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Design and manufacturing of large range, discrete step chirp standards

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Abstract
Ultraprecison diamond turning is used to manufacture standards for tactile and non-contact measurement devices at Physikalisch-Technische Bundesanstalt (PTB). Besides different types of roughness standards and depth setting standards, a novel chirp artefact is developed to determine the transfer function and topography fidelity of optical measuring devices. Reaching the limits of these instruments, the mechanical manufacturing technology reaches its limits too with a radius of curvature of a single micrometre. The nickel-phosphorus-plated standard has an outer diameter of 84 mm. It incorporates coarse structures with a depth up to 24 µm and in addition modulated but stepwise discrete periodic structures with wavelengths in the range from 3.2 µm to 13 µm and amplitudes in the range from 400 nm to 1 µm. The first main challenge for the turning process is the limited lifetime of the small diamond tool. The second is the use of two tools with the necessary spatial correlation of different tool centre points for working the same workpiece. The design of the standards is optimized for this task. Measurement results of optical and tactile instruments as well as atomic force microscopy are compared. The suitability of the functional design can be shown. Furthermore, it can be concluded, that the chipping mechanism of nickel-phosphorus may change with the size of the small diamond tool.

Design, Turning, Ultra-Precision, Measurement

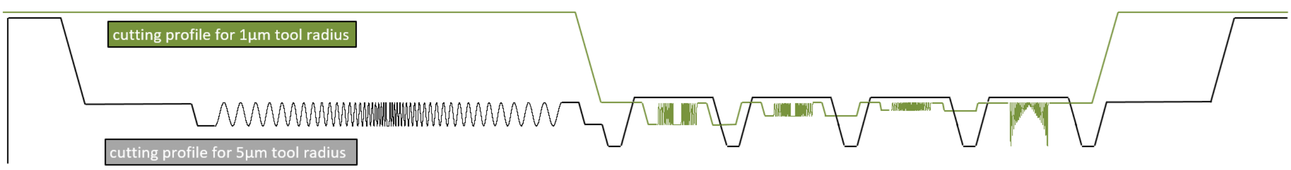

Figure 1. Partial sectional view and sketch of designed chirp standard

1. Introduction

Chirp structures are designed to help users to obtain the limits of their measurement setup within a single measurement [1, 3, 5, 7]. For the identification of the limitations of the equipment, the users simply must count structures with adequate transferred structure amplitudes. These allow an easy classification of the used setup. The structures´ purpose is to characterize the topography fidelity as a part of the limitation of optical instruments [2].

The herein proposed design ("generation III") of a classical chirp-standard provides five different functional areas with varying frequencies and amplitudes in a broad band. The wavelengths in the coarse areas vary from 91 µm down to 11 µm in 23 discrete steps, providing a structure height of 1 µm. Within the fine structure areas, the wavelengths vary from 12 µm down to 3 µm in 15 discrete steps with amplitudes of 1.0 µm down to 0.4 µm. In addition, one area provides 13 discrete amplitude shifts from 2 µm down to 0.1 µm with a frequency of 8 µm.

Nevertheless, when reducing the structure height and the wavelength of the structures down to the wavelength of light, the limits of mechanical manufacturing and optical measurements are reached [4, 6].

Therefore, for the manufacturing of such standards even technologies of semiconductor processing can be involved, see e.g. [7]. Discrete processing and areal machinability may limit the design of a standard in this case. Thus, in this study an ultraprecision face turning process is chosen for manufacturing. Diamond tools with nose radii down to one micrometre are rare and custom made, but they are commercially available and used for this study.

2. Design

Protruding steps are integrated into the surface design of the standards to protect the sensitive structures from mechanical contact e.g. during handling or cleaning processes or putting it down on its face plane by accident. The step height is chosen with respect to the working distance of the measurement equipment, which is used to characterize the standard.

The second purpose of the steps is an easier access to and an identification of a single structure with a specific height distribution. Finally, the steps are necessary for machining different structure sizes with different tools. A sectional view and sketch of the design of the chirp standard is shown in figure 1. The radial travel for the lower structure part is 12 mm.

3. Manufacturing

The Nanotech 250UPL lathe is used for turning the standards. Nickel phosphorous coating on an oxygen free copper substrate is chosen for its optical surface quality and process stability in ultraprecision manufacturing. Nose radii of the single crystal diamond tools are 1 µm and 5 µm. Turning operation is driven with 2000 rpm, feed is 1 mm/min and uncut chip thickness is 1 µm for the 5 µm nose radius. Feed is 0.1 mm/min and uncut chip thickness is 1 µm for the 1 µm nose radius.

Different nose radii of diamond tools are necessary for the turning process to realize the wide range of curvatures of the designed structure. Due to the limited lifetime of the small tool, a second tool must be integrated into the process chain for preparing the surface for the fine structures and for finishing the coarse structures. Different tool centre points (TCPs) need to be correlated for machine control. A vision system with camera is used, as implemented in the ultraprecise lathe, to identify the nose radii with an accuracy of approximately one micrometre. The optical resolution reaches its limits. For a more exact determination of the relative shift between the two TCPs, two flanks of the workpiece are used, which are not relevant for the main measurement task. First, all planes of the rotation symmetric flat are turned with the larger tool. In a second step, one of such fabricated face surfaces and one of the angled steps are touched with the smaller tool. Due to the optical quality of the surfaces, a scratch of a single path of the small tool can be identified with submicron resolution by means of scattered light. The relative distance between both TCPs can be deduced in this way.

Form error due to the tool radius must be corrected for steep structures. Figure 2 shows the results of a simple numerical simulation of the difference between toolpath and machined surface of a perfect tool with the given point interval. It reveals differences of 50 nm nanometres for the critical high frequency structures of the actual standard. Thus, a radius compensation is applied. The morphological filter dilation is a proven tool and used for this purpose [1].

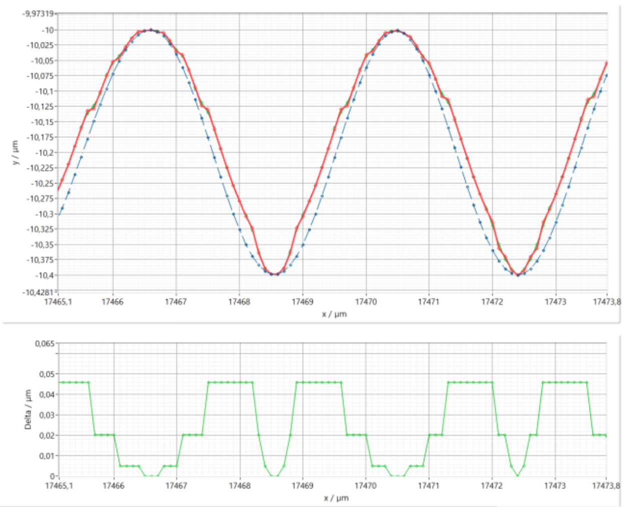

Figure 2. Calculated difference (green line, bottom) between target contour (blue line, top) and surface generated by envelope of tool with nose radius of 1 µm (red line, top), radial increment ∆x = 100 nm

Optical investigation of the tips and resulting assessment of the cutting radius provides an individual value for each tool.

Due to the use of different tool nose radii and the different feeds of the tool on the machine, slightly different roughness parameters of the generated surface can be predicted. According to these theoretical calculations, the influence of the effect on surface roughness is marginal for the chirp standards. The tool with 5 µm nose radius causes a residual roughness of Ra = 1.6 nm and the tool with 1 µm nose radius a value of Ra = 0.1 nm, see figure 3.

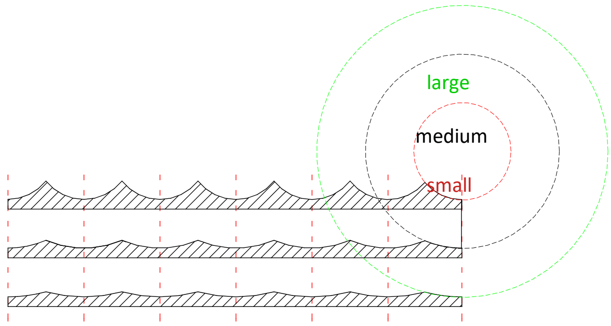

Figure 3. Effect of tool diameter on roughness of manufactured surface – all turned with same feed

With decreasing surface structure size, an increasing part of the tool flanks works the designed surface elements. Larger parts of the tool are in contact with the workpiece for a longer time and affect thermal and mechanical loads during the chipping process, see figure 4. The ratio of energy and volume becomes more critical.

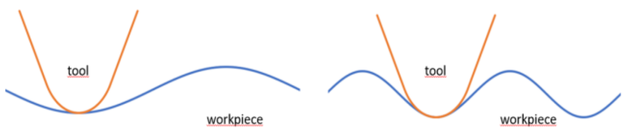

Figure 4. Sketch of the tool and surface frequencies

Finally, heat, positioning error and degradation of the cutting edge may cause geometric deviations of the finished surface. The following investigations with different measuring systems show both the ability to manufacture such a standard and its limitations, and even the limitations of the used measuring instruments.

4. Results and evaluation of the standard

4.1 Optical measurement

Optical measurements reveal, that the target topography was manufactured with low form deviation and good surface quality.

Structures with wavelengths larger than 5 times the tool nose radius can be reproduced very well. With a decreasing structure size, form deviations increase and adverse effects appear.

Figure 5 shows the intensity distribution of the manufactured surface along the fine structure zones.

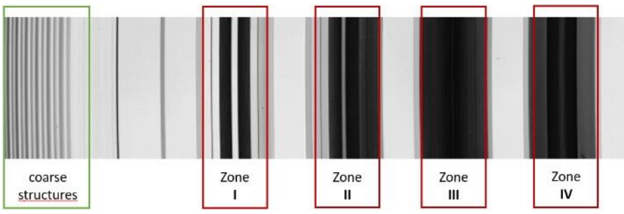

Figure 5. Intensity image of surface section

On the left side of figure 5, a small part of the coarse structure is visible. To the right, four zones with low intensity are visible. These are the areas of the fine structures. Due to the light scattering of steep slopes, most of the reflected light will no longer be reflected into the optical path of the instrument and thus the areas appear darker. Areas with flat surfaces, as they occur in each structural zone, should reflect with undiminished intensity. In zone I in figure 5, the slope areas are symmetrically and interrupted by three clear visible areas of flat surfaces. This characteristic can no longer be recognized in zone II or III. Even on their flat areas the surface intensity seems to reduce with a gradient from the left to the right side of the image.

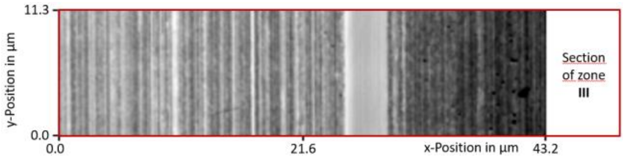

Figure 6. Intensity image of zone III, manufactured with fine tool

The intensity plot of zone III in figure 6 reveals a high roughness. This change of roughness increases along the x-axis. Atomic force microscopy examination of the surface confirms this observation.

From the left to the right, an increase of roughness along the x-profile can be observed. The Ra values increase along zone II and III to approx. 20 nm and stagnate on the rest of the profile.

4.2 AFM Measurement

Atomic force microscopy (AFM) measurements can provide very high lateral resolution. Figure 7 shows the results of an AFM-measurement along the x-axis inside zone I. On the flats A, B and C in figure 7, the roughness parameters were determined with the same profile length.

Tool degradation, wear and tear may be responsible for the quality loss along the workpiece. The life cycle of the 1 µm tool nose is limited, resulting in the requirement of a short tool path with low process loads.

4.3 Stylus measurement

Like optical devices, profilers are subject to lateral integration of data points, whereby the tip acts as a low pass filter for the surface profile. Thus, due to the geometric dimensions of a stylus tip, the curvature of a surface limits the measurement capabilities of such a profiler. Profile fidelity shrinks, once the stylus tip cannot follow the surface because it's radius is larger than the concave curvatures of the surface. The dimensions of the present structures are close to the limits of mechanical machinability, but the stylus instruments reach their 3D-resolution limits too. The red dashed line in figure 8 shows, from left to right, a steadily limited scanning depth of stylus profiler in comparison to the blue line, which represents the AFM-measurement.

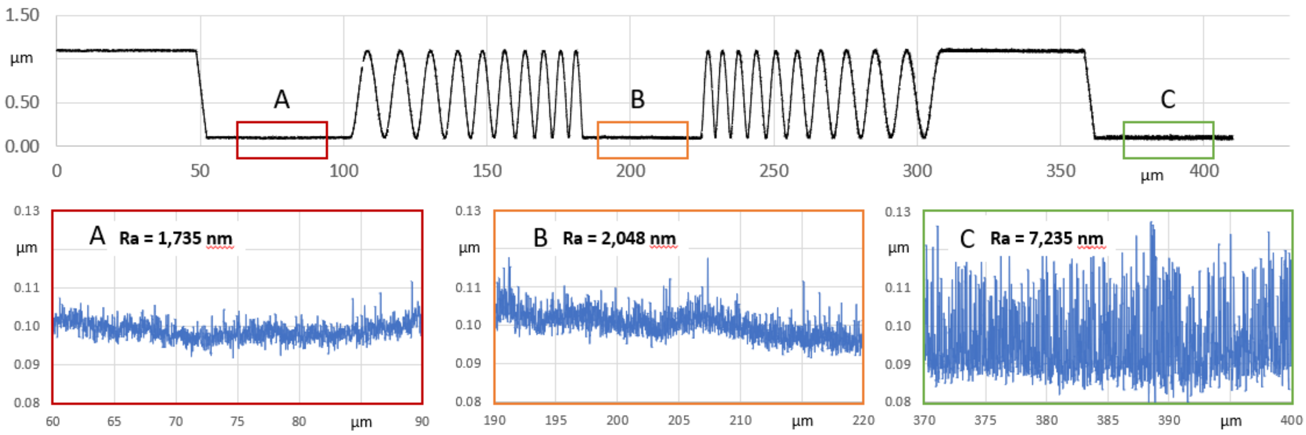

Figure 7. AFM measurements of flats of chirp standard

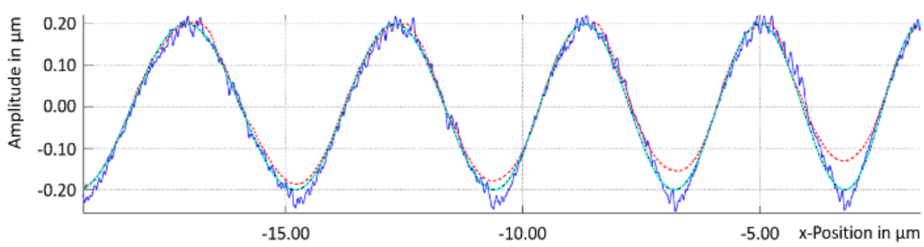

Figure 8. Comparison of measurement results of zone III; red line: profiler, blue line: AFM measurement, turquoise line: command profile

4.4 *SEM visualisation*

Scanning electron microscopy (SEM) reveals parasitic filaments at the nanoscale, see figure 9. These may arise due to the change of the structure size of the chipping process or the change of the spatial stress field in the deformation zone.

These superposed, sub-wavelength sized structures may be optically active by means of a shading effect, which can be observed on the surface. They may be one reason for the apparently dark areas in figure 6.

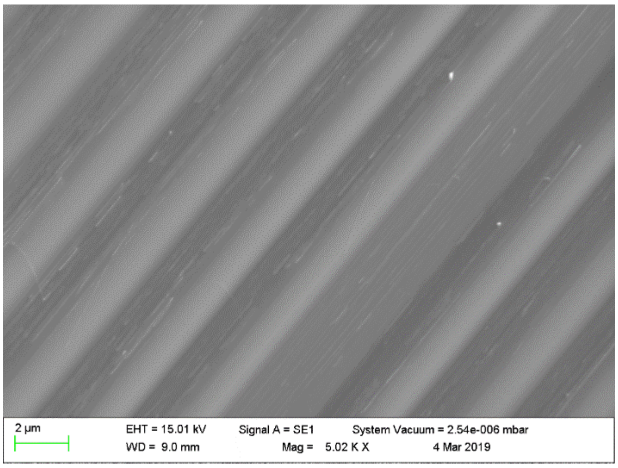

Figure 9. SEM picture of fine structure

5. Discussion

Measurement results show, that the required topography is manufactured with low form deviation and good surface quality. Due to appropriate tool compensation for the machining process, the elements of the coarse areas are close to the designed value. The smaller the required structures on the surface and the steeper the slope of the elements, the larger the negative effects of machining. Heat, change of cutting edge, wear and tear may affect the surface quality. The change of the chipping process with the nose radius of 1 µm must be better understood to be able to develop further compensation algorithms, see e.g. [8, 9].

The standards were measured with various optical and tactile measuring systems, as well atomic force microscopy and electron microscopy. The different measuring devices capture the same 3D-data of the surface. Due to the use of different physical effects, the resolution, the filter effect on the surface, the field of view and the recording times vary. Finally, each measuring device has individual and unique strengths and weaknesses. The user must choose the appropriate device depending on the requirements of the respective measurement task.

6. Summary and outlook

A novel multi wavelength chirp standard is presented. The design is optimized for the measurement task and the manufacturing process and the handling procedures.

Due to the small structure sizes of the standard with curvatures down to 1 µm, the optical measurement equipment reaches its limits and the mechanisms of chipping seem to change during the manufacturing process. For an improvement of the surface quality of the manufacturing process of such standards with small wavelengths, further detailed investigation of the chipping mechanism on the microscale is necessary.

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