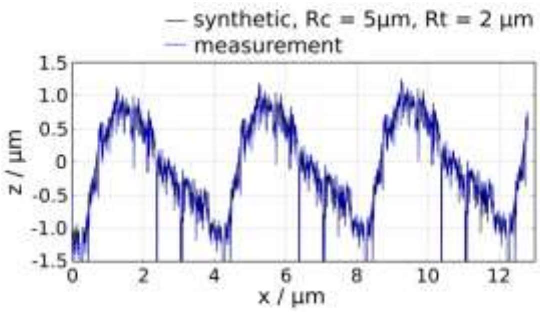

Figure 2. Radial profile on calibration artefact: simulated data obtained with ideally circular cutting edge (black solid curve, r_C=5µm, r_t=2µm); radially scanned profile (blue dashed curve).

2. Methods

To assess and verify profilometric measurements of standardized roughness parameters, artefacts of rough profiles with well-defined deterministic structures representing apparently stochastic rough topographies are employed according to ISO 5436-1. Depending on the roughness quantified by Ra and Rz, specific evaluation lengths are defined in ISO 4288 accordingly. The material standard regarded represents Ra = 0.25 µm and Rz = 2.9 µm, so that the evaluation length has to be ln = 4 mm, as to be applied for Ra/µm in (0.1, 2.0] and Rz/µm in (0.5, 10]. Thus, the design of the one-dimensional topography of the profile has a periodicity of 4 mm in the radial direction and a constant height level in the axial direction. The Moore 250 UPL lathe was used for turning with trajectory interpolation point distances of 10 nm and with radii of curvature being consistent with the cutting edge radius r_C = 5 µm. The manufactured artefacts have been scanned by the tactile profiler Tencor P16+ with a tip radius of r_t = 2 µm and a sampling interval of 100 nm. To compare the target topography with the actual topography, the raw design data set needs to be corrected by the radii of the cutting edge and the profiler tip. We have therefore simulated the cutting process by performing the morphological operation of erosion on the data set of 10 nm lateral resolution. This was undertaken once for an ideally circular cutting edge with r_C = 5 µm and then secondly with a shape referred to as a template. Subsequently, the convolution by the probing tip was simulated by performing the morphological operation of dilation on downsampled subsets of the eroded data sets. Further details of the numerical procedure can be found in [2].

3. Results

The enlargement of the measurement and ideal synthetic data plots reveals some unexpected design details. As a possible reason for this, the geometrical aberration of the circular tool tip was identified.

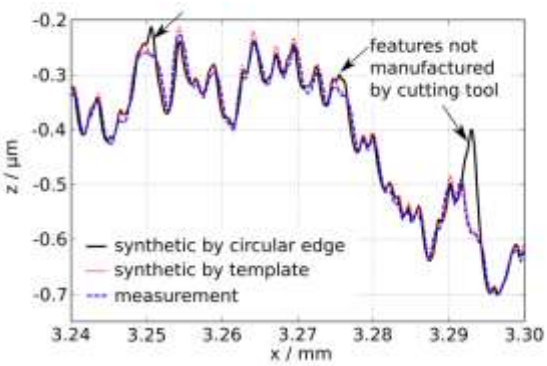

Figure 3. Radial profile on calibration artefact: detail of figure 1.

Figure 3 shows an enlargement of an interval of 60 µm width, which reveals that the design has defined structure details, which were not reproduced. The design eroded by the ideal circular cutting edge and subsequently dilated by the circular tip of 2 µm is shown in a black solid curve.

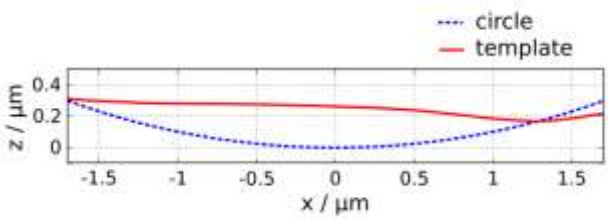

Figure 4. Geometry of the cutting edge used for morphological operation, erosion, as a structuring element: ideally circular (blue dotted curve) and template deduced from measured profiles (red solid curve).

To represent the contour of the cutting edge, a template has been estimated from the measured data of the structure parts whose design defines symmetric, round valleys. It has been employed as a structuring element for the morphological erosion and is shown in figure 4 as the red solid curve.
Erosion with the template and subsequent dilation by a circular structuring element representing a probing tip of radius r_t = 2 µm delivers the red dash dotted line in figure 3.
While the numerical cutting edge has been kept constant, the physical one may have undergone some wear, which can be seen by viewing the details in figure 5. Comparing the blue line of long dashes, showing an interval between 3.03 mm and 3.10 mm, with the green line of short dashes, showing an interval between 11.03 mm and 11.10 mm, a non-negligible lateral shift is visible over a path of 8 mm. This has to be investigated in the future.

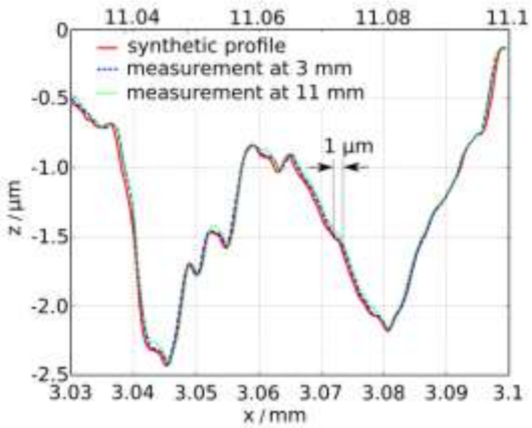

Figure 5. Simulated profile (red solid curve: eroded with template, dilated with circular tip as a structuring element) in comparison with the measured profile at two intervals of 8 mm distance (blue and green dashed curves).

The template could characterize the geometry of the worn diamond tool well. Only very small details have been changed slightly, probably due to further wear and the non-repeatability of the processes between two 8 mm distant intervals.

4. Summary

An effective numerical tool for the generation and comparison of numerical profile data with measurement data of diamond-turned roughness standards is presented. Both the manufacturing tool and the measurement tip geometry are taken into account. The method is a sensible tool for analysing geometrical errors in manufacturing and for measuring calibration artefacts. In a next step, an iterative algorithm will be discussed.

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