euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017

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Ion beam assisted sphericity error correction of Si spheres as new kg artefacts

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Abstract

Full spheres made of silicon exhibiting a very high degree of roundness and a mass of 1 kg are utilized as artefacts for the accurate determination of the Avogadro number N_A in the framework of the International Avogadro Coordination project. The knowledge of an accurate value of N_A with low relative uncertainty is required for a redefinition of the SI unit mole. It may also contribute to the redefinition of the SI unit kilogram which is awaited to take place in 2018. Furthermore, silicon spheres of 1 kg can be used as artefacts for dissemination of the new kg. Since the sphericity error of such spheres significantly contributes to the measurement uncertainty in interferometric sphere volume determination it is desirable to further reduce the surface error of such spheres. Further improvement of the form error aiming at values of <10 nm PV has been investigated by deterministic ion beam figuring. The ion beam figuring utilizing low energy ions of 500-1000 eV is an established process for optical surface correction. One of its key features is its assumed insensitivity of the material removal mechanism with respect to crystalline orientation. The process has been adopted for the figuring of silicon spheres. A multi-axis CNC motion system equipped with ion beam source as well as with sensors for sphere alignment has been set up to treat the full sphere. Based on the surface topography measurement provided by PTB a bespoke dwell time calculation algorithm and process simulation combined with a spiral tool path has been developed and applied to a sphere correction process. As a result a partial improvement of the sphere surface could be achieved. The interferometric measurement and the machining process will be presented and discussed.

Avogadro project, silicon spheres, ion beam figuring

1. Introduction

The awaited redefinitions of the SI unit kilogram based on the Planck constant h and the unit mole based on the Avogadro number N_A in 2018 require new procedures for application and dissemination of mass standards. Two different approaches have been investigated for many years, namely, the watt balance experiments and the International Avogadro Coordination Project (IAC). The central artefacts of the latter project are extremely round isotopically enriched single crystal silicon spheres with diameter of approximately 93 mm and a mass of 1 kg. Counting the atoms which constitute the sphere by means of specialised interferometric volume measurements provides a correlation between the sphere's mass and N_A or h, respectively[1]. The demanded total relative measurement uncertainty of less than $2x10^{-8}$ for the mass determination requires highly spherical artefacts with form errors of less than 10 nm PV in order to ensure sufficiently precise interferometric measurements. Over the past 5 years silicon sphere polishing has been improved to achieve sphericity errors of less than 30 nm PV. However, the polishing process shows a certain response to crystallographic orientation ending up with more or less regular patterns on the surface topography that can hardly be avoided.

Ion beam figuring (IBF) is known to be a sub-surface damage free finishing technology applied in high precision optics manufacturing [2]. Its main advantage consists in non-mechanical material removal based on the interaction between energetic atomic particles and the surface atoms (i.e. physical sputtering). The impinging particles induce collision cascades in the surface leading finally to an amorphous layer of approx. 7 nm thickness that masks to some extent the crystallographic orientation of the silicon crystal. Hence, the material removal rate is expected to be independent on the orientation.

In contrast to an IBF process used in optics manufacturing where convex or concave mirror or lens surfaces are machined with standard configurations of 3-axis or 5-axis CNC motion systems, the treatment of a sensitive full 3D object is more complicated with respect to mounting, alignment, motion and machining. In a previous work we reported on the extensive alignment procedures to mount a sphere in an IBF system [3]. The current paper presents first machining results on a Si sphere and evaluates the ion beam process and its side conditions regarding the material removal behaviour and process immanent alignment problems.

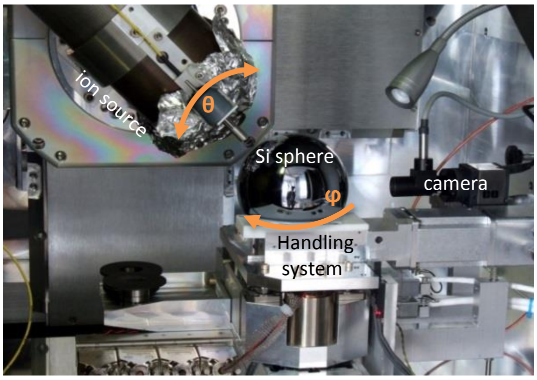

Figure 1. Ion beam figuring system for sphere surface correction

2. Ion beam figuring system

Fig. 1 depicts the ion beam system inside a high vacuum chamber. The ion beam source is moved by combination of two linear axes and a tilt axis to perform a motion along the θ coordinate. The sphere rests on a rotary stage that carries out the motion along the φ coordinate of a spherical surface coordinate system, leading to a spiral path of the ion beam over the surface. With this configuration only the upper hemisphere is accessible for the ion beam in one processing step. Hence, a sphere handling system is attached that lifts the sphere from the turntable and rotates it by 180° around a horizontal axis. In this way a full sphere can be treated in two consecutive steps. Ion beam energy has been set to 1000 eV which is a common value to minimize surface damage at high sputter yield.

Deterministic machining requires accurate alignment of the workpiece with respect to the machine coordinate system. This is done by a semi-automatic procedure using a camera and a chromatic distance sensor that aligns a narrow laser generated fiducial mark located on the sphere surface to the motion system. Furthermore, the material removal function of the ion beam source has to be determined by test etchings prior to machining. The applied removal function exhibits a rotationally symmetric Gaussian shape with full width at half maximum of 5.5 mm and an amplitude of 1.5 nm/s. The sphericity error topography has been measured by a dedicated sphere interferometer at PTB [4].

3. Machining results and discussion

Fig. 2 (a) shows the initial topography of a full silicon sphere exhibiting error value of PV = 36 nm and RMS=6.43 nm. The regular pattern originates from the mechanical polishing process reflecting the respective crystallographic structure of the silicon single crystal. The IBF machining process altered the topography as can be seen in Fig. 2(b). On the northern hemisphere a significant reduction of the regular structure has been achieved. The masked area in the polar region was contaminated by carbonaceous species from the ion beam source that resulted in deposition of an ion etch-inhibiting layer. Contamination took place during the ion source warm-up phase while the beam was directed to the free space inside the vacuum chamber. Sputtered material from the chamber wall spread diffusely through the chamber and deposited on the sphere.

The height of the error structures on the southern hemisphere has been reduced as well. However, a slight overetching has occurred leading to an inversion of the structures. Obviously, the etching rate stability was not sufficient during the machining process for the full sphere which lasted approximately 5h. The step of PV = 2 nm along the equator line is probably caused by a slight workpiece misalignment during the 180° rotation between the machining of the northern and southern hemisphere.

The machining result can be evaluated by displaying topography data in the form of height histograms which are shown in Fig. 3. The initial topography data exhibit a rather broad distribution (red curve). Taking the absolute radius values from interferometer measurements into account the centroid of the topography data shifts by approx. 20 nm due to an overall sphere radius decrease. The distributions of the topography data after the machining process on the northern (blue curve) and southern (green curve) hemisphere show a higher degree of symmetry and smaller width, meaning that the height values are more evenly and closely distributed around the new centroid.

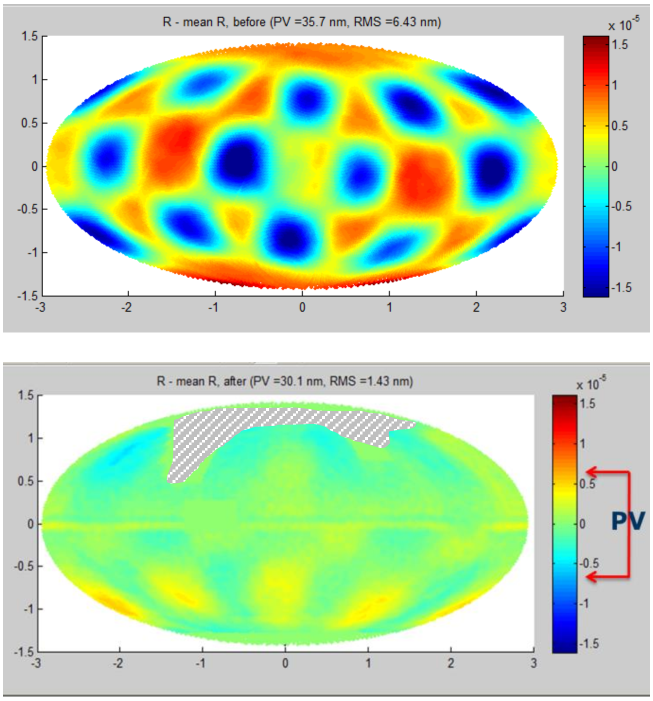

Figure 2. (a) Initial topography of the full Si sphere with PV = 36 nm and RMS= 6.43 nm, (b) Topography of machined surface with PV=15 nm and RMS = 1.43 nm.

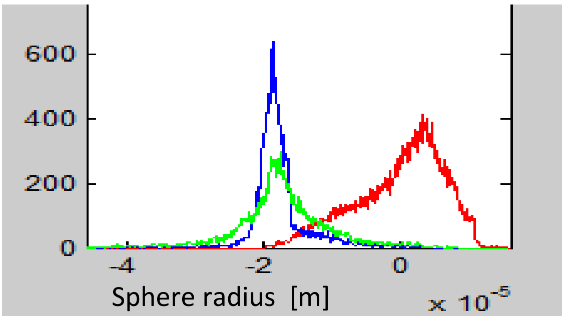

Figure 3. Histograms of sphere radii. w.r.t. mean radius before machining. Red line: distribution of initial error, Blue line: radius distribution on northern hemisphere after first machining, green line: radius distribution on southern hemisphere after first machining

4. Summary

The paper presents the successful error correction of a Si sphere by means of deterministic ion beam figuring technology. Albeit parts of the surface have unintendedly been covered by an etch inhibiting layer the prevailing area has been improved to a PV value of 15 nm. Further work will be performed to prevent surface contamination (e.g. by optimized ion beam source heating-up procedure and shieldings) and to stabilize the material removal rate during the ion etching process. More Si spheres are planned to be treated with ion beams in order to reduce the figure error below PV 10 nm on the full sphere.

References

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