Feasibility analysis of using machinable glass ceramics to manufacture non-contact measurement approach metrological artefacts

P Zapico1*, B J Alvarez1, V Meana1, A Telenti2 and E Cuesta1

1 Department of Construction and Manufacturing Engineering, University of Oviedo, Campus of Gijón, Gijón, Spain
2 PMG Asturias Powder Metal S.A., Polígono Industrial de Baña, Mieres, Spain

*Corresponding author: zapicopablo@uniovi.es

Abstract: Rather than measurement contact methods, non-contact ones are more desirable in case of on-machine and in-process measurement due to their great accessibility and high acquisition rates. Nevertheless, it is well known that these methods commonly present different issues related to the surface properties of the digitized material and other external factors. Thus, an important characterization work must be carried out by exposing each non-contact technique to different conditions. For this characterization work, the use of metrological gage artefacts is mandatory. These artefacts must be made of materials on which non-contact methods will work properly. Therefore, the analysis of new materials is still an important issue nowadays. Among the current possible materials, those that can be easily formed in typical artefact geometries stand out, while maintaining the required properties such as low thermal expansion, high hardness, etc. In this work the feasibility of a machinable glass ceramic named Macor® to produce a metrological artefact to be used with a non-contact digitizing sensor is analysed. Once stated the benefits of this material and proposed some machining conditions, an artefact is manufactured and digitized with a non-contact laser triangulation sensor, comparing its results regarding to a widely used metrological reference system.

Keywords: Machinable glass ceramic, Macor, Non-contact measurement, Metrological artefact, Laser triangulation.

1. Introduction

In recent decades, numerous non-contact measurement methods have been developed. These methods permit to capture much more quantity of information than contact ones in less time and usually with less problems of accessibility. These advantages convert them in ideal solutions for on-machine and in-process measurement tasks systems. Nevertheless, it is widely known that the quality of the results obtained by them is greatly influenced by different conditions, which are usually indifferent to contact methods. These conditions not only have to do with internal factors of the sensor, as configuration parameters [1], but also with external factors, as the location of the digitized surface with respect to the sensor [2,3], lighting conditions, as well as digitized surface characteristics [4,5]. The latter are related to finishing conditions of the digitized surface, i.e., roughness grade, color, etc., as well as to inherent characteristics of the material itself. This fact, combined with the important need for metrological artefacts that can assess the quality of measurement results and their traceability, reinforces the
importance of developing metrological artefacts specifically focused on non-contact measurement. These artefacts must be produced using materials that avoid the characteristic problems arising during digitizing with non-contact sensors.

In this work, the feasibility of a commercial machinable glass ceramic to manufacture metrological artefacts for non-contact laser triangulation sensors is analysed. Macor® machinable glass ceramic of the commercial trademark Corning is studied [6]. First, the viability of using this ceramic glass compared with other widely used artefact materials, i.e., zirconium and stainless steel, to manufacture an artefact that can be used with a non-contact triangulation sensor is analysed in a preliminary test. Then, different machining conditions to shape this material in a typical artefact geometry are studied, performing varied recommendations. Following these recommendations, a stepped metrological artefact is manufactured. This artefact is then used to evaluate the results achieved after being measured by a non-contact sensor compared with those measurements obtained by a Coordinate Measurement Machine (CMM) equipped with a touch probe (TP). The results obtained in this case-study demonstrate the feasibility of both the machining conditions proposed and the application of this ceramic glass to the manufacturing of a metrological artefact for assessing the measurement quality of non-contact laser triangulation sensors, allowing the detection of typical sensor bias errors.

2. Materials and methods

2.1. Materials

Macor® of the commercial trademark Corning is a machinable glass ceramic. Offered in various formats as plates and rods, this material has the versatility of a high-performance polymer along with the machinability of a soft metal under certain machining conditions, as described below in this work. Due to its ceramic nature, this material has similar properties to those of other materials widely used in metrological artefacts that are interesting to this aim, i.e., low Coefficient of Thermal Expansion (CTE), young modulus, hardness, etc., see table 1. Moreover, this glass ceramic is characterized by a matte white finish, which normally permits a good behaviour of non-contact laser digitizing sensors, avoiding measurement defects caused by high-reflective surfaces as well as others derived from low light intensity received by the sensor.

| Table 1. Interesting Macor® properties for metrological artefacts [6]. |
|-----------------------------|-----------------|
| Units                        | Value |
| Density g/cm³               | 2.52  |
| CTE (25 to 300 °C) (°C⁻¹)  | 9 · 10⁻⁶|
| Young Modulus GPa           | 66.9  |
| Knoop Hardness (100 g) kg/mm² | 250   |

In this work, this machinable ceramic glass is inspected in different conditions using different metrological equipment. In order to verify the feasibility of using this material in metrological artefacts designed for non-contact sensors assessment, a HP-L-10.6 Hexagon laser triangulation sensor mounted in a CMM DEA Global Image was used to digitize this material in different measurement tasks. The results obtained with the non-contact sensor, whose specifications are presented in table 2, were compared with those obtained using the TP of the same CMM in terms of form error detection. The metrological specifications of this machine, maximum permissible error in length measurement ($E_{0,MPE}$) and maximum permissible limit of repeatability range ($R_{0,MPL}$), are summarized in equation 1.

$$E_{0,MPE} (\mu m) = 2.2 + 3 \cdot 10^{-3} L, \text{ being } L \text{ in mm}; R_{0,MPL} = 2.2 \mu m$$ (1)

Once the feasibility of Macor for this purpose was verified, its machinability aimed at manufacturing stepped metrological artefacts was analysed. For that, Macor was machined in a 3-axis Machining
Centre (MC) Lagun Lean L1000 was used in different milling conditions, that is, using both different tool types and cutting conditions. In some conditions a polyester resin was used to embed the material. Moreover, a contact profilometer Tesa Rugosurf 10 surface tester was used to correlate milling conditions with surface roughness shown by the material and a portable microscope was used to qualitatively evaluate the machined surface.

Table 2. HP-L-10.6 main specifications [7].

|                                      | Units | Value |
|--------------------------------------|-------|-------|
| Laser wavelength (visibly red)       | nm    | 690   |
| Standoff and working range           | mm    | 170 ± 30 |
| Probe dispersion value\(^a\)         | µm    | 34    |
| Probing form error\(^b\)            | µm    | 22    |
| Point spacing (min)                  | µm    | 30    |
| Laser Line Width (at standoff)       | mm    | 24, 60 or 124 |
| Lines per second (max)               | Hz    | 53    |
| Data rate (max)                      | pts/s | 30000 |

\(^a\) According to ISO 10360-8:2013
\(^b\) PForm.Sph.D95%:Tr:ODS (MPL)

2.2. Preliminary test: Feasibility of Macor for non-contact digitizing

In order to evaluate the feasibility of Macor for non-contact digitizing by means of the non-contact laser triangulation sensor, a preliminary test was prepared. In this test, two planar surfaces, PL1 and PL2, of a prismatic specimen manufactured in this material were digitized using the non-contact sensor, comparing the form error obtained with that detected by means of the TP. Moreover, this test was repeated using two other materials widely used for metrological gages, as are zirconium and stainless steel, checking not only the feasibility of using Macor, but also its advantage with respect to these other typical materials. In fact, metrological block gauge surfaces of those materials were measured in these tests. Upon all of these planar surfaces, an area of 7x15 mm\(^2\) was digitized by means of the non-contact sensor selecting the smallest line width and the maximum resolution, 123 mm and 16.8 points/mm respectively, i.e., the more accurate parameters. During scanning, the sensor is displaced along the minor dimension of the digitized area at a constant speed of 5 mm/s. In case of the stainless-steel block gauge, not valid digitized data were obtained due to its high-reflective surface. In case of Macor and Zirconium, frequency distributions of the deviation of digitized points with regard to the best-fit plane (least squares fit plane), obtained for each specimen, are shown in figure 1.

![Figure 1](image_url)

Figure 1. Deviation of the digitized points to corresponding best fit planes: (a) Macor, (b) Zirconium.

This information is summarized in table 3. As it can be noticed, the quantity of points that the sensor is able to digitize in case of Macor is almost the double of that obtained in the case of Zirconium, see
points density \( (P_{\rho}) \) in table 3. Moreover, the flatness, \( F \), detected in the latter is worse than in the former. Considering that the actual flatness of the Macor specimen surfaces is 3.1 \( \mu m \) for PL1, 1.7 \( \mu m \) for PL2, both obtained by means of CMMs’ touch probe, and that the actual flatness of the Zirconium specimen surfaces is supposed to be even lower (as they are surfaces of a Grade 2 block gauge), it can be stated that non-contact sensor results are more accurate in the case of Macor. Nevertheless, the failure to detect the form appears to be an issue in both cases, even using a \( 2\sigma \) outlier filter, see \( F_{2\sigma} \) in table 3. Unfortunately, this is a typical behaviour of non-contact sensors. Although Macor is not able to eliminate this undesirable behaviour, it is able to smooth it, comparing with Zirconium.

### Table 3. Form information detected by the non-contact sensor.

| Material | Specimen | \( P_{\rho} \) (Pts/mm\(^2\)) | Max | Min | \( F \) | \( \sigma \) | \( F_{2\sigma} \) |
|----------|----------|-------------------------------|-----|-----|------|------|--------|
| Macor    | PL1      | 184                           | 115.615 | -72.837 | 188.452 | 11.358 | 45.530 |
|          | PL2      | 185                           | 89.205  | -55.431 | 144.636 | 9.722  | 39.079 |
| Zirconium| PL1      | 93                            | 88.159  | -94.552 | 182.711 | 16.944 | 67.589 |
|          | PL2      | 87                            | 100.910 | -93.682 | 194.590 | 16.978 | 68.136 |

#### 2.3. Glass ceramic machining

The manufacturer announces Macor as a machinable glass ceramic for industrial applications. Thus, a machining guidance for this material is provided [8]. This guidance recommends specific cutting conditions for different machining and finishing processes. In case of milling, these recommendations are presented in table 4.

### Table 4. Recommended cutting conditions for milling Macor [8].

| Units             | Range        |
|-------------------|--------------|
| Cutting speed     | m/min        |
| Chip load         | mm/tooth     |
| Depth of cut      | mm           |
|                   | 3.81 – 5.08  |

#### Figure 2. Machined Macor block: (a) breakage after first milling try, (b) embedded in polyester resin, (c) crater in the machined surface (0.05 mm/(rev·tooth), 10 m/min, 1 mm, D=25 mm).

When the authors first intend to machine Macor in the MC the results were not satisfactory. The very brittle nature of this material caused that it catastrophically broke just after the tool started to cut, see figure 2(a). The breakage was not only due to the action of the tool, but also to the clamp. To solve this problem, one of the recommended solutions, although not mandatory, involves embedding the material into a polyester resin, figure 2(b). On the other hand, other factors, such as the use of climb (down) milling, a solid end mill instead of an indexable mill, and the application of cutting fluid, permits to machine the Macor without breakage. Once this problem was solved, different cutting conditions in the neighbourhood of the milling conditions recommended by the manufacturer were tested in order to obtain the best surface finish. Table 5 shows the \( Ra \) and \( Rz \) measured values of the surfaces milled according to the four best combinations of cutting conditions found from the tests. To find these
conditions, various tests using several cutting conditions were carried out. In those tests, in which the material did not break, the surfaces obtained were inspected by means of a portable microscope, which helps to detect topographic defects on the surfaces before measuring the roughness. An example of an image captured by the microscope in one of these successful but defective tests is shown in figure 2(c). Note that graphite powder was used to increase the contrast of the image.

As it can be noticed observing table 5, very fine surface roughness can be obtained using greater cutting speed and lower feed rate and cutting depth than those recommended by the manufactured.

| Conditions          | Units       | #1 | #2 | #3 | #4 |
|---------------------|-------------|----|----|----|----|
| Cutting speed       | m/min       | 67 | 49 | 35 | 26 |
| Feed                | mm/(rev · tooth) | 0.053 | 0.038 | 0.028 | 0.020 |
| Depth of cut        | mm          | 3  | 3  | 3  | 3  |
| Ra                  | µm          | 1.16 | 1.02 | 0.99 | 0.70 |
| Rz                  | µm          | 8.53 | 6.40 | 5.64 | 4.24 |

Table 5. Some of the best milling conditions encountered to optimize surface roughness (25 mm cutter diameter).

Figure 3. Macor stepped artefact manufactured: (a) actual artefact in MC, (b) measured distances and planes codification, (c) orientations of the laser sensor used during digitizing.

2.4. Glass ceramic stepped artefact

Thanks to the knowledge gained in the preliminary tests, it was possible to manufacture the Macor stepped artefact shown in figure 3(a). This artefact was digitized twice; first, with the TP of the CMM and later, with the HP-L-10.6 sensor, in order to compare the results of both methods. This comparison comprised the evaluation of the following tolerances (figure 3(b)): form deviation of vertical / horizontal planes \(PL_1^X \) to \(PL_4^X \) / \(PL_1^Z \) to \(PL_4^Z \), 3D distances between vertical/horizontal planes \((X_1 \) to \(X_3 \) / \(Z_1 \) to \(Z_3 \)), parallelism between vertical/horizontal planes (setting \(PL_1^X \) and \(PL_1^Z \) as reference), and perpendicularity between the two planes that form each of the steps, \((PL_1^X \perp PL_1^Z \), \(PL_2^X \perp PL_2^Z \), etc). In the case of the non-contact sensor, a line laser width of 123 mm with 16.8 points/mm and a 5 mm/s scanning speed were set for digitizing the stepped artefact. During this operation, the sensor was set according to the three orientations referred as A, B, C in figure 3(c), being A and C contained in the OYZ plane and B in the OXZ. The movement direction of the sensor during the scanning in these orientations was parallel to X axis in orientations A and C, and parallel to Y axis in orientation B. In all these orientations the sensor was tilted at a 45° angle with respect to the horizontal orientation. After this digitizing task, the captured data were processed by means of a point cloud treatment software, which permitted to isolate those points that belonged to each plane. Subsequently, a 2σ filter was applied to each point cloud fragment to remove outliers, i.e., points located further apart from the reconstructed best fit plane. After removing outliers, a new best fit plane fit was obtained for each of these fragments. Finally, data obtained in this
manner were used to compare the results obtained by means of the non-contact sensor with respect to the TP results. In case of the latter, a regularly distributed 7x10 grid of points was digitizing in each plane, without applying any filter, just a fitting plane procedure. It is worthy to remark that this artefact measurement procedure was not aimed at detecting the deviations of the artefact from its nominal geometry, but it is intended to be applied in the assessment of the feasibility of Macor for detecting usual bias errors when non-contact sensors are used.

3. Results and discussion

Table 6 and figure 4(a) show the number of points captured by the non-contact triangulation laser sensor, during digitizing of the stepped artefact. These points were used to fit a plane for each of the eight surfaces, see figure 3, and the results of flatness, F, and perpendicularity error between planes forming each step, \( \alpha \), were compared to those obtained by means of touch probe of the CMM. These comparisons are also shown in table 6 and summarized in figure 4(b) and 4(c) in terms of differences between laser sensor and TP results.

| Plane | Points | Flatness | Perpendicularity error |
|-------|--------|----------|------------------------|
|       |        | \( F_{TP} \) | \( F_{L} \) | \( F_{L} - F_{TP} \) | \( \alpha_{TP} \) | \( \alpha_{L} \) | \( \alpha_{L} - \alpha_{TP} \) |
| PL\(_x\) | 17268  | 4.8  | 35.2  | 30.4  | 21   | 72   | 51   |
| PL\(_z\) | 77387  | 6.3  | 41.6  | 35.3  | 11   | 52   | 41   |
| PL\(_x\) | 15326  | 6.4  | 31.6  | 25.2  |       |       |      |
| PL\(_z\) | 61324  | 4.3  | 104.4 | 100.1 |       |       |      |
| PL\(_x\) | 12791  | 7.4  | 31.6  | 24.2  | 8    | 49   | 40   |
| PL\(_z\) | 70155  | 2.6  | 111.5 | 108.9 |       |       |      |
| PL\(_x\) | 8977   | 7.6  | 42.7  | 35.1  | 16   | 52   | 37   |
| PL\(_z\) | 76758  | 2.7  | 116.3 | 113.6 |       |       |      |

![Table 6](image)

**Table 6.** Comparison between non-contact sensor and TP measurement results regarding flatness and perpendicularity error.

**Figure 4.** (a) Number of points captured by the laser sensor, (b) differences between flatness results (laser sensor vs. TP), (c) differences between perpendicularity error results (laser sensor vs. TP).
Observing the number of points captured for each surface, a main conclusion can be stated, that is, the number of points captured by the laser sensor is much bigger in horizontal planes than in vertical ones. This is due to the used orientations of the sensor during the digitizing of the artefact. In case of horizontal planes, points were captured in all the three orientations used, whereas in case of vertical ones, only in B orientation, see figure 3(b) and 3(c). Nevertheless, as can be noticed in form detection, figure 4(b), more points does not necessarily mean a higher quality of detection. In fact, the differences regarding TP results are lower in case of vertical planes. That can be related to the fact that the more quantity of points the bigger probability of capture noise that distorts the form detected, in spite of the filtering procedure applied for outlier removal.

Moreover, a slight positioning error of the sensor after an orientation change could be an additional issue. On the other hand, differences regarding perpendicularity between planes forming a step decreases slightly as the step is located at a higher Z coordinate, lying between 37 and 51µm. This can be related to a characteristic bias of this non-contact sensor.

### Table 7. Comparison between non-contact sensor and TP measurement results regarding parallelism error and distance between planes.

| Datum | Target | β_{TP} | β_{L} | β_{L} - β_{TP} | d_{TP} | d_{L} | d_{L} - d_{TP} |
|-------|--------|--------|-------|-----------------|--------|-------|-----------------|
| PL_{1} | PL_{2} X | 74 | 34 | 27 | 12.489 | 12.480 | -9.3 |
| PL_{1} | PL_{2} X | 74 | 36 | 28 | 24.983 | 24.967 | -16.3 |
| PL_{1} | PL_{2} X | 14 | 47 | 33 | 38.512 | 38.488 | -24.4 |

![Figure 5](image-url) **Figure 5.** Differences between measurement results (laser sensor vs. TP) regarding: (a) parallelism error and (b) distance between planes.

The results obtained by the laser sensor and the TP both in terms of parallelism error, \( \beta \), and distance between planes, \( d \), are shown in table 7. The differences between laser sensor and TP measurement results are represented graphically in figure 5. Observing figure 5(a) it can be noticed that, similarly than in case of form detection, differ higher in case of horizontal planes. That can be related to the same reason, that is, the more quantity of points captured by the sensor and its associated issues. However,
observing figure 5(b), it can be noticed that distances are not affected by this phenomenon. In that case, differences are lower in horizontal planes than in vertical ones (that is in vertical distances than in horizontal ones), all of them within 33 µm wide interval. This differential effect has to do with the fact that noisy points significantly affect the orientation of the plane, and not so much its position, due to their nature as points of influence. Moreover, observing the distance differences, it can be noticed that they are negative in case of horizontal distances and positive in vertical ones. This could be related to characteristic bias of this sensor, considering that both horizontal and vertical distances between planes are equivalent to the sensor based on its orientation during digitizing. On the other hand, the differences regarding distances between planes increase with the value of the distance. Actually, this is a common bias in distance measurement systems, and can be described as a linear error fitting of $-0.646 \cdot 10^{-3}$ for horizontal distances and $0.243 \cdot 10^{-3}$ for vertical ones, both of them with a r-square above 0.99.

4. Conclusions
In this work, the feasibility of using Macor®, a machinable glass ceramic from the commercial trademark Corning, to manufacture a metrological artefact that can be used with non-contact laser triangulation sensors, is analysed. In a preliminary test, the benefits of using this material with a wide extended laser triangulation sensor, i.e., Hexagon HP-L 10.6, was demonstrated in comparison to use other wide extended metrological gauges materials, i.e., Zirconium and stainless steel. With the aim of manufacturing a typical metrological artefact geometry made of this material, several machining tests were carried out, starting from the milling cutting conditions recommended by the manufacturer. Although different problems were detected in these tests, finally a set of milling conditions was achieved which permit to machine the material and obtain a typical artefact geometry. Among these conditions, it is worth to remark the use of a solid-type cutter, the election of a climb milling strategy, and the application of cutting fluid during machining. With the knowledge acquired throughout these machining tests, a stepped artefact was manufactured. This artefact was digitized both with the non-contact laser sensor and a touch-trigger probe mounted on the same CMM. The differences between the results obtained with both technologies (considering contact measurement results as reference values) were then analysed. This analysis permitted to detect a set of characteristic biases of the laser sensor and also to compare the advantages and the drawbacks of using different sensor orientations during the digitizing of a typical artefact geometry. In conclusion, the results achieved demonstrate the feasibility of using Macor to manufacture metrological artefacts for assessing the measurement quality of non-contact laser triangulation sensors.

As a future work, the use of Macor artefacts with different non-contact digitizing methods, and in other measurement conditions, is scheduled.

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