Validation of the sandblasting process in the manufacturing of precision spheres for non-contact metrology

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Abstract: In order to ensure the measurements that can be made with non-contact metrology technologies, it is necessary to use verification and calibration procedures using precision artefacts as reference elements. In this environment, the need for increasingly accurate but also more cost-effective calibration artefacts is a clear demand in industry. The aim of this work is to demonstrate the feasibility of using low-cost precision spheres as reference artefacts in calibration and verification procedures of non-contact metrological equipment. Specifically, low-cost precision stainless steel spheres are used as reference artefacts. Obviously, in order for such spheres to be used as standard artefacts, it is necessary to change their optical behaviour by removing their high brightness. For this purpose, the spheres are subjected to a manual sandblasting process, which is also a very low-cost process. The equipment used to validate the experiment is a laser triangulation sensor mounted on a Coordinate Measuring Machine (CMM). The CMM touch probe, which is much more accurate, will be used as a device for measuring the influence of sandblasting on the spheres. Subsequently, the influence of this post-processing is also checked with the laser triangulation sensor. Ultimately, the improvement in the quality of the point clouds captured by the laser sensor will be tested after removing the brightness, which distorts and reduces the quantity of points as well as the quality of the point clouds. In addition to the number of points obtained, the parameters used to study the effect of sandblasting on each sphere, both in contact probing and laser scanning, are the measured diameter form error, as well as the standard deviation of the point cloud regarding the best-fit sphere.

Keywords: Sandblasting, Precision spheres, Non-contact metrology, Laser scanning.

1. Introduction
Metrological verification using optical equipment is of increasing interest in industry. The possibility of improving this equipment through adjustment and calibration processes has been one of the main focus of the most recent research [1,2]. The idea is to assess the measurements that can be made with these non-contact technologies, thus extending their application beyond typical reverse engineering applications.

The aim of this work is to validate the sandblasting process as a process for modifying the surface condition of precision spheres in order to use these spheres as reference artefacts for adjustment, verification and/or calibration of optical sensors and non-contact reverse engineering equipment [3].

The final target of this research is to find out whether a low-cost process (manual sandblasting) can be applied to stainless steel precision spheres, of very low cost as well, to materialize calibration spheres for non-contact metrology. It is expected that the loss of precision in both diameter and form error of
the post-blasting spheres will be low enough for this purpose. Ideally, the form errors of the sandblasted spheres should be at least one order of magnitude lower than the measurement uncertainty of the optical equipment. In any case, this experimentation will reveal which equipment is suitable for being calibrated with this type of sandblasted spheres.

Nowadays, the manufacturing of precision ceramic spheres (grades G3, G5 or G10, with sphericity $< 0.25 \text{ µm}$, $Ra < 0.020 \text{ µm}$, according to ISO 3290/DIN 5401 [4]) is very costly. This is mainly due to the fact that they are built specifically for this purpose, starting from ceramic powder, sintered and subsequently polished. They also require high hardness and wear resistance, using materials such as ruby, alumina, sapphire or zirconia, among others. However, when they are intended to be used as reference elements, neither high hardness nor high wear resistance is required. In the context of the aim presented in this work it is in fact sufficient that they are made of stainless materials, for example aluminum alloys or steels of qualities such as AISI 304, AISI 306, or similar.

The spheres used in this research are stainless steel precision balls commonly used in the bearing industry whose cost is lower but also featuring worse manufacturing qualities (G50 or G100 [4], with sphericity $< 2.5 \text{ µm}$, $Ra < 0.1 \text{ µm}$).

For optical applications, G100 accuracy or lower (according to ISO 3290) is enough unless the spheres show excessive brightness. Precisely, the idea of the experiment is to eliminate the very shiny finish (mirror-like) of the sphere surface, checking the variations in both diameter and form error caused by the sandblasting process. Another very important objective of the experiment is to quantify (if it exists) the improvement in the quality of the point clouds achieved by a laser triangulation equipment with respect to the cloud obtained on the polished, pre-sanded sphere.

The shot peening process, in this case sandblasting, will be carried out in a manual sandblasting machine using fine grain size sand. Obviously, a certain variability is added even though the process variables are under control (grain size, exposure time, distance and the incident direction of the sandblasting stream onto the spheres). This variability must be studied so that the detected wear (or surface attack) will be assessed as rigorously and objectively as possible.

Therefore, the work includes sandblasting tests on stainless steel spheres of different diameters, evaluating (by CMM measurement) the variation of the mean diameter value and especially the loss of form error. In addition, it will also be interesting to analyse the variation of the standard deviation of the point cloud, as this is a crucial parameter in the measurement of the quality of the laser point cloud [5].

2. Methodology and experimental procedure

Since the process chosen to perform the modification of the surface condition is manual sandblasting, it requires statistical validation to be considered valid, minimizing the operator’s influence on a given sphere. Therefore, the experimentation includes a range of different sets of spheres, each set corresponding to a different nominal diameter.

Specifically, 3 sets of spheres of different size were analyzed (3 plates including 10 spheres each, of diameters 10, 18 and 25 mm, respectively, as shown in figures 1 and 2). From these analyses, the average values and standard deviations are determined for each one of the sets of 10 spheres, which are distributed over the corresponding plate with a similar layout. The diameter and form error values of the spheres of each set have been measured by contact (CMM with SP25M scanning probe) and by laser triangulation (Hexagon HP-L-10.6 sensor mounted on the CMM), first at their original polished state, before the surface attack, and secondly after being surface treated by sandblasting.

Contact measurements of the spheres were carried out with a coordinate measuring machine (CMM), the DEA Global Image 091508 model, equipped with a PH10MQ indexing head. A Renishaw SP25 contact scanning probe can be mounted on this head. PC-DMIS 2018 R2 software was used to configure the CMM, setting parameters, paths, and number and distribution of points. The tip used was a Ø1.5 mm ruby sphere for both polished and post-sanded spheres. The accuracy of this CMM is given by the manufacturer (Hexagon Metrology) according to ISO 10360-2 [6] and according to the latest calibration $E_{0,MPE} = 2.2 + 0.003 \cdot L (\text{µm})$, $R_{0,MPL} = 2.2 \text{ µm}$. 

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Although this MPE parameter is no substitute for uncertainty of dimensional or form measurement, the use of a sufficiently representative number of spheres, as well as several repetitions (at least 3 for each sphere), provides enough traceability of the measurements. This is especially true when working with calibrated equipment and obtaining average values.

For the non-contact measurement, a laser triangulation sensor from Hexagon Metrology, HP-L-10.6, was used also attached to the CMM. This sensor comes with calibration certificate (ISO 10360-8) [7] with a maximum error specification of 0.020 mm. On the other hand, the surface treatment of the spheres was carried out with the Sablex S-2 machine using WFA F100 alumina oxide (average grain size 106 ~ 150 µm, and true density 3.9 g/cm³) as an abrasive element, projected onto the sphere surface at a pressure of 4 bar.

Figure 1 shows the diagram illustrating the methodology followed and the equipment used for the development of the research.

Figure 1. Research methodology

The procedure begins with the manufacture of three spheres sets. Each set consist of one rectangular plate with 10 spheres of the same diameter mounted on it (figure 2). The layout of the spheres of each plate makes handling easy and allows the univocal identification of each sphere inside. The base plates were also made of stainless steel (AISI 316L), the same material as the spheres.

The plates were also sandblasted prior to any measurement to avoid reflections on the spheres. The precision spheres were drilled using two hemispherical jaws, so that the drill bit did not produce any permanent marks or deformations. Each hole in the sphere was then threaded, in order to screw the sphere onto the base plate. All spheres are made of precision AISI 316 stainless steel of commercial grade G100 quality, with a sphericity of less than 2.5 µm and an arithmetic mean roughness Ra < 0.1 µm.

Next, the 30 spheres were measured. First, by contact with the coordinate measuring machine (CMM) obtaining high accuracy reference values, both dimensional and geometrical. Likewise, this 30 spheres were digitalised using non-contact measurement techniques by means of a laser triangulation sensor.
Figure 2. Plate with 10 spheres of the same diameter. (a) Designation of the spheres and reference system. (b) CMM Contact measurement of a set of ten spheres (25 mm diameter) on the original base plate. (c) CMM contact measurement of a sandblasted base plate.

Once all (original) spheres were measured, the surface condition of the spheres has been modified by means of a sandblasting process with alumina oxide projection, obtaining sets with less brightness and a different texture. Similar to the previous one, CMM measurements have been repeated for the post-sandblasted spheres, both by contact (post-sandblasting reference measurements) and non-contact, with the laser triangulation sensor.

Figure 2(a) shows the 3−4−3 matrix design of each set of 10 spheres. This arrangement allows easy sandblasting of each sphere without influence from the adjacent sphere. In addition, it also facilitates the access of the laser triangulation sensor beam (especially above the equator) as well as the contact probe. The designation of the 10 spheres of each of the sets and the coordinate axes of the reference system used for the measurement procedure are also presented in figure 2(a).

The coordinate system of each plate is defined from 3 spheres in such a way that it is independent of the supporting plate. According to its nomenclature (figure 2(a)), the coordinate system is formed by spheres 1, 3 and 8 (XY plane), with sphere 1 being the origin and sphere 3 defining the Y axis. The same alignment definition has been applied for each of the 3 plates with spheres of 10, 18 and 25 mm. Figure 2(b) shows a detail of the CMM contact measurement (pre-sandblasting) on 25 mm spheres set.

Finally, the values of the measurements obtained from the contact measurements of the spheres before and after the sandblasting process have been compared, as well as the point clouds obtained in both cases from the non-contact measurements.

3. Results

3.1. Pre-sandblasting measurements

During the non-contact measurement of the spheres in their original state (pre-sandblasting) reflections caused by the brightness of the base plate were observed (figure 2(b)). These reflections added glare and reduced the quality of the point cloud captured by the laser sensor. This made it necessary to sandblast the base plate (figures 2(c)), previously to the insertion of the pre-blasted spheres. Once the two measurements (both contact and non-contact laser) had been made with the pre-blasted spheres, the spheres were sandblasted. A uniform and completely matt finish was obtained in the three sets (figure 3(a)).

Contact measurements were carried out with the SP25 head with a Ø1.5 mm diameter ruby tip. The laboratory has an air conditioning system that maintains the temperature within 20±1ºC. Measurements were made on the three sets of spheres with a minimum scanning density of 1 point/mm² for each of the hemispheres (only the upper half of each sphere is measured) of diameters of 10, 18 and 25 mm, respectively.
Table 1 shows the results of the contact measurements of the spheres in their original surface state before the sandblasting process. These data constitute the reference values for the subsequent comparative analysis that will be carried out with the measurements after sandblasting will be carried out later. Regarding contact measurements, the dimensions evaluated are the diameters of the spheres, the positions of their centres and the form error. The average diameter values were 10.0026 mm for the Ø10 mm spheres, 17.9977 mm for the Ø18 mm spheres and 25.0049 mm for the Ø25 mm spheres, while the average form deviation was 0.0035 mm, 0.0023 mm and 0.0028 mm, respectively. In general terms, these results correspond correctly to the estimated accuracy G100 for stainless steel spheres.

The spheres were then measured using a laser triangulation sensor (HP-L-10.6 from Hexagon Metrology) assembled in the CMM (figure 3(a)). In order to obtain a real and accurate comparison with the contact measurements, all measurements have been carried out under the same environmental conditions (light and temperature) and with the same procedure of alignment and sequence of the spheres. For the sphere captures, 5 orientations were used (4 at 45º from the cardinal points and one from the vertical position, at 0º). These orientations were sufficient to capture at least the upper hemisphere of each sphere without problems. The software used to capture the point clouds is the same PC-DMIS that controls the CMM, although Geomagic Control X software was preferred for point cloud processing. This treatment involved removing points belonging to the base plate and points located below the equator of the spheres. Finally, a standard "2·Sigma" filter has been applied to this trimmed cloud (hemisphere) to remove spurious points, clearly far from the spheres and which would distort all measurements.

| Ø 10 mm | Ø 18 mm | Ø 25 mm |
|---------|---------|---------|
| 10.0026 | 17.9977 | 25.0049 |
| 0.0137  | 17.8486 | 24.8608 |
| 0.0111  | -0.1132 | -0.1441 |

Table 1. Measurement results of the original (pre-sanded) spheres.

The results obtained are also shown in the central area of table 1. In addition to the diameter and the form deviation, the value of the standard deviation has been obtained when the cloud is fitted to a best-fit sphere (Least-square fitting). The average standard deviations are significantly larger than in the case of contact measurement, which corroborates the idea that a bright surface finish (these are "mirror polished" spheres) is not suitable for being captured with optical equipment. Note (table 1) that both diameter and form deviation values are far from the reference values (even up to -0.144 mm for Ø25 mm spheres or 0.187 mm for Ø10 mm spheres).

On the other hand, the standard deviation of the values obtained by non-contact measurement on polished spheres (original state) reaches high values, of the order of 0.031 mm, regardless of the diameter value. These data show the problems that arise when non-contact measurement systems are used on polished parts because the surface brightness (see figure 2) causes the generation of point clouds with poor metrological quality. In the case of pre-sandblasted polished spheres, an overall in the case of 10 mm spheres, it was usually not possible to obtain accurate diameter values due to insufficient point cloud data. Only by using high gain mode (low sensitivity), instead on normal gain mode (high sensitivity), it was able to capture enough points for all the spheres, filling at least the upper hemisphere completely (figure 3(b)). Thus, only this high gain mode allows the comparison between the pre- and post-sandblasting states.
3.2. Sandblasting and post-sandblasting measurement

In accordance with the main objective of this work, the surface sandblasting treatment of the test samples was carried out using WFA F100 alumina oxide as the abrasive. The Sablex S-2 blasting machine was programmed to work at a constant pressure of 4 bar. In this case, the measurements made by contact with the CMM machine show higher values for both the diameter of the spheres and the form deviation (table 2). Note that the sandblasting process generates a dimensional deviation with an average value of only 2.7 µm and an increase in the form deviation of about 1.7 µm. At this point, it should be taken into account that this value is even lower than the maximum permissible error of the CMM. This error is around 2.2 µm. It can therefore be concluded that, apart from a minimal variation in diameter, sandblasting has also kept the form deviation of the spheres practically unchanged.

The values obtained in the non-contact laser triangulation measurement were generated, as in the pre-sanding stage, using the capture mode with low sensitivity (high gain). The same type of spurious point filter was then applied, although now these defects appeared to a much lesser extent. In this case, the number of points captured with the laser sensor has increased for all of the three ranges of spheres, being 13975 points for each of the Ø10 mm, 43052 points for each of the Ø 18 mm, and 80126 points for each of the Ø 25 mm (table 3). The increase with respect to the pre-sanded spheres has reached 33.98%, 11.87% and 9.64%, respectively.

Table 2. Comparison of contact measurement results regarding diameter and form deviation pre- and post-sandblasting.

| Average Diameter [mm] | Average Form Deviation [mm] |
|-----------------------|-----------------------------|
|                       | Pre | Post | Difference | Pre | Post | Difference |
| Ø 10 mm               | 10.0026 | 10.0054 | 0.0028 | 0.0035 | 0.0046 | 0.0010 |
| Ø 18 mm               | 17.9977 | 18.0004 | 0.0027 | 0.0023 | 0.0044 | 0.0021 |
| Ø 25 mm               | 25.0049 | 25.0075 | 0.0026 | 0.0028 | 0.0047 | 0.0020 |

Regarding the measured data for the diameter of spheres, table 3 shows that, while for the larger spheres (Ø18 and Ø25 mm) the pre-sandblasting results are lower than the nominal value, for the Ø10 mm sphere the average value is higher than the nominal value. However, the comparison before and
after sandblasting provides values much closer to the nominal values. This can be considered a success of the sandblasting process, which, by eliminating brightness, allows the laser to measure diameters much closer to the reference ones, even compensating differences as large as 0.116 and 0.164 in spheres of Ø18 and Ø25 mm, respectively. A comparison of the form deviation data before and after sandblasting is also shown in table 3. Initially, the laser measurement averaged large form deviations, on the order of 0.15 to 0.19 mm. However, once the spheres are sandblasted, the laser measurements also offer very sharp improvements, ranging from 0.092 to 0.123 mm, leaving the form deviations at values in the range of 0.052 to 0.068 mm, also closer to the reference values.

Table 3. Comparison of laser measurement results regarding diameter and form deviation pre- and post-sandblasting.

| Average Diameter [mm] | Average Form Deviation [mm] | Average No. Points |
|-----------------------|-----------------------------|--------------------|
| Ø 10 mm               | 10.0137                      | 9.9976             | -0.0161 | 0.1908 | 0.0681 | -0.1227 | 13975 |
| Ø 18 mm               | 17.8846                      | 18.0006            | 0.1161 | 0.1501 | 0.0574 | -0.0927 | 43052 |
| Ø 25 mm               | 24.8608                      | 25.0250            | 0.1642 | 0.1492 | 0.0518 | -0.0974 | 80126 |

The standard deviation value is one of the parameters that best characterizes the quality of a point cloud [5], especially when considering its approximation to a mathematically well-defined geometry, as is the case of the sphere. This value is even a good substitute for metrological form deviation (ISO 1101:2017), measuring how good the point cloud is when fitting to a perfect sphere.

With the laser equipment available, two types of improvements could be contrasted. On the one hand, the improvement in the density and coverage of the point cloud. This improvement was evident, since the coverage with pre-sanded spheres was very poor. In fact, in some cases (Ø10 mm spheres), not all spheres could be correctly reconstructed. Consequently, the pre- and post-sandblasted comparison was only possible on all spheres when using high gain.

The second improvement achieved is related to the dimensional approach of the laser measurements to the CMM measurements (reference). Meaning by improvement the relation (%) between the parameter measured by laser with respect to the parameter measured by contact. In other words, a 100% improvement in any of the measurements would mean that the laser obtains the same measurement as the CMM by contact. Thus, figure 4 shows the improvements ratio obtained in the values of all the considered parameters: diameter, form error and standard deviation. The improvements are substantial, although not homogeneous, in all of the range of diameters. An even greater improvement is noted in the large spheres, Ø18 and Ø25 mm, where all the improvement ratios are very high (> 65%) and, in the case of the diameters obtained, those are very close to the reference values of the spheres. Regarding the form deviation, the average improvement was 63.80%. On the other hand, in the data relating to the standard deviation of the point cloud, an average percentage improvement of 59.21% was observed between all the three diameters considered. All the values refer to non-contact measurements obtained on the spheres in a post-sandblasted state.

4. Conclusions
The pre- and post-sandblasting comparison of the spheres by contact and non-contact (laser triangulation sensor) measurement provides interesting data on the modification suffered by the sphere surfaces. Three parameters have been considered for the study: the sphere diameter, the form deviation (sphericity) and the standard deviation of the point cloud with respect to the best fit sphere. The first two measurands are perfectly defined from a metrological point of view, while the third (standard deviation) is preferable as an indicator of the form deviation of the surface for high density point clouds.
As a first conclusion, the effect of sandblasting on the spheres is acceptably small, with minimal changes in diameter (2.7 µm) and, more importantly, in form deviation (1.7 µm). These characteristics validate the use of these spheres as reference artifacts for calibrating optical equipment, whose estimated accuracies are in the order of 25 µm to 40 µm (or even more).

Fig. 4. Improvement ratio in non-contact measurement for the three parameters studied and for the three diameters considered.

As a second conclusion, and now derived from the laser measurements, it can be observed that the increase in the density of the point cloud after sandblasting the spheres is very remarkable. So much so that, at normal gain, the laser sensor was not able to capture clouds with good coverage. This defect was much more pronounced in small spheres. Even in the case of high gain, the improvements in the quality of the point cloud are considerable, with values of improvement in the order of 60 to 70%, both in terms of diameter and form deviation obtained with the best-fit cloud. Therefore, this type of surface finish can be considered as a good solution for the application of these spheres as reference artefacts in GD&T measurements with laser triangulation equipment.

As for the analysis performed with the standard deviation parameter, it can be seen how the value of the standard deviation between the point cloud of the pre-sandblasted and post-sandblasted sphere drops by almost half. That is, the fit of the point cloud to a sphere (value similar to the form deviation) is twice as good (almost 100% improvement) when sandblasted spheres are used. It can be stated that the brightness elimination of the spheres has not involved an important loss of sphericity that, on the contrary, has been kept within acceptable limits of accuracy.

This study demonstrates that sandblasted spheres, with average sphericity lower than 0.005 mm, can be used as reference elements for non-contact measurement equipment with accuracies in the order of 0.040 ~ 0.050 mm. The validity of this statement is further supported by the low cost of the finishing process (manual sandblasting) and by the low cost of the stainless steel spheres commonly used in industrial bearings.

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