DOI 10.5162/SMSI2020/E1.1

Innovative Mass Standards for the Worldwide Transfer of the Redefined Unit Kilogram

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Summary:
Manufacturing processes and handling procedures for new stable silicon mass standards with unprecedented accuracy have been developed and transferred to industry. The patented manufacturing process and the high precision calibration procedures were developed by PTB. Both the manufacturing process for the spheres and the handling of the spheres were extended to two small and medium-sized enterprises (SME). The transfer was part of the three-year transfer project “Si-kg” for industrial requirements and placed on the market with great success.

Keywords: Silicon, Kilogram, mass standard, sphere

I. Introduction

The Physikalisch-Technische Bundesanstalt (PTB) was significantly involved in the redefinition of the International System of Units [1]. In the field of mass, for example, the 130-year-old International Kilogram Prototype (IPK) was replaced by kibble balance methods and by several unique spheres with nominal mass of 1 kg made of monocrystalline isotopically enriched silicon (^{28}Si) [2]. In case of the silicon sphere, the unit kilogram is linked to the mass of its individual atoms and "traced back" to them [3]. A key challenge of this new approach has been to produce spheres with unprecedented accuracy in roundness and surface quality. In order to minimize measurement errors and the influence of undesirable environmental conditions, many physical barriers had to be overcome. For this purpose, PTB developed a manufacturing process for monocrystalline silicon. Since the high-cost and the complex enrichment process of the isotopically enriched material, only 12 spheres made of ^{28}Si will probably be available in the world.

Therefore, alternatives had to be developed for National Metrological Institutes, Calibration Laboratories and manufacturers of weighing instruments to reliably disseminate the unit kilogram via silicon spheres.

II. Know-How Transfer of Manufacturing Silicon Spheres to Industry

The manufacturing process was transferred to a small and medium-sized enterprises (SME) in order to produce spheres of natural monocrystalline silicon (^{nat}Si).

The patented manufacturing process of the purpose-built machine provides contaminant-free spheres showing only minor shape errors, low roughness and a very uniform and stable oxide-layer [4]. Despite the robust crystal structure, the polishing process enables due to the special composition of the polishing paste to physically remove atoms from the surface without scratches nor subsurface damage of the crystalline structure. The polishing process achieves very low roughness and achieves a defined thickness of oxide layers. As a result, mass standards made of silicon achieve a long-term stability that has not been achieved before.

The manufacturing partner is able to use the transferred process for the production of a large range of spheres. This includes spheres made of other materials as well as spheres that can be used as density standards.

Figure 1 Polishing machine to manufacture high-precision spheres

III. Know-How Transfer of Handling, Transportation and Cleaning of Silicon Spheres

The know-how about handling silicon spheres and the necessary tools were passed on to a second company which has a long experience in manufacturing weights. In a series of trials and practical tests lasting several years, PTB has identified materials with which silicon spheres can be safely handled, stored and transported. In order to guarantee the extremely high mass stability, the silicon spheres are mounted on special rings which neither scratch the sphere nor leave any adhering to the surface of the sphere.

In contrast to other mass standards, silicon spheres can be cleaned in a simple, efficient and cost-effective way to remove all surface contamination. This cleaning procedure enables the high stability. Therefore, special cloths and handling equipment were developed and optimized with the industrial partner. In addition to the spheres, the cleaning and handling equipment, the sales partner offers training courses for silicon spheres handling.

In close cooperation a broad selection of accessories for silicon spheres like transport container and transport case, special tongs and fork (shown in Figure 2) and sphere holder for universal applications were designed [5].

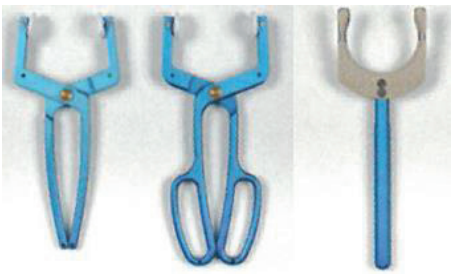

Figure 2 New designed special handling tools (tongs and fork) for silicon spheres

IV. Results

With the transfer of the sphere's manufacturing technique to an industrial company and the transfer of handling to a second SME, a worldwide unique ready to use infrastructure has been realised which allows highly stable and accurate mass standards to be delivered.

During the project period, the requirements for the high-precision manufacturing were even more than exceeded. Silicon spheres with form deviations (RONt) of less than 20 nm can now be manufactured by industry. Table 1 shows the achieved measurement uncertainties of the silicon spheres manufactured by the industrial cooperation partner [6]. All spheres are adjusted to 1 kg +/- 200 mg.

Tab. 1: Measurement uncertainties U(k=2) of silicon spheres manufactured by manufacturing partner. All measurements are done by PTB

Parameter	U(k=2)
Mass in air	50 µg
Mass in vacuum	25 µg
Density (hydrostatic)	0.004 kg/m³
Roughness S_a	< 0.5 nm
Form deviation RONt	10.2 nm
Average layer thickness	0.4 nm

The established infrastructure can meet the increasing global demand for stable high-precision mass standards. This is underlined by the sales of six silicon spheres, which were already sold to international customers during the project period. In addition, more than 12 spheres were distributed to leading national institutes worldwide for individual practice.

V. Summary

Processes for the production of mass standards made of highly enriched silicon with nominal mass of 1 kg have been developed in the preparation of the redefinition of the unit Kilogram. The methods and procedures were successfully transferred to industry for the manufacturing of spheres made of natural silicon. The transfer of the patented manufacturing process to two SMEs led to previously unattained small form deviation (RONt) of less than 20 nm in industrial production of spheres. An infrastructure which includes user-friendly handling tools and the needed accessories for the cleaning procedure was established. In future the procedures can be modified in order to manufacture spheres made of different materials and with different diameters.

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