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Enhancing porcelain whiteware quality assessment by means of Reverse Engineering-based procedures

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Abstract

During manufacturing, porcelain whiteware changes its shape due to the sintering process. For this reason, leader companies in the field of ceramics apply strict controls on final products in order to reach high quality standards. Typically, three quality parameters are considered: *drop of the bottom*, *bending of the rim* and *roundness*. To date, the assessment of such parameters is still based on visual inspections and manual measurements. In the present paper, authors propose a new quality assessment procedure based on *reverse engineering* (RE), able to measure the most relevant quality parameters in an effective, reliable and repeatable way.

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Keywords: porcelain; quality control; quality parameters; reverse engineering; 3D scanning; 3D reconstruction; 3D model; whiteware; measurement; porcelain tableware.

1. Introduction

Porcelain is one of the most diffused ceramic materials finding applications in a wide range of fields (electrical components, whiteware, tiles, bathroom fittings, etc.) due to its unique properties in terms of hardness, whiteness,

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impermeability, low electrical and thermal conductivity. Porcelain is considered, by far, one of the most complex ceramics, since its properties and its behavior change during manufacturing [1-5]. Due to the complexity of the sintering reactions and the difficulties in controlling the process variables (such as temperature and thermal exchanges), deviations may occurs even in the same batch of items, especially for critical and challenging shapes. This is particularly true for whiteware where the aesthetic appearance is a key factor for obtaining a high quality product. In fact, the leader manufacturers are required to adopt strict quality controls on the final artefacts to comply with quality standard. Especially in the case of flat geometries (e.g. plates and vessels), three main parameters are traditionally measured downstream the manufacturing process: the *bending of the rim*, the *drop of the bottom* and the *roundness*. The current praxis is to submit all pieces to a fast visual inspection by trained operators followed by a manual measurement of the above-mentioned parameters performed by using calipers and comparators. With the exception of the rapidity of the operation and the affordability of the required tools, these handmade measurements are affected by typical drawbacks that a manual assessment encompasses: low accuracy, low repeatability and – in case of dimensional measurements - limited number of measured points.

The present paper proposes a new quality assessment procedure based on *reverse engineering* (RE), able to measure the most relevant quality parameters in an effective, reliable and repeatable way. Taking advantage from the availability of the entire 3D digital geometry of the artefact (obtained by using a commercial 3D scanner), the proposed method allows to investigate the artefact shape without the limits of a typical handmade inspection. Accordingly, the typical manually assessed quality parameter are redefined thanks the availability of the whole 3D geometry.

The devised method has been applied in collaboration with *Richard Ginori*, one of the most important fine porcelain manufactory companies in Italy, established in 1735.

In particular, the test bed for the proposed procedure is defined by some plates from the most iconic *Richard Ginori* collections: *"Antico Doccia"* (round platter, dinner plate, dessert plate), *"Vecchio Ginori"* (dinner plate, dessert plate) and *"Impero"* (dinner plate, soup plate) (Fig. 1).

Fig. 1. From left to right, *"Antico Doccia" dinner plate, "Vecchio Ginori" dinner plate, "Impero" soup plate.*

These items present a fundamental criticality for a standard visual inspection or handmade dimensional measurement: in fact, their overall round shape does not offer enough reference points to ensure repeatability for such evaluations, thus causing a low accuracy of the results or – in order to avoid this – the adoption of time consuming methods.

2. Traditional quality parameters definition

The shape of a plate, whose overall diameter is D_0, could be divided into three main parts: 1. bottom (or well), the circular region where the food is placed; 2. foot (or base), the part on which the plate lays; and 3. rim, that corresponds to the frame of the plate (Fig. 2a).

The above-cited regions can be defined geometrically as portions of the plate surface, delimited by virtual coaxial cylindrical surfaces (Fig. 2b):

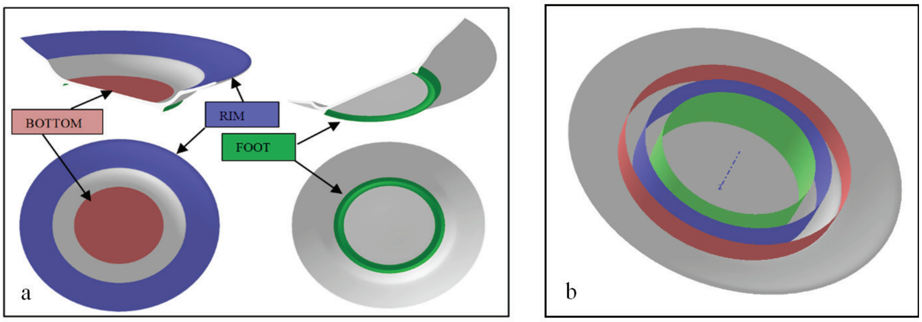

Fig. 2. (a) Regions of a plate; (b) Virtual coaxial cylindrical surfaces.

- Bottom: region of the upper face, delimited by a cylindrical surface of diameter D_1;
- Foot: region of the lower face, included between two cylindrical surfaces, respectively of diameter D_1 and D_2;
- Rim: external region of the upper face, comprised between the edge (diameter D_0) of the plate and a cylindrical surface of diameter D_3.

This nomenclature (and these diameters) will serve as a reference for defining the traditional quality parameters (used in *Richard Ginori*) as described below:

- *Drop of the bottom*: measures the vertical distance from the center of the bottom and the ideal bottom plane, as shown in Fig. 3. Quality test is successfully passed if the *drop of the bottom* is less than 1% of the diameter of the bottom itself, in terms of absolute value (Eq. [1]). This measurement is manually performed simply using a caliper.

$$P_1 = |\delta/D_1| < 1\% \quad (1)$$

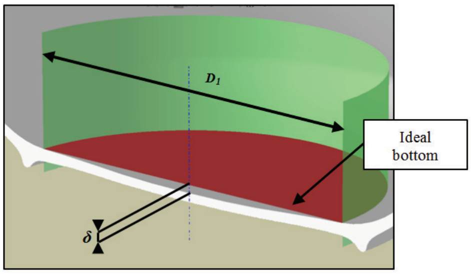

Fig. 3. Drop of the bottom.

- *Bending of the rim*: measures the maximum variation of the bending angle of the rim (α) all around the plate (Fig. 4), i.e. the angle between the rim and the base plane. If the value exceeds 2°, the item is rejected, according to Eq. [2]. Also this measurement is manually assessed using a comparator.

Fig. 4. Bending of the rim.

$$P_2 = \alpha_{MAX} - \alpha_{MIN} \leq 2° \quad (2)$$

- *Roundness of the plate*: adopted only for round whiteware (e.g. *"Impero"* plates [Fig. 1]) is evaluated by measuring diameters (D) of the plate itself. If the difference between the maximum measured diameter (D_{MAX}) and the minimum one (D_{MIN}) exceeds 2% of their mean value (D_{AVG}), the artefact is rejected, according to Eq. [3]. This parameter is hard to be manually measured and the only available method is to use a set of jigs to be visually compared with the sample.

$$P_3 = (D_{MAX} - D_{MIN})/D_{AVG} < 2\% \quad (3)$$

As mentioned above, such quality parameters are manually measured by company staff, after a visual inspection based on a complete observation of the piece, using calipers, comparators and jigs. Despite the skill of the production staff, manual inspection does not allow a precise and accurate measurement. In addition, a complete shape examination is unfeasible with traditional methods since the quality assessment is carried out only with reference to a few, often randomly selected, measures. In particular, the *drop of the bottom* is evaluated only at the center of the bottom (which may not correspond to the lowest point). Dealing with the *bending of the rim*, it is evaluated only in a few points of the rim itself, selected by means of a jig; obviously for round artefacts, which do not offer sufficient reference points, positioning and measurement mistakes are unavoidable. Analogously, for the *Roundness of the plate* only a limited number of diameters is usually evaluated (e.g. 4-5); therefore the measured D_{MAX} and D_{MIN} may not be the actual maximum and minimum ones.

3. RE-based quality parameters assessment

With the aim of overcoming the drawbacks typical of the manual inspection, an alternative methodology based on reverse engineering procedure is provided. Such a method can be schematically drafted as follows:

1. 3D acquisitions of the artefact;
2. reconstruction and alignment of the 3D scanned data;
3. definition of the RE-based quality parameters.

3.1. 3D acquisition of the artefact

The first step of the proposed method consists on the 3D virtual reconstruction of the artefact under inspection. Several scanning techniques have been considered [6, 7], such as photogrammetry and 3d vision [8], which have interesting potentialities and enable to detect both shapes and colors (in case of painted items). Unfortunately, commercial devices do not reach the required accuracy yet. For this reason, the 3D acquisition has been performed by means of a commercial 3D laser scanner (triangulation scanner "RS1" mounted on the anthropomorphic "Romer Absolute" arm). Such a scanner provides a volumetric accuracy in the range ±0.079 mm within the measurement range of 1.2 m and a point repeatability lower than 0.044 mm, according to the ASME B89.4.22 certification.

Due to the shape of the inspected products, is necessary to implement some expedients during the 3D scanning phase in order to facilitate/make it possible the successive RE operations. First, as common for many RE applications, a set of markers have to be applied on the surface of the object, in order to facilitate the alignment between scanned data. It is important to highlight that at least two positioning of the artefact are required: one to acquire the top side (normal position) and one to acquire the bottom side (reversed position) of the plate. Consequently, at least two groups of scanned data have to be generated, one for each position of the plate. In the normal position, the artefact lays on a calibrated granite horizontal plate, which will be successively used as reference plane during the reconstruction phases. Conversely, in the reverse position, the artefact is arranged downwards and its bottom lays on a centrally placed support. This setup allows the operator to perform a partial scanning of both the lower face and of a part of the upper face thus ensuring a large overlapping region (crucial for the subsequent alignment of acquired point clouds).

3.2. Reconstruction and alignment of the 3D scanned data

Thanks to the scan setup described above, the subsequent 3D reconstruction steps can proceed quite easily. Both of the main groups of scanned data can be placed in the correct reciprocal position and the following merging and triangulation phases can be carried out, using commercial RE software packages (in this work Polyworks® and Geomagic® software package have been used). For example, alignment has been performed by means of the well-known combination of coarse and fine point cloud alignment: coarse alignment is achieved by manually selecting a set of corresponding points, while fine registration is obtained by using the ICP method [9, 10]. The final result consists of a point cloud defining the 3D geometry of the plate, which, afterward, serves as a basis for mesh construction.

The last step consists in the alignment of the obtained polygonal geometry to the global reference system, since this one is used for the extraction of the new quality control parameters.

This phase consists of 4 steps as described in [11]. Referring to the cited procedure, it has to be pointed out that – in order to obtain mesh segmentation [12, 13] and to retrieve reference entities (axes, planes) – typical tools implemented within the adopted RE software have been used. The outcome of this process consists of the plate polygonal model, where the supporting plane corresponds to the *xy*-plane and the plate revolution axis coincides with z-axis.

3.3. *Definition of the RE-based quality parameters*

3.3.1. Drop of the bottom

In order to provide a new parameter for evaluating the drop of the bottom, only the mesh portion relative to the plate bottom needs to be taken into account. Following the definition given in the previous chapter, this is obtained by subdividing the polygonal model with a cylindrical surface of diameter D_1; and maintaining only the internal partition of the upper surface.

The maximum drop is measured as the distance between two planes represented by the upper and lower faces of the bounding box (aligned with the global reference system) of the considered mesh portion (i.e. relative to the bottom), as in Fig. 5.

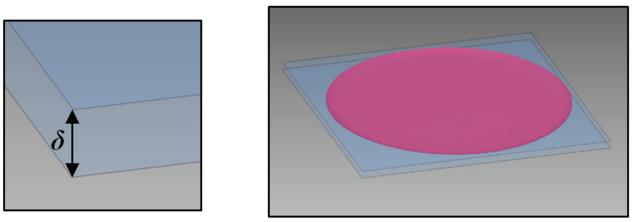

Fig. 5. Drop of the bottom measured as a distance between planes.

Differently from the manual inspection, where the drop of the bottom is measured with reference to the center point of the plate, measurement provided by this new definition takes into account also the possibility that the lowest point could not coincide with such a center (i.e. does not lie on the estimated revolution axis). In other words, this measurement detects the actual drop.

3.3.2. Bending of the rim

Focusing on the rim of the plate, two issues arise: 1. the ideal shape of the rim is not frustum-conical (i.e. presents convexities or concavities), 2. the edge may present a decoration. In order to overcome such problems, the procedure to measure the bending angle of the rim surface is structured as described below:

1. Definition of measurement area (Fig. 6.a): two cylindrical surfaces, with diameter D'_1 and D'_0 and whose axis coincides with the z one, are drafted. In particular D'_1 is defined as the 110% of $D_1$and D'_0 is equal to

90% of D_0. This allows to exclude the problems due to the presence of discontinuities or decoration on the edge.

2. Definition of cylindrical cross-section curves (Fig. 6a): two curves (3D splines) obtained as intersection between the upper face of the polygonal model and the two cylindrical surfaces described in step 1 are extracted.
3. Radial cross-section curves definition (Fig. 6b): a number of curves as intersection between the polygonal model and a sheaf of angularly equidistant semi-planes, sharing the *z*-axis (estimated revolution axis) are obtained. In the example figure, the number of planes is limited to 10.
4. Retrieval of measurement points (Fig. 6c): for each radial cross-section curve, a point pair (A_i, B_i) is retrieved on the intersections with the two cylindrical cross-section curves. In such a way the rim profile is approximated to the straight segment that links its extreme points (A_i, B_i) in order to neglect possible convexities or concavities.

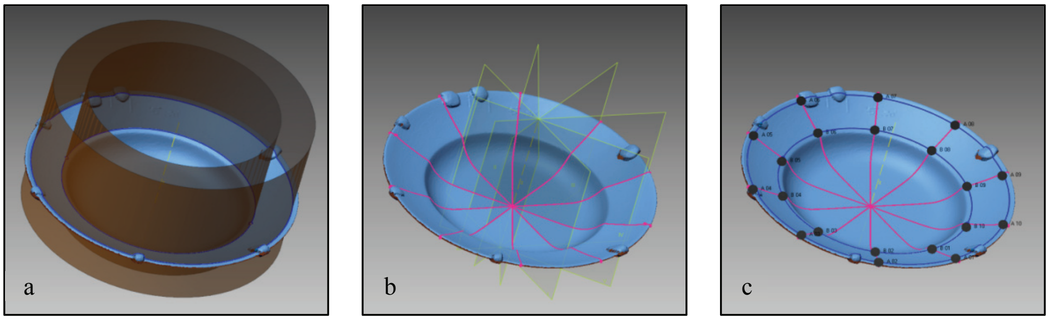

Fig. 6. (a) Cylindrical cross-section curves; (b) radial cross-sections curves; (c) measurement points.

5. Computation of the bending angle α and evaluation of the quality parameter along each radial direction, according to Fig. 7 and Eqs. [4-8].

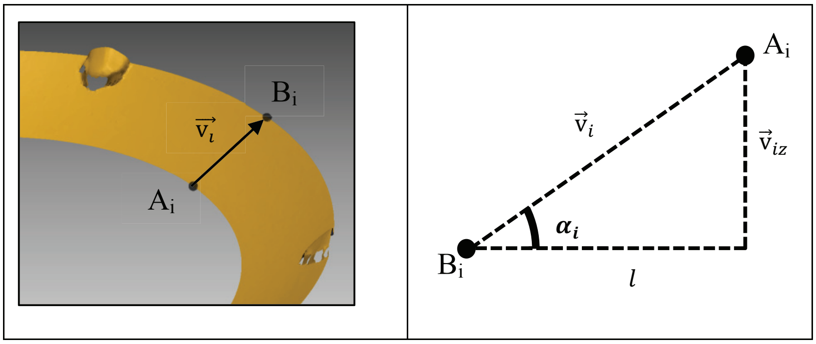

Fig. 7. Computation of the bending angle.

$$\vec{v}_i = A_i - B_i \quad (4) \qquad l = r_1 - r_2 \quad (5)$$

$$\vec{v}_{iz} = \partial\vec{v_i}/\partial z \quad (6) \qquad \alpha_i = \tan^{-1}(\vec{v}_{iz}/l) \quad (7)$$

$$P2 = |\alpha_{MAX} - \alpha_{MIN}| \leq 2° \quad (8)$$

3.3.3. Roundness of the plate

The last proposed RE-based quality parameter is meant to evaluate the roundness of the edge of the plate, retrieved as projection (along *z* direction) of the polygonal model itself on *xy*-plane. This can be obtained by means of a *virtual rescan* operation [14]. In order to not affect the resolution of the original scan data, a fine mesh grid must be imposed (in this case, equal to 0.2x0.2 mm). The obtained polygonal model is shown in Figure 8a.

The intersection of the polygonal model with the *xy*-plane defines the edge profile to be measured. On the same plane, two circles - concentric with *z*-axis - are drawn: the first one is internally tangent to the retrieved profile while the second one is externally tangent (see Fig. 8b). Therefore, the rating of the quality parameter is directly deduced from the ratio of their diameters D_{MAX} and D_{MIN}, according to Eq. [3].

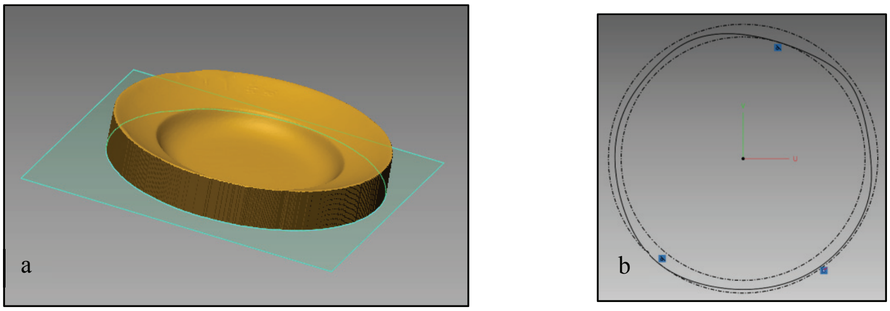

Fig. 8. (a) Virtual rescan to *xy*-plane; (b) internally and externally tangent circles (the deformation of the edge is magnified).

4. Conclusions

In this paper, three parameters (*drop of the bottom*, *bending of the rim*, *roundness of the plate*), commonly adopted by the most important fine porcelain manufactory companies to assess quality controls, are redefined exploiting the potentiality of RE techniques. The traditional handmade analysis is replaced by a new method based on digital models, with a series of relevant advantages such as repeatability and the possibility of analyzing the whole geometry instead of only a subset. For what concerns the assessment of the *drop of the bottom*, for instance, the proposed approach allows to evaluate the actual maximum drop instead of the drop of the center. Moreover, for the *bending of the rim* is possible to repeat the measurement along an arbitrary number of radial directions, making the assessment process more complete. In addition, rigorous definitions of both the quality parameters and the measurement procedures to assess them are given. All of these factors make it possible to enhance the accuracy and the repeatability of the quality parameters assessment as also demonstrated in Tab.1.

On the other side, it has to be underlined that the overall RE-based procedure results more time consuming than the traditional approach based on visual inspection and handmade measurement. In fact, even if the proposed measurements on the virtual model can be performed quickly, the 3D reconstruction phase, by means of a "general-purpose" 3D laser scanner and traditional RE operation, are rather slow (generally, 20' for each sample, against 5-6' for manual inspection). On the other hand, for laboratory inspection the achievable accuracy using the proposed method justifies an increase of control time. Moreover, with the future perspective of realizing an inline QC station, that will host a properly devised 3D laser scanner and will adopt an automated version of the proposed RE-based procedures, timings are expected to be drastically reduced.

Table 1.

Parameter	Traditional measurement	Accuracy	Proposed approach	Accuracy
Drop of the bottom	Single measurement on the plate center (no guarantee the point is the lowest)	0.05 mm	Single measurement on the actual lowest point of the well.	0.03 mm
Bending of the rim	Visual inspection by means of a set of jigs	n.a.	Multiple radial directions	0.03 mm
Roundness of the plate	Visual inspection by means of a set of jigs	n.a.	Multiple	Approx. 0.1°

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