

Influence of mounting on the optical surface figure in optical reference surfaces

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ABSTRACT: The paper presents the effect of mechanical mounting of optical reference elements on their surface shape. Optical reference surfaces are key elements when traceable, highly accurate and precise optical surface measurements are required. In order to calibrate measuring instruments and compare the metrological capabilities of different metrology institutes, universities and other stakeholders, the reference artefacts were developed. Different measurement instruments require a different way of mounting and the reference artefacts are supposed to be useful for reliable and repeatable calibration of a great majority of the instruments worldwide. However, not only their shape was critical, but also the way of mounting was crucial. FEM analyses followed by experiments have revealed an unacceptable surface shape error in the order of hundreds of nanometres in the case of the commonly used screw mount, even for low applied torques. Other mounting options, such as the collet chuck or the Morse taper, are examined by means of FEM analysis and verified by interferometric measurements. It is shown that only the Morse taper can fulfil the strict criterion of less than 30 nm for surface shape deviation due to mounting, which is required in optical surface shape metrology.

KEYWORDS: Optics; Overall mechanics design (support structures and materials, vibration analysis etc); Manufacturing; Interferometry

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1 Introduction

Due to the ever growing need for more precise surfaces of optical elements, the requirements for precise measurements have increased significantly. In a substantial amount of optical systems at least one element has an aspherical surface form and it is obvious that surfaces without rotational symmetry, so called freeforms, have become an important part of the segment. Aspherical and freeform surfaces are key elements for optical system performance tuning and the benefits of their applications in the systems are enormous [1, 2]. Current high-end applications require optical surface form deviations to be below 50 nm and the metrology needs to be even more accurate. Thus, the metrology of such surfaces requires sophisticated apparatus and sophisticated methods of measurement. This also brings new issues in terms of measuring instruments calibration. Easily traceable reference spherical surfaces must be replaced by a set of non-spherical elements having various surface geometry. Moreover, it has been shown that measurement results from different machines are not easily comparable [3]. To define new procedures, algorithms, and methods for repeatable, comparable, and traceable metrology of aspherical and freeform surfaces, the European Metrology Programme for Innovation and Research (EMPIR) and specifically the FreeFORM project (15SIB01) were created to address the above-mentioned issues [4].

One of the important parts of the project is the development and manufacturing of metrological reference surfaces. In the metrological traceability determination, the metrological reference surfaces (MRSs) are used to calibrate and verify aspherical and freeform metrology systems [5, 6]. MRS application is following: after MRSs are designed and manufactured they are precisely characterized by different metrology institutes, stakeholders and other project partners and important data and deviations are derived from those measurements. Analysis of these data helps to estimate

the real shape of the MRS and also they show how different measurement apparatus could be off the correct shape figure. Another application of those MRS is the calibration of the measurement apparatus or the whole chain, of device, data handling and data evaluation. It is important to note that these MRS are mounted on a removable shank because some measuring instruments are capable of measuring the element with the shank (for example in a hydraulic expansion holder) while others, for example “2.5D” coordinate measuring machines, need a smaller specimen height and the shank has to be removed. However, within the project the requirements for the uncertainty of the form measurements of aspherical and freeform surfaces are extremely high, reaching repeatedly and reliably uncertainties below 30 nm. Therefore, no detail of the element handling can be neglected. Significant effort was devoted to the selection of the element material regarding its hardness, low thermal expansion coefficient and also to the shape of the element optical surface. It soon became obvious that the mounting of the removable shank could have a considerable impact on the final shape and that appropriate mounting could be more important than other parameters. For the realization of an appropriate mounting, the challenge lay in the need to mount and dismount the elements in different workplaces without a significant impact on the surface shape.

Apart from immediately clear MRS’s properties like hardness and low thermal expansion of material as well as the shape of the optical surface, the mounting of the removable shank has an essential impact on the final shape. Therefore, an appropriate mounting has to be developed.

The requirements for properties of optimal mounting system are as follows:

- 1) Easy and fast to mount and dismount the RMS (minutes)
- 2) Low Z height and removable chunk
- 3) Very low shape change of MRS between mounted and unmounted state
- 4) Very good centration, the best-self centration
- 5) Very low impact on surface shape when temperature changes
- 6) Easy to produce

To meet this requirements, several systems of mounting were investigated, and the influence of mounting was simulated and also measured by an interferometric setup.

In this paper we propose an appropriate way of MRS mounting with a negligible impact on the optical surface shape. The results are validated by FEM analysis as well as by interferometric measurements.

The paper is structured as follows: In the first section, FEM analyses of the effect of mounting on surface shape for various parameters (e.g., thickness or type of mounting) are introduced. Two surface shapes (plano-like and spherical one) are considered. In the third chapter, the FEM analyses were validated by experiments. The results of a flat surface measurement using a Fizeau interferometer are presented in 2.1, while section 2.2 is devoted to the analysis of spherical elements. The results of the measurements are compared to the FEM analyses and discussed.

2 FEM analysis of the effect of mounting on surface shape

2.1 Complex (plano-like) element

To study the impact of mounting on the optical surface shape of MRS, we first selected two elements varying in height (see figure 1). The shape is a disk or cylinder with a prismatic section on top of the disc and, on the prismatic section, there is a spherical surface with a spherical fiducial mark in each corner of the prismatic base. This element was selected because it had been used for the validation of the holographic method [7] and its model was available for the first analysis. Two different materials (aluminium and steel) were set as parameters of the models used for finite element method (FEM) analysis.

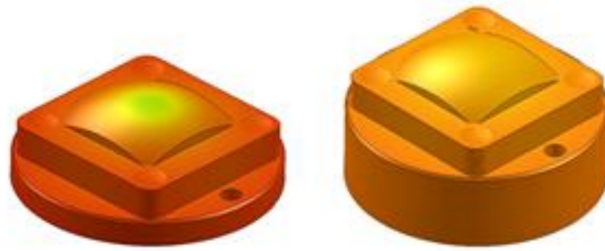


Figure 1. Plano-like elements with different heights for FEM analysis.

Three different types of mounting (screw, collet chuck, and Morse taper) were simulated as a mounting base (see figure 2).

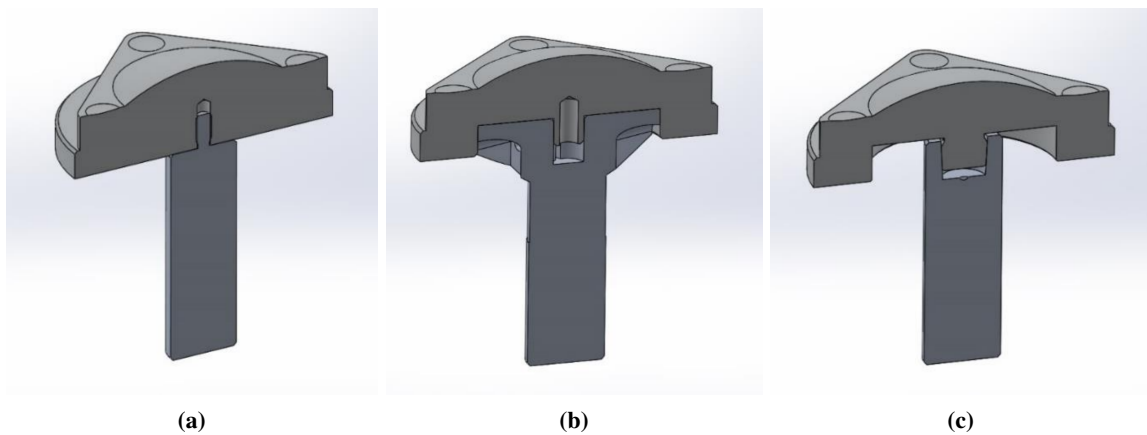


Figure 2. Types of mounting: a) screw; b) collet chuck; c) Morse taper.

2.1.1 Screw mount

The simplest and probably most common type of mount, which would be the method of first choice, is the screw mount. A simple M6 threaded hole in the central bottom part of the element was analyzed. In order to always mount the element in a controllable way, the torque wrench was introduced to the process. The first clamping system tested was a post with a standard screw (see figure 2a). However, it was shown that a screw mount introduces huge deformations to the

surface. FEM analyses were done for two materials (aluminium and steel), for two thicknesses of the cylindrical base (10 and 30 mm), and also for two torques applied on the screw. The torques of 2.8 Nm and 5.7 Nm were selected so that the tension of 20 kN and 40 kN was obtained. First, the aluminium element with a cylindrical base 10 mm thick was tested. The torque applied to the screw was 2.8 Nm. Figure 3 left shows a side cut view with the position of forces. The deformation shown in false colors in figure 3 right reveals that the displacement is far from the required values (i.e., deformation below 30 nm). Second, the same torque of 2.8 Nm was simulated on the 30 mm thick steel element. It caused a deformation of 200 nm peak-to-valley (PV). The results obtained for other parameters are summarized in table 1. They show that a different type of mounting must be used to meet the requirements of a deformation below 30 nm.

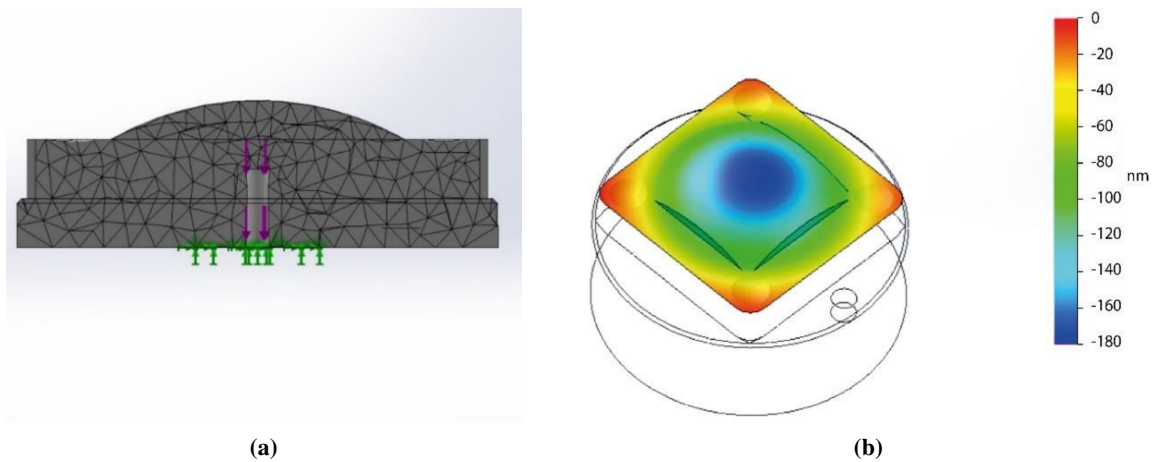


Figure 3. (a) Forces defined in the screw mount, violet arrows-tension applied to the screw inside the hole, green arrows-pressure applied by the flange of the pole to the base of the element; (b) The top surface deformation for the screw mount system, thickness 30 mm, steel and torque of 2.8 Nm.

Table 1. Results of FEM analysis for complex surface-screw mount.

Material	Al	Al	steel	steel	Al	Al	steel	steel
Thickness [mm]	10	10	10	10	30	30	30	30
Torque M_u [Nm]	2.8	5.7	2.8	5.7	2.8	5.7	2.8	5.7
dh/dM_u [nm/Nm]	855	842	276	270	238	233	71	70
Deformation h [nm]	2393	4800	774	1538	667	1330	200	400

2.1.2 Collet chuck

The second virtually tested clamping system is based on a collet chuck. A band around a stump in the middle of the element is tightened by a screw. The hole in the center of the shank (figure 2b) is designed to prevent the surface from bulging as the holder is tightened. The holding force tested was 500 N (low load). Again, two materials and two thicknesses were tested: aluminum and steel with the cylindrical base thicknesses of 10 mm and 30 mm. The results of the analysis for the

10 mm thick steel element are illustrated in figure 4 while the results for the other parameters are summarized in table 2.

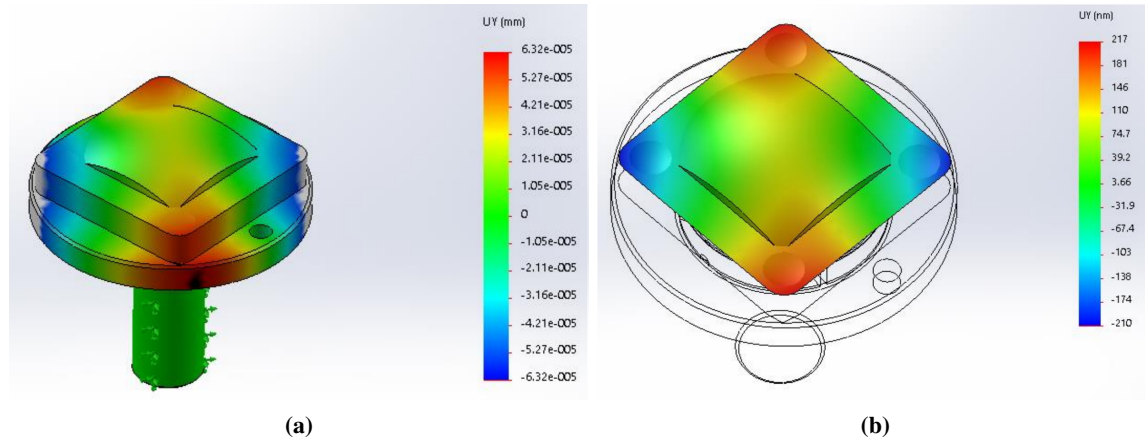


Figure 4. (a) Displacement of surface elements of the element for the collet chuck system, thickness 10 mm, steel, and holding force 500 N. Red and blue color represent limit displacement values of $+63.2\text{ nm} - 63.2\text{ nm}$; (b) The top surface deformation for the collet chuck system, thickness 10 mm, aluminium, and holding force 500 N (PV 427 nm).

It is obvious that the deformation of the optical surface is lower compared to the screw mount. However, the outcome is still not sufficient for the intended purpose.

Table 2. Results of FEM analysis for complex surface-screw mount.

Material	Al	steel	Al	steel
Thickness [mm]	10	10	30	30
Holding force [N]	500	500	500	500
Deformation h [nm]	427	131	162	50

2.1.3 Morse taper

Finally, the Morse taper mounting method (figure 2c) was tested. The main advantage of this construction is a symmetric load on the shank. The same materials, aluminum and steel, were tested with a base thickness of 10 mm and a pressure of 0.5 MPa on the surface of the taper. This pressure approximately represents the force of easy insertion. Some results are shown in figure 5, while table 3 introduces values obtained for different parameters.

The results show that the Morse taper type of mount only introduces a very low undesirable deformation in the range of a few nanometers to the optical surface form.

2.2 Spherical elements

Since the FEM analysis of the complex surface revealed the importance of the mounting, the FEM analysis has been applied to simpler spherical surfaces. Spherical surfaces are easier to manufacture

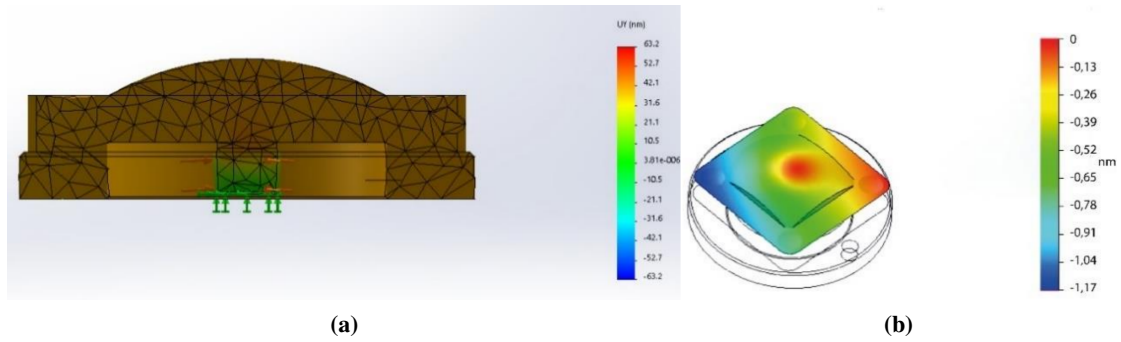


Figure 5. (a) Displacement inside the element for the Moser taper system, thickness 10 mm, aluminium, and pressure of 0.5 MPa. Deformation within the element is in the range of 0 to 40 nm and most of it is concentrated in the shank; (b) The top surface simulated deformation for the Morse taper system, thickness 10 mm, aluminium, and pressure 0.5 MPa (PV 1.3 nm).

Table 3. Results of FEM analysis for complex surface-screw mount.

Material	Al	steel	Al	steel
Thickness [mm]	10	10	10	10
Pressure [MPa]	0.5	0.5	1.0	1.0
Deformation h [nm]	1.3	0.4	2.6	0.8

and measure and, therefore, the spherical surface shape was used to verify the FEM analysis by experimental results. Three spherical elements made of aluminum RSA 6061 with a radius of $R=40$ mm and a diameter of $D=40$ mm were generated for the FEM analysis:

- Element A) Screw mount (M6), element height 20 mm
- Element B) Screw mount (M6), element height 40 mm
- Element C) Morse taper, element height 20 mm

The calculated deformations introduced for the different elements are shown in figure 6 and are summarized in table 4.

Element A was used for measurement and therefore the sensitivity dh/dMu of the element deformation h with respect to the applied torque Mu was computed from the FEM simulation results. Using linear regression, for element A holds:

$$\frac{dh}{dMu} = 263 \text{ nm/Nm} . \quad (2.1)$$

3 Validation of FEM simulations

The flat and the spherical surfaces with a specific radius were selected in order to verify the FEM simulation results by experimental results. The form of the flats as well as the sphericity of the spherical surfaces are easy to measure with a classical Fizeau interferometer (figure 7). Furthermore, the radius of the spherical surface form can be measured with an interferometric radius measurement bench [8].

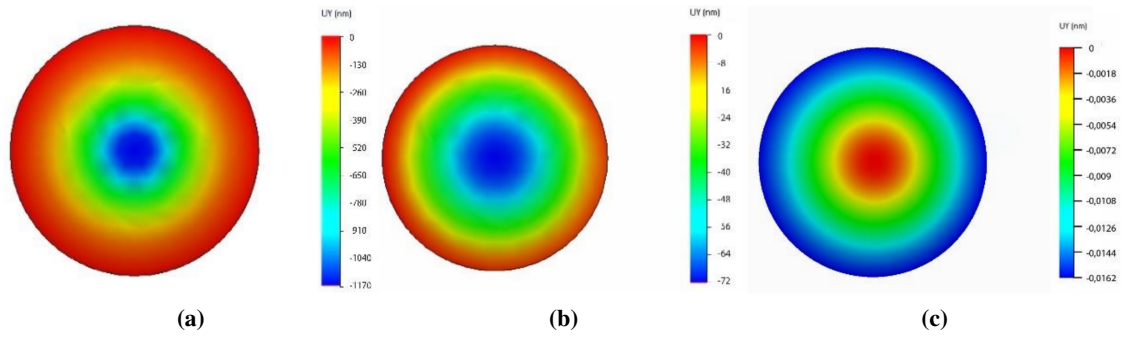


Figure 6. Deviation from nominal shape (a) element A at torque of 5 Nm; (b) element B at torque of 5 Nm; (c) element C at torque with pressure of 0.01 MPa.

Table 4. Results of FEM analysis for spherical elements A, B, C. For A and B the torque is the independent parameter, for C it is the force / pressure.

Tightening torque Mu [Nm]	Element A deformation h [nm]	Element B deformation h [nm]	Pressure [MPa]	Element C Deformation h [nm]
2.5	660	36	0.001	0.0018
5	1300	72	0.01	0.018
7.5	2000	108	0.1	0.18
10	2600	144	0.5	0.9
20	5300	288	1	1.8

3.1 Deformation of a flat surface

In order to experimentally verify the same behavior as observed in FEM analysis, first, a flat surface (60 mm diameter, 20 mm thickness) was manufactured using RSA 6061 aluminum. It was attached to a post with a screw, applying different amounts of torque using a torque wrench. Initially, the surface shape was measured without any torque applied. The measured deviation from the design is shown in figure 8. Further, the shape measurement was carried out when applying a torque of 8 Nm, see figure 9. The results show a 1547 nm PV deformation of the surface form due to the mounting. Assuming a linear approximation, the deformation sensitivity of $dh/d\mu = 193 \text{ nm/Nm}$ can be calculated from the results. The uncertainty of the height measurement is in the range of 2% (10 nm) while the torque wrench uncertainty was specified being 6% and this was verified by calibration measurements. The deformation is in the same range as obtained by FEM simulations for complex surface (see table 1) and the mounting influence was confirmed. The discrepancy between FEM analysis and the measured values is primarily caused by different element shapes and, therefore, spherical elements were manufactured and used for verification.

3.2 Spherical elements testing

For testing the impact on the surface shape, three spherical elements (radius 40 mm, diameter 40 mm) were manufactured from RSA 6061 aluminum (elements A, B, C introduced previously), see figure 10.

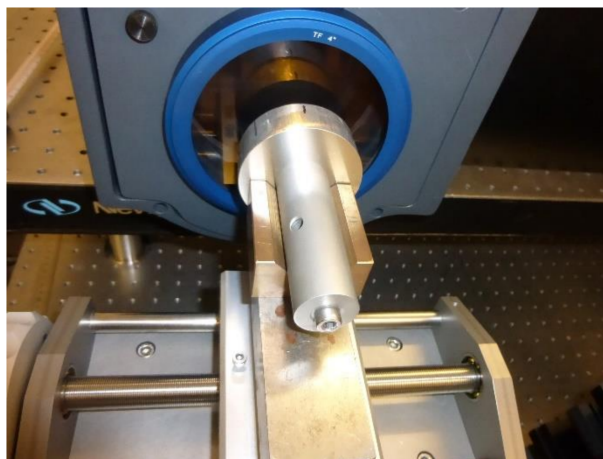


Figure 7. Flat surface with attached post during the measurement.

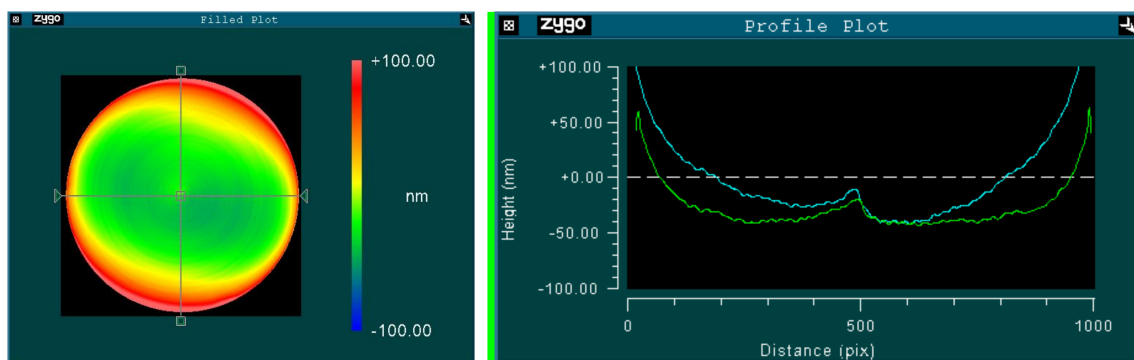


Figure 8. Initial surface shape (flat surface).

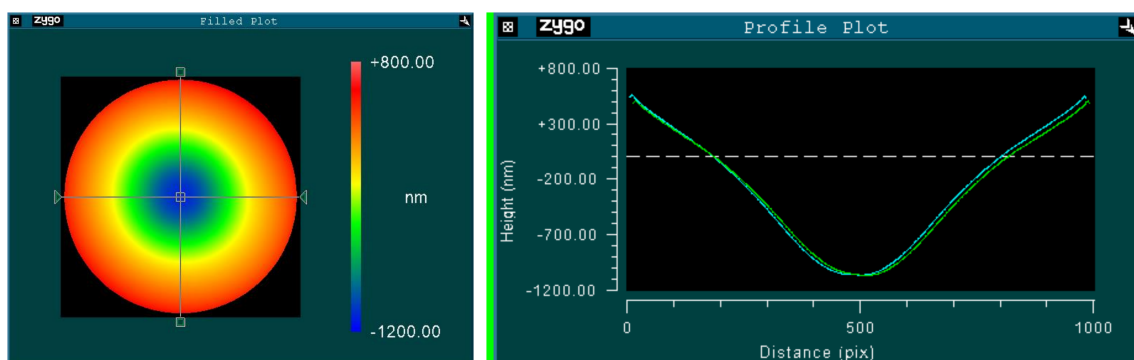


Figure 9. Surface topography when torque of 8 Nm is applied.

Sample A with a height of 20 mm was measured using different amounts of torque and compared to the result expected from FEM simulations. In the first measurement, the basic sphericity of the element without applied torque was measured by a Fizeau interferometer and the measurement was subtracted in advance. Therefore, only the additional effect induced by the torque can be evaluated in the next measurements. The measurement result for an applied torque of 7.5 Nm is shown in

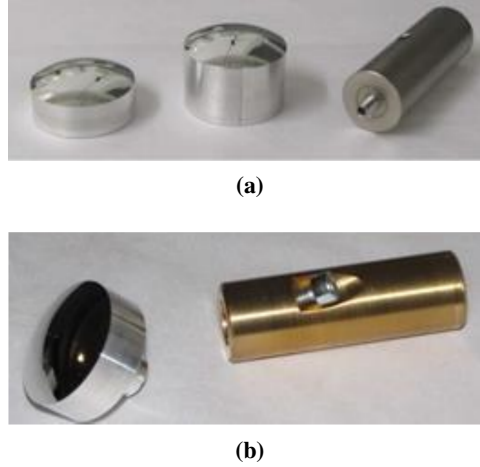


Figure 10. Spherical elements with a screw mount (a) and the Morse taper mount (b).

figure 11. The peak-to-valley deviation amounts to only about 50 nm and is, therefore, much lower than the expected value of 2000 nm PV obtained by FEM analysis in table 4. The measurements were carried out on a Fizeau interferometer (Zygo VeriFire MST) with a transmission sphere (figure 12), where defocus is a free parameter. The system-immanent subtraction of the spherical contribution in the Fizeau interferometer could cause the big gap between the FEM simulations and the measurement results. Moreover, the FEM simulations presented in figure 6 show that a spherical deformation is the most significant contribution to the total deviation. Therefore, the absolute radius measurement was carried out by a radius measurement bench for different amounts of torque to also measure the deformation in the spherical contributions and verify the results of the FEM simulations.

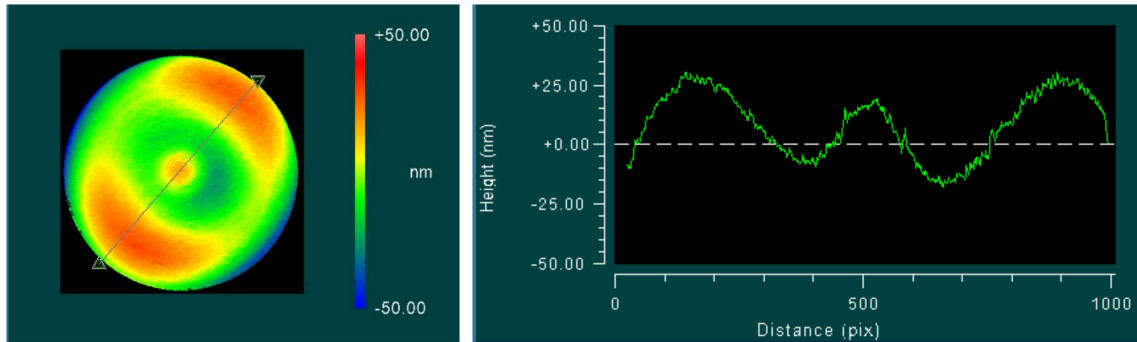


Figure 11. Results of the sphericity measurement (measurement at 0 Nm torque subtracted) of the element with 40 mm diameter and 20 mm thickness at a mounting torque of 7.5 Nm.

The radius was measured with a radius measurement bench. The setup is based on an interferometric measurement, where the radius can be determined from the distance between two distinguished positions: the cat's eye position and the confocal position [8]. The relative uncertainty of the radius measurement is in the range of 10^{-5} and thus has no apparent influence on the verification. The elements were measured applying different values of the torque used for fixation. The torque μ was sequentially increased from 2 Nm to 6 Nm by a torque wrench with a nominal

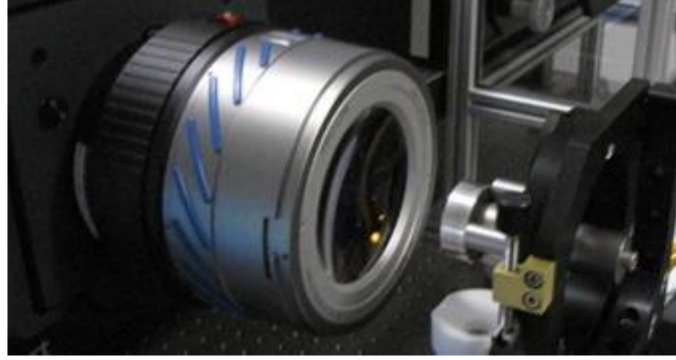


Figure 12. Measuring the sphericity of the spherical elements at different mounting torques.

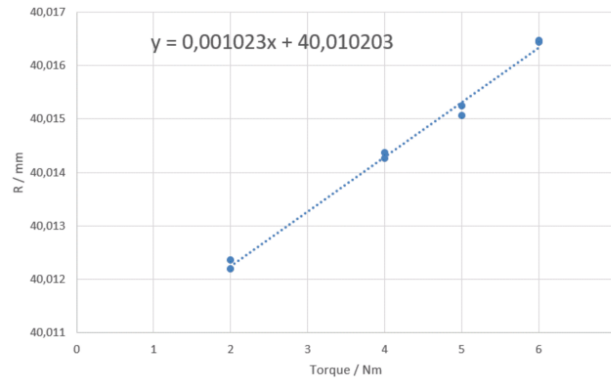


Figure 13. Radius measurement of spherical element at different torques and linear approximation.

accuracy of $\pm 6\%$ (verified by torque measurements at a reference setup at PTB). The results of the measured radii are plotted in figure 13. The measured radii values can be approximated by a linear regression:

$$\frac{dR}{dMu} = -0.0010 \text{ mm/Nm}. \quad (3.1)$$

In order to have comparable results between the FEM simulations and the measured radii, spherical deformation h was transformed into radii R using:

$$\frac{dh}{dR} = 1 - R \left(R^2 - \frac{D^2}{4} \right)^{-\frac{1}{2}}, \quad (3.2)$$

where D stands for surface diameter. Geometrical assumptions are derived from figure 14.

Putting values obtained by FEM analysis (2.1) into (3.2) yields $dR = -6.5 dh$ and the radius error sensitivity for the FEM analysis of sample A can be rewritten as:

$$\frac{dR_{\text{FEM}}}{dMu} = -0.0017 \text{ mm/Nm}. \quad (3.3)$$

The approximate agreement between simulated (3.3) dR_{FEM}/dMu and measured (3.1) dR/dMu results confirms the validity of the FEM simulations.

There are several contributors to the discrepancy between (3.1) and (3.3). Some parameters of the FEM analysis can only be estimated. One example can be the tightening torque coefficient,

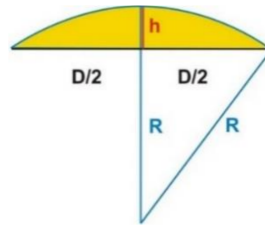


Figure 14. Geometrical assumption for radius-sphericity (power) values conversion.

which is commonly within the range of 0.08–0.15 (we used 0.12 in the FEM analysis presented here). Moreover, in (3.3) it is assumed, that the shape deviation (PV value) is composed only of a sphericity error (power or defocus term).

Therefore, the performed measurements confirm the results of the FEM simulations and show that it is necessary to employ the Morse taper as a mounting method in order to ensure a repeatable mounting of the MRSs or any other optical element, especially when the goal is to reach an overall measurement uncertainty of well below 30 nm.

4 Conclusion

Three types of clamping of HD25 shank to the metrology element were tested. The main rating factor was the peak-to-valley value of the top surface deformation caused by adding a HD25 shank. Since the aim of the EMPIR FreeForm project is the development of metrology systems for aspherical and freeform surfaces with an uncertainty of well below 30 nm, the deformation of the reference elements induced by the clamping needs to be significantly lower. The testing was based on FEM analysis. Fixing the element by a screw mount proved unsuitable for our purpose and the deformation effects shown should also be considered in other applications. In each tested screw mount variant, the top surface was deformed in the order of hundreds of nanometers. The system based on the collet chuck leads to an improvement in the results. However, even for the most rigid variant, the top surface was deformed by 50 nm PV, which is still a non-negligible surface deformation. The last mounting method that was investigated was the Morse taper. This mounting method leads to a significant reduction in the top surface deformation introduced by the process of mounting. All the combinations tested caused deformations in the range of 0.4 nm to 2.6 nm. These values fully meet the requirements concerning top surface stability. The results of the FEM analysis were verified by interferometric form and radius measurements.

Acknowledgments

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