Calibration of Photomasks for Optical Coordinate Metrology

Felix Meli

Federal Office of Metrology METAS, Laboratory for Nano- and Microtechnology, Lindenweg 50, CH-3003 Bern-Wabern, Switzerland

Abstract

Optical coordinate measuring machines (CMMs) are widely used in industrial production for fast measurements on complex components. According to ISO 10360-7 the calibration and verification of these CMMs requires certified line scales or grid plates. Additionally, for the determination of the probing error of the imaging probe, masks with form calibrated test circles are compulsory. Using the photomask measuring instrument developed at METAS and using new specific procedures, it is possible to calibrate not only structure positions but also the diameter and roundness of circular structures with competitive uncertainties.

Keywords: photomask, optical coordinate metrology, ISO 10360-7, test circle, roundness

1 Introduction

Today, industry is interested in fast and accurate dimensional measurements on diverse mechanical parts. In recent years, multisensor coordinate measuring machines having combined tactile and optical sensors made substantial progress and are now often used for such applications. Especially CMMs equipped with imaging capabilities are frequently used for fast, non-contact measurements on mainly flat parts. The strong competition among manufacturers of such instruments and the demand for sub-micron accuracy has led to standardised tests which help to compare and validate instrument performance. Since 2011, acceptance and reverification tests for coordinate measuring machines with imaging probing systems are described in detail in the standard ISO 10360-7 [1].

The calibration, verification and also error correction of optical CMMs is mainly based on measurements using reference line scales or two-dimensional grid plates. Furthermore ISO 10360-7 requires photomasks with form calibrated test circles in order to determine the probing error of the used imaging probe. The required calibration of the reference line scales and grid plates is usually performed at national metrology institutes using photomask measuring instruments. Up to now, however, there were no services available for traceable form calibrations of the required test circles.

This paper reports on the current state of photomask measurements at METAS and on recently developed methods to calibrate form deviation of test circles.

2 Requirements of ISO 10360-7

The ISO 10360 series of standards deals with acceptance and reverification tests for coordinate measuring machines and is part of the geometrical product specification standard system (GPS). Part 7 covers CMMs equipped with imaging probing systems. This part defines parameters and methods to characterize length measurement errors and the probing performance of optical CMMs.

The standard strictly distinguishes between bidirectional and unidirectional measurements. Bidirectional measurements are measurements on both sides of a structure in order to measure its width. Unidirectional measurements determine distances between identical structures. Unidirectional measurements are in general much more accurate than bidirectional measurements.

Important parameters defined in the standard are the bidirectional length measurement error E_B and unidirectional length measurement error E_U applicable to imaging probe CMMs that are capable of three-dimensional spatial measurements. For imaging probe CMMs that are only capable of making measurements in the two-dimensional XY plane the length measurement errors E_{BXY} and E_{UXY} should be used. In total the standard defines more than 34 parameters including the maximum permissible errors (MPE) and it describes also the procedures to be followed in order to measure these parameters.

For example, in order to determine the length measurement error E_U a calibrated line scale of the appropriate length, i.e. at least 66 % of the range of the measured direction, has to be placed in 7 different positions (locations and orientations). In each position 5 distances have to be measured with 3 repetitions giving finally a total of 105 results. Finally all measured length deviations are plotted in a diagram and compared to the maximum permissible error (MPE) according to the machine specifications. The effort needed to determine each of these parameters is substantial. By using two dimensional grid plates instead of line scales the procedures are somewhat simplified because with a single placement of the plate various measurement directions can be verified.

Three specific quantities are defined in the standard ISO 10360-7 to characterise the image probing system, namely the length measurement error E_{BV} or E_{UV}, the probing error P_{F2D} and the probing error of the imaging probe P_{FV2D}.

For example, in order to determine the probing error P_{F2D}, a calibrated test circle with a nominal size of at least 150 % of the smallest axis of the field of view but no greater than Ø 51 mm must be used. 25 points, evenly distributed around the full circle, have to be measured in such a way that the CMM stage has to move between each measured point. The measuring window inside the field of view is required to be shifted at each point so that finally the entire field of view is covered, see figure 1.

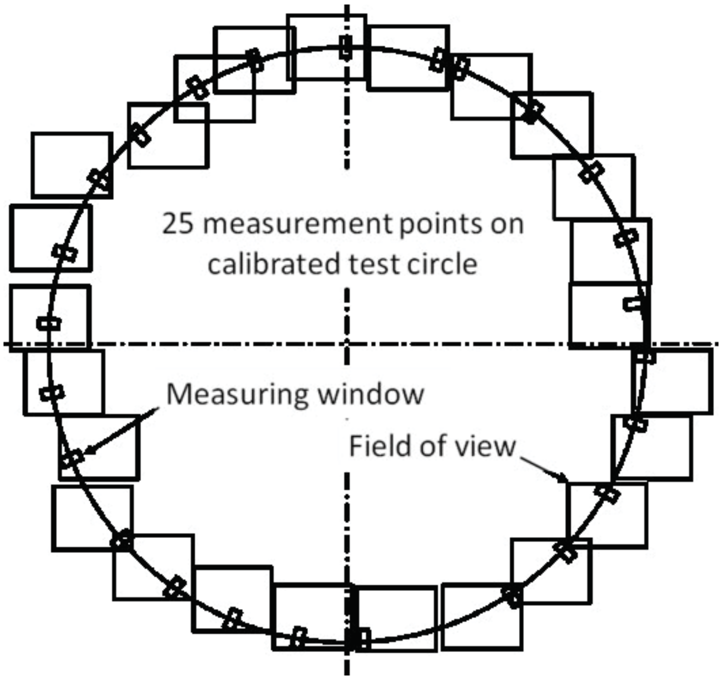

Figure 1: Possible point pattern for measuring the probing error P_{F2D} in accordance with ISO 10360-7

The use of high quality test circles is essential since the probing error P_{F2D} of the CMM under test cannot be specified better than what is supported by the roundness of the available test circles. The form of the test circles, i.e. their roundness deviation, is required to be calibrated.

3 The METAS photomask measuring instrument

The photomask measuring instrument developed at METAS consists of a high-precision, air bearing x-y stage for the positioning of the mask, a differential two axis plane mirror interferometer and a digital video microscope system for the localization of the structures. The measurement range is 400 mm x 300 mm (Fig. 1).

The objects under test are supported in three well defined points to obtain predictable and reproducible conditions. Line scales are usually supported at the Bessel-points which results in minimal bending. Measurements are always made with the chromium structures on top using episcopic illumination. To minimize the travel of the focus stage photomasks are leveled out by piezo motor driven supports.

The instrument is situated inside a temperature and humidity controlled clean room cabin of class 100. The temperature of the objects is measured by two in house calibrated super stable thermistors and any remaining difference to 20°C is numerically compensated. Low expansion materials such as quartz or Zerodur are the preferred choice for the mask substrate.

In a measurement sequence, the table positions the structure to be measured to the center of the field of view of the microscope. The stage is then clamped to the granite base table and therefore completely standing still during the measurement. The relative location of a pattern within the field of view is determined by digital image analysis. At the same time the interferometer measures the stage position. The control software allows free programmable measurement sequences.

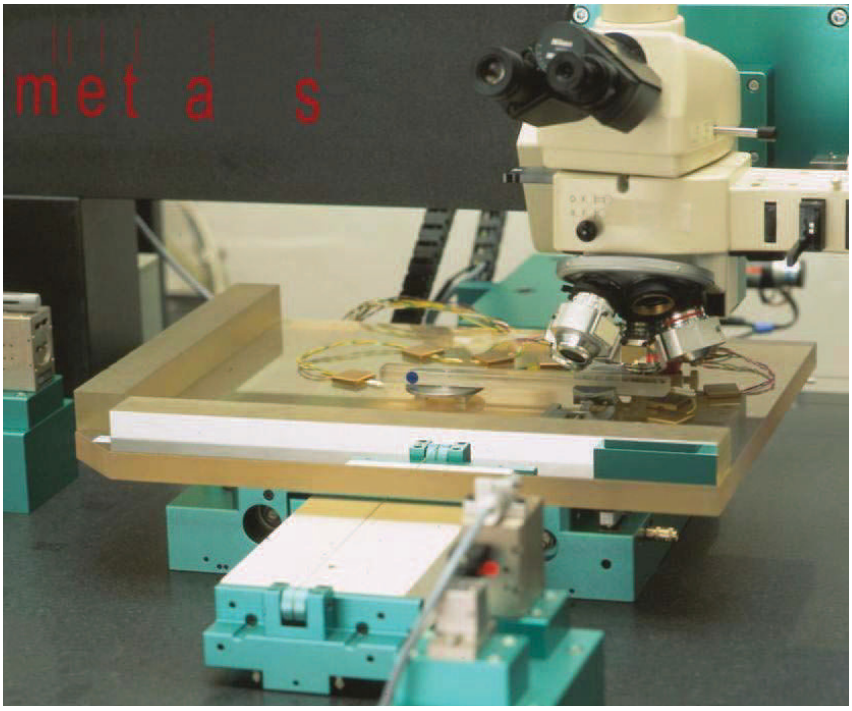

Figure 1: Overview photograph of the photomask measuring instrument.

3.1 The x-y translation stage

The x-y translation stage was designed for very small rotational errors. By the use of vacuum air bearings a single reference surface is sufficient to obtain a high quality guiding. The rotational errors of the movements are essentially determined by the flatness and straightness of three reference surfaces. First, the top surface of the granite table with a flatness in the working range of less than 0.2 µm (Fig. 2c). Second, the surface which defines the straight motion in the x-direction which is a part of the back side of the granite table (Fig. 2a) and third, a ceramic straight edge which is moved by the x-stage which provides the guiding in the y-direction (Fig. 2b).

The stage is moved by strings, driven by two speed controlled servo motors. The string actuation has the advantage of very low lateral forces applied to the stage. Sinusoidal electronic commutation and zero backlash reduction gears are used. The servo motors dissipate only a few milliwatt of power during the movement of the stage. No heating was observed due to the motors which are placed at a reasonable distance from the stage. During a point to point movement speed and acceleration remain below given limits so that masks do not move although they are not fixed to the Zerodur base plate other than by their proper weight. The stage can be positioned to better than 1 µm which is sufficient. Due to the low friction of the air bearings and the weak coupling of the drive by the strings, the stage is quite sensitive to vibrations in the x-y plane. Therefore, once positioned the stage is clamped to the granite base table by a vacuum break and the measurement is initiated in this static situation.

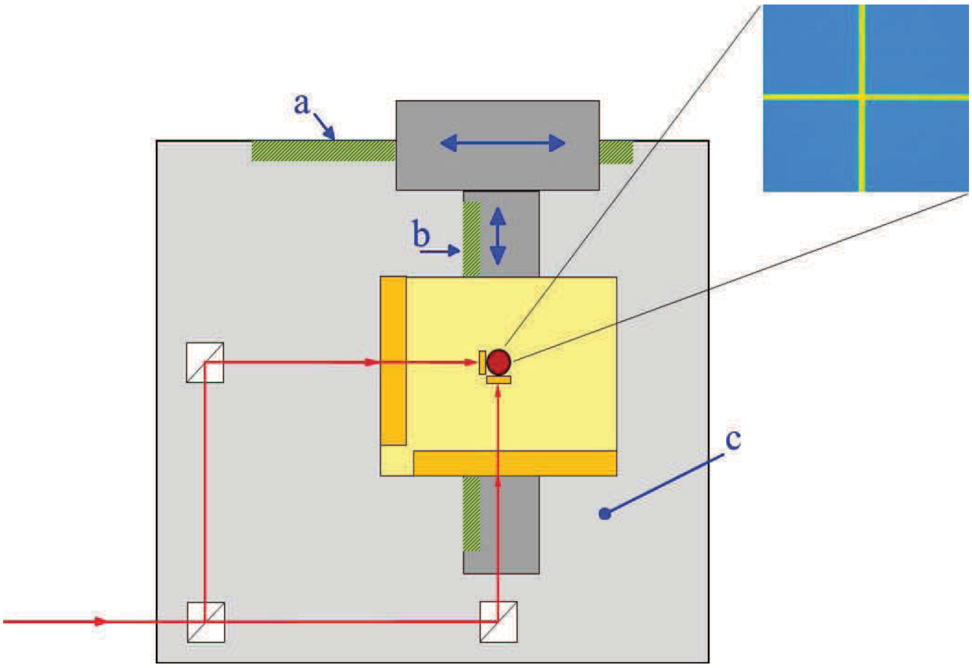

Figure 2: Schematic of the guiding and the interferometer beams. a) and b) guideways for the x- and y-movement with straightness better than 0.2 µm, c) reference plane for the x-y movement consisting of the granite table top surface with flatness better than 0.2 µm.

3.2 The interferometer

Two differential, double pass plane mirror interferometers are used to measure the position of the stage. The HP heterodyne laser has a wavelength of 633 nm and is traceable to our metre realisation consisting of an iodine stabilised laser. The resolution for a single reading is 5 nm and the nonlinearity should be better than 2 nm. The measurements are made differentially between the Zerodur reference mirror system and mirrors attached to the microscope objectives (Fig. 3). The measurement beams have nominally no Abbe offset. For a position measurement the interferometer readings are averaged during approximately one second. To compensate for linear drift, always two interferometer readings are taken, one before and one after the image capturing. Simultaneously, air pressure, temperature, humidity and CO_2 content are acquired to determine the refraction index of the air by the Edlén formula [2]. Special care was taken to obtain perfectly aligned laser beams to avoid any cosine errors.

The laser is a considerable heat source of approximately 30 W and is therefore placed outside the temperature stabilised clean room cabin.

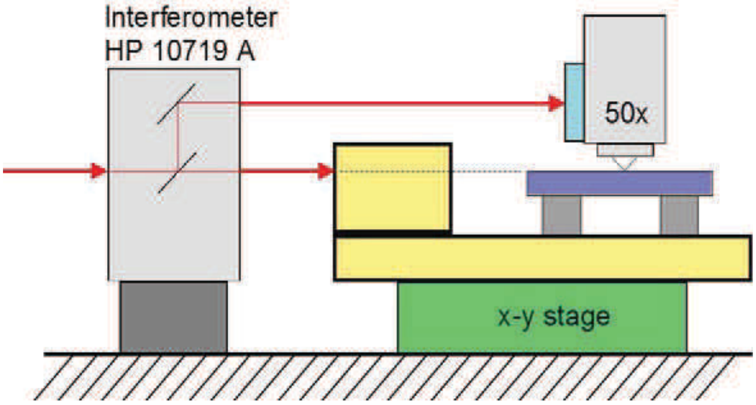

Figure 3: Schematic of the differential interferometer with measurement and reference beams.

3.3 The video microscope

A microscope with a CCD camera and numerical image processing is used to localise the position of the structures like edges, lines, crosses or dots. The commercial microscope (Nikon) has a motorised turret and focus drive. Four objectives can be used with magnifications from 5x to 150x and with respective numerical apertures (NA) from 0.3 to 0.9. The CCD imager has 752 x 582 pixels with 8 bit resolution. Besides the video signal also the pixel clock is transmitted to the frame grabber to reduce image jitter. Before an image is captured an automatic focussing is performed by maximising the image contrast.

Each row of pixels within the region of interest (ROI) in the image is analysed individually. To determine a line centre location typically the left and the right line edges are detected. The edge locations are determined with a moment based edge operator. A line is fitted through all edge points within the ROI. Halogen or metal halide lamps are used for the episcopic illumination. To minimise the heat sources near the instrument, the light is led by a long flexible light guide to the microscope head. The 1.4 W power dissipation of the CCD camera is the largest single heat source in the clean room cabin.

4 Calibration of the 2D reference mirror system

The reference mirror system is made out of a thick Zerodur base plate with two Zerodur mirror stripes on top. The mirrors were aligned and fixed to the base plate at METAS. The orthogonality deviation after assembling was in the order of 5 µrad. The reference mirror system is kinematically held in three points on the x-y stage.

The calibration of the 2D reference mirror system was performed in two steps. In a first step initial straightness data of high positional resolution but with some long range distortion were measured on a straightness measuring instrument. In a second step an in-situ calibration was made directly on the photomask measuring instrument which can correct the orthogonality and the long range straightness deviations.

This second calibration was made by means of a 400 mm quartz line scale which was placed in axial and in two diagonal directions on the Zerodur reference mirror system. The measurements parallel to the x- or y-axis are not influenced by any form deviation of the mirrors and can serve as a reference [3].

During the last 10 years these calibrations were frequently repeated. Some minor shape changes were observed which were probably due to changed loading forces on the reference mirror system during that period (Fig. 4).

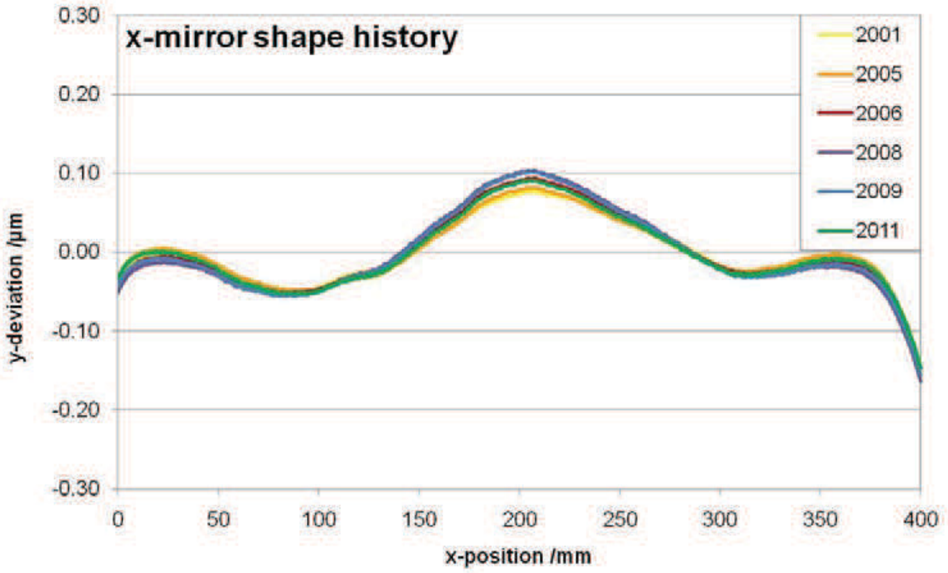

Figure 4: Calibration history of the x-mirror shape.

After the implementation of the mirror shape correction in the software of the photomask measuring machine a final verification measurement showed that the agreement between the axial and the diagonal measurements was better than 10 nm (Fig. 5).

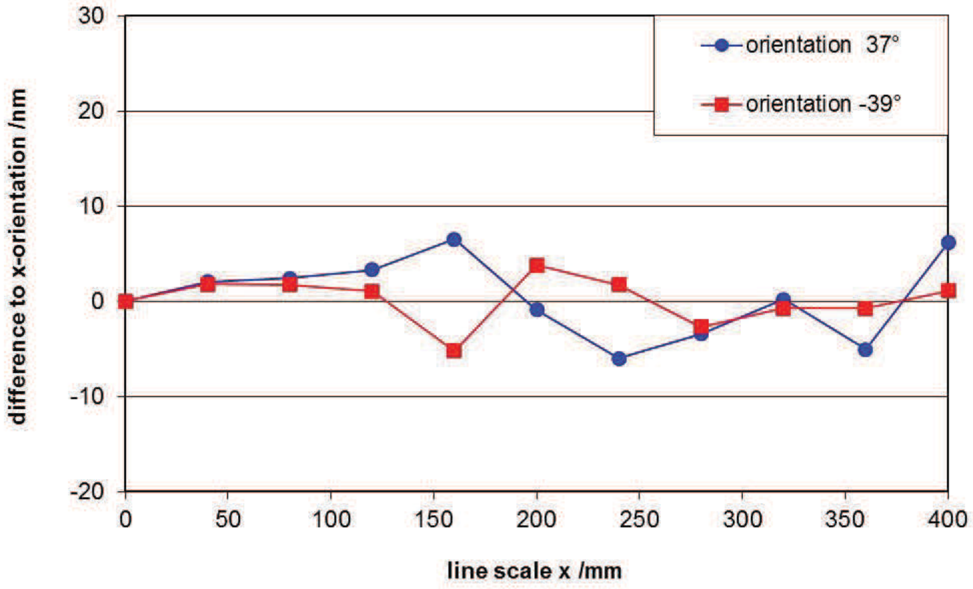

Figure 5: Deviations of the line scale measurements in the two diagonal orientations with respect to the scale calibration when positioned in x-direction.

5 Performance of the photomask measuring instrument

Using a 400 mm quartz line scale the repeatability was determined. 40 lines were measured 10 times. Figure 6 shows the standard deviation of these measurements which was below 5 nm for each line. If the left most line is used as the zero reference then the standard deviation is slightly increasing with distance. If, on the other hand, the average of all deviations is used as a reference then the standards deviations remain mostly constant and independent of the line position.

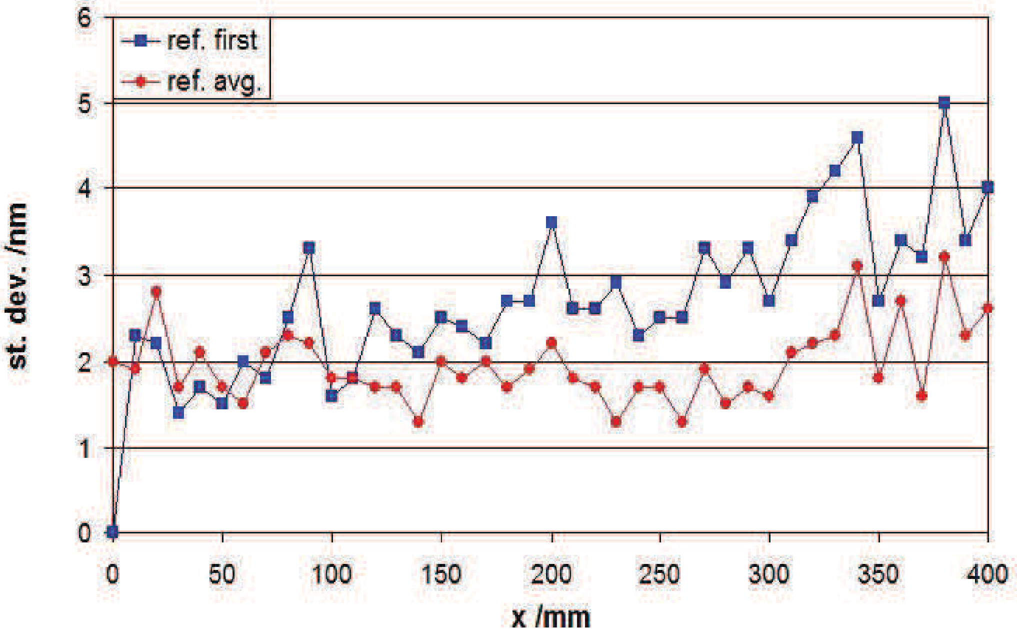

Figure 6: Standard deviation of 10 repeated measurement on a quartz line scale of 400 mm length.

Additional line information can be extracted from the acquired video images which help to judge the quality of the scale and to improve the measurement uncertainty estimation. As an example, figure 7 shows the evaluation of the variation of the line angles. If the graduations of a line scale are not perfectly parallel to each other, an additional contribution to the uncertainty must be taken into account, especially if there is a deviation from the defined line of measurement. The result of 10 times repeated measurements on a quartz line scale of 400 mm length shows clearly that the line parallelism deviation is larger than the repeatability of the line angle measurement.

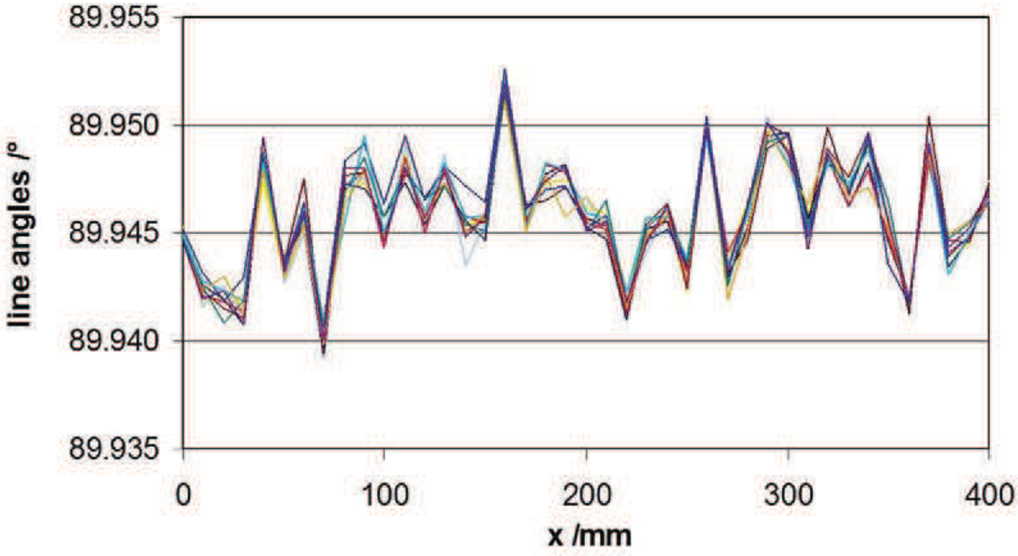

Figure 7: Angle of lines measurement on a quartz line scale of 400 mm length.

During the past ten years some line scales were measured at regular intervals. Among them were a 400 mm quartz line scale and a 280 mm Zerodur line scale. While the quartz line scale showed undetectable drift, the Zerodur line scale displayed a clear long term drift behaviour. The drift rate was approximately 26 nm/year for the longest interval of 280 mm (Fig. 8). A similar behaviour was observed during a three year period in a CCL line scale comparison [4].

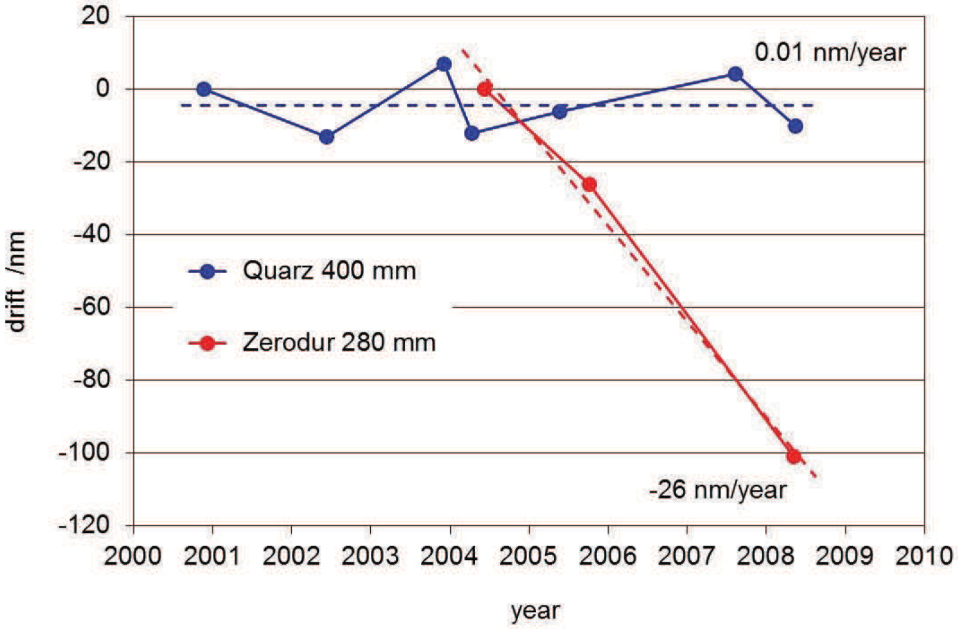

Figure 8: Long term stability study for a 400 mm quartz and a 280 mm Zerodur line scale.

6 New procedures for roundness calibrations of test circles

In order to determine the probing error P_{F2D} or the probing error of the imaging probe P_{FV2D} of an optical CMM as defined in ISO 10360-7 test circles with calibrated form are required. The quality of the used test circles is critical in this measurement since the form deviation will directly influence the test result and shall be taken into account when proving conformance or non-conformance with the specification [3].

For the above mentioned test, 25 equally spaced points have to be measured. However, because the starting point is not fixed, a test circle might be used in any possible point on the circumference and therefore the whole border of the test circle needs to be form calibrated. The obtained raw profile should be filtered with a Gaussian filter. Depending on the test circle size, filters with 50 UPR or 150 UPR seem reasonable considering the profile fraction which would typically lie inside the measuring window during the test.

New procedures developed for the METAS photomask measuring instrument allow the calibration of diameter and roundness of test circles. The parameters and specification operators for roundness used are in accordance with ISO 12181-1 [5] and ISO 12181-2 [6].

6.1 Border evaluation steps

From the test circle border, overlapping images are taken which cover finally the complete circumference. For low uncertainty, high resolution objectives and a small region of interest (ROI) are required. This means that only a very small fraction of the circumference is captured in a single image. The process of collecting all border data might therefore be quite long and result in quite large data sets for later compilation. To reduce the amount of stored data the border is only stored as a list of points rather than in complete 2D matrices. All border points within the threshold range of about 10%-90% are retained including their respective intensity information. After collecting all border points in this way some additional steps are required before the actual roundness evaluation can start.

First all duplicated points from overlapping regions must be detected and deleted. Second the remaining points are sorted into connecting point groups to distinguish the borders belonging to different circles and to suppress points generated due to dust and defects (Fig. 9 right). For the final sub-pixel border interpolation the points belonging to a single circle have to be sorted in the direction of the circumference.

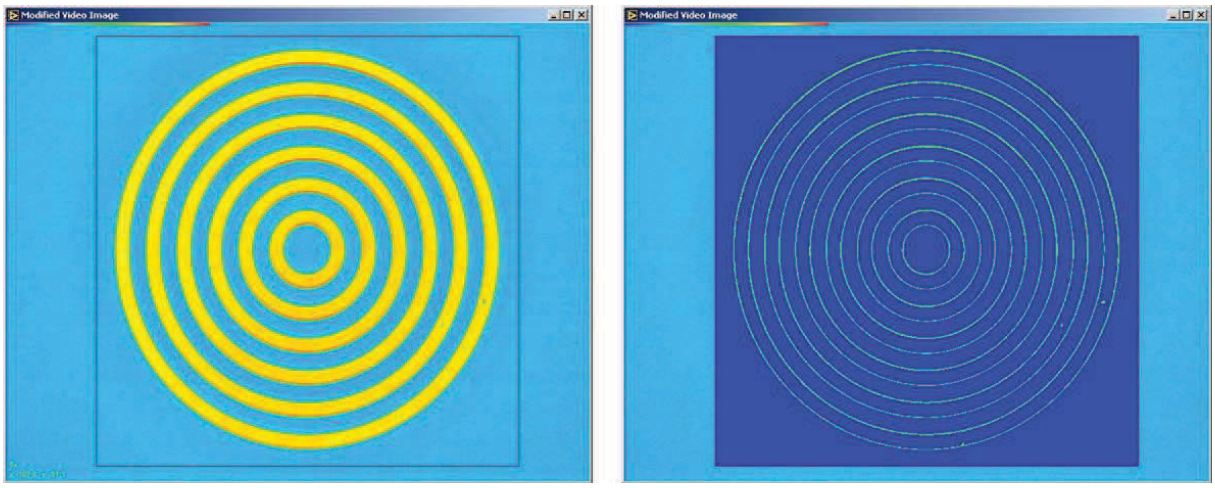

Figure 9: Border extraction for concentrical circles and separation into connecting point groups.

Even with a high magnification objective a single pixel remains quite large. In order to get a border line with sub-pixel resolution in radial direction the following steps were implemented. Small sections, with a little bit more points than contained across the border width, are weight averaged to give a single sub-pixel resolved point in the raw data set of the circumferential line. The weights used are based on the intensity information and reflect the distance to the border center (Fig. 10).

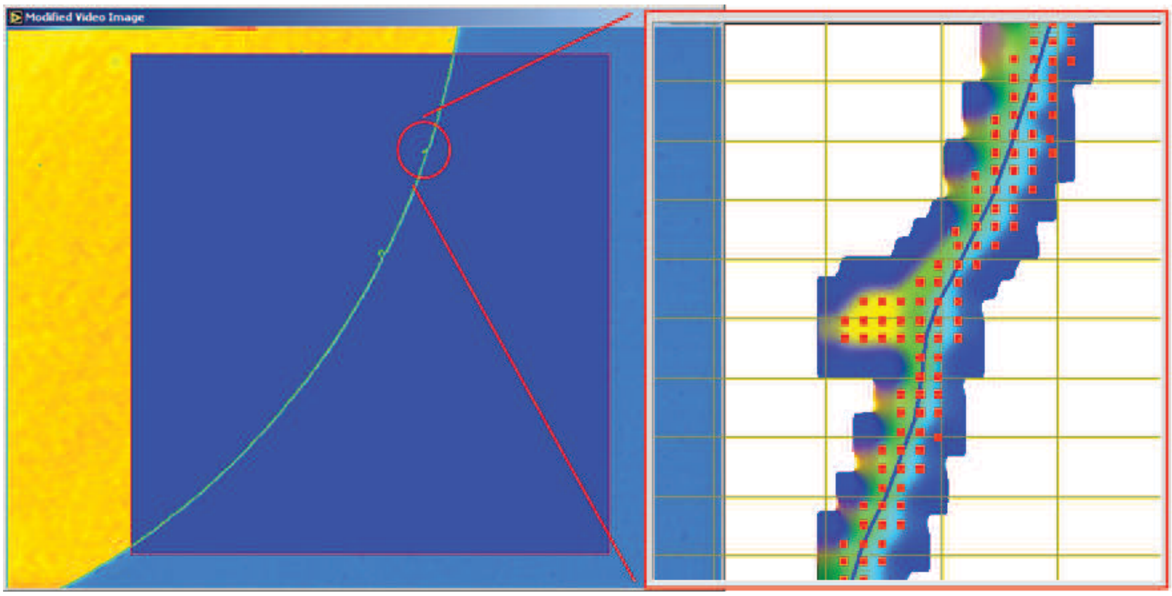

Figure 10: Magnified border section to illustrate the sub-pixel border interpolation. Right: The intensity information of each border pixel is retained and used to determine blue circumferential line.

6.2 Filtering and roundness evaluation

Roundness is a property of a circle [5] which is determined form the digital representation of the extracted circle border with respect to a fitted reference circle, typically the least squares reference circle (LSCI) is used. Before a certain roundness parameters, such as the peak-to-valley roundness deviation (RONt), is determined, the extracted circle border line must be filtered. The filter determines how many periodic sinusoidal undulations per revolution (UPR) are included [6]. Depending on the test circle size, filters with 50 UPR or 150 UPR seem reasonable considering the later application to determine a CMM probing error.

The following evaluation steps were included in the procedures developed for the METAS photomask measuring instrument: From the extracted circumferential line (raw data) dust, or defects can be removed by deleting step by step points with the largest deviation from the reference circle. This step is optional and should be used with great care and only in cases if it is sure that the removed features are not part of the circle. Filtering requires equidistant points which is reached by linear interpolation in polar coordinates. The reference circle is obtained from a least squares fit using the filtered profile. Finally the diameter and the peak-to-valley roundness (RONt) are computed. It was verified that the filtering does not change the diameter value (Fig. 11).

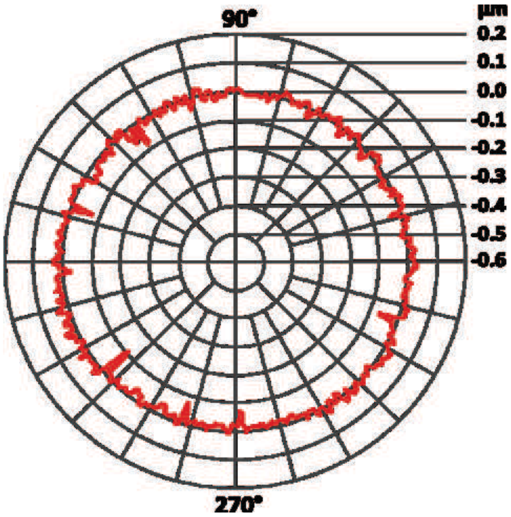

Figure 11: Measurement result for a chrome on glass test circle with diameter (1.9994 ± 0.0009) mm and roundness deviation (0.15 ± 0.07) µm filtered with 150 UPR.

Depending on the character of the roundness deviation the roundness value changes with the applied filter. For low order roundness deviations like elliptical deformations the roundness is almost independent of the filter. For noisy profiles, the roundness deviation is reduced with increasing filter length. Also the estimated uncertainty depends on the used filter (Fig. 12).

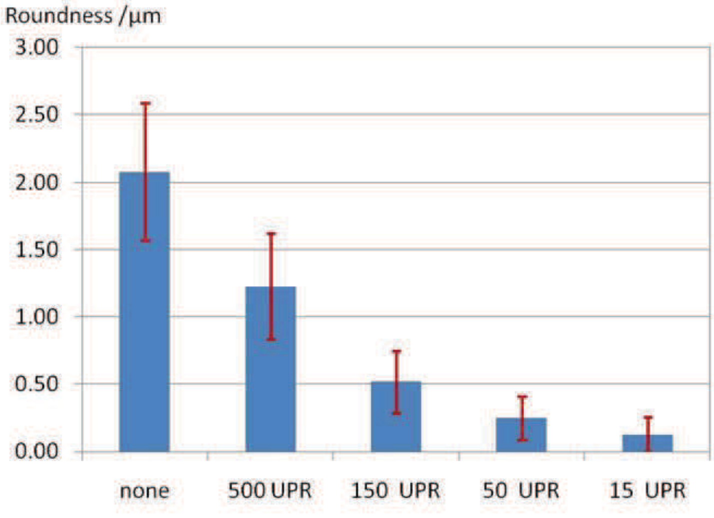

Figure 12: Decrease of roundness and its uncertainty vs. the applied filter length.

6.3 Achievable diameter and roundness uncertainty

The finally achievable uncertainty of a roundness measurement depends on many parameters. An important method for the estimation of the various effects was to use an error separation technique. By measuring various test circles in different orientations (rotations) and by comparing the obtained profiles the following groups of contributions were identified:

1. The single pixel location accuracy depending on the stage position accuracy and the size of the test circle, the video image calibration and image distortions, the size of the region of interest within the video image (ROI size) and finally on drift.

2. The resolution and sub-pixel interpolation depending on pixel size and optical resolution, the border width and the intensity range covered by the border points.

3. The filtering process depending on the undulations per revolution UPR and the number of points in profile.

Filtered roundness parameters can be determined with 500 UPR, 150 UPR, 50 UPR and 15 UPR. The measurement uncertainty is in the range from 0.05 µm to 1 µm and is a function of the quality and size of the test circles. Because resolution and pixel size depend mainly on the used objective the best achievable uncertainties given in table 1 were estimated for each of the three mainly used magnifications.

Table 1: Achievable uncertainty for diameter and roundness measurements using various objectives.

Objective	5x	20x	50x
U_{95} roundness /µm	0.76	0.15	0.07
U_{95} diameter /µm	1.5	1.0	0.7

7 Conclusion

The characterization of an optical CMM according to ISO 10360-7 is a quite complex and laborious task. Using two dimensional grid plates instead of line scales the procedures could be simplified somewhat because with a single placement of the plate various measurement directions can be measured.

The photomask measuring instrument is a versatile tool to provide the required calibrated line scales and 2D grid plates of low uncertainty. For the first time such an instrument was also used for traceable form calibrations of test circles in agreement with applicable standards. In future, these new measurement capabilities should be validated by international comparisons. The uncertainty estimation could be further improved by numerical simulation methods.

References

[1] ISO 10360-7:2011, Geometrical product specifications (GPS), Acceptance and reverification tests for coordinate measuring machines (CMM), Part 7: CMMs equipped with imaging probing systems.

[2] Bönsch G and Potulski E, Measurement of refractive index of air and comparison with modified Edlén's formulae, Metrologia **35**, 1998, 133-139.

[3] Meli F, Jeanmonod N, Thiess Ch and Thalmann R, calibration of a 2D reference mirror system of a photomask measuring instrument, Int. Conf. on recent developments in traceable dimensional metrology, Proceedings of SPIE, Vol. 4401, Munich, 2001, 227-233.

[4] H. Bosse, W. Häßler-Grohnde, J. Flügge, R. Köning, Final report on CCL-S3 supplementary line scale comparison Nano3, Metrologia 40 (Technical Supplement 2003) 04002.

[5] ISO 12181-1:2011, Geometrical product specifications (GPS), Roundness, Part 1: Vocabulary and parameters of roundness.

[6] ISO 12181-2:2011, Geometrical product specifications (GPS), Roundness, Part 2: Specification operators.