PRESSING, WITH FLAT CERAMICS METHODS, OF CURVED CERAMICS WITH HIGH-PRECISION GEOMETRY SPECIFICATIONS

Julio Serrano Mira[(1)], José Miguel Castellet Martí[(1)], Ramiro Bonaque[(2)], Agustín Poyatos[(2)], Fernando Romero Subirón[(1)]

[(1)] Universitat Jaume I, Castellón, Spain
[(2)] Macer S.L., Almazora (Castellón), Spain

jserrano@esid.uji.es

ABSTRACT

In order to obtain high-precision three-dimensional pieces by dry pressing, two approaches were studied: modelling the material flow and strain during pressing; and evaluating the bulk density (Da) distribution in a pressed piece and using shrinkage models that allow the post-firing geometry to be predicted. It would thus become possible to act in the design phase (functional geometry and rear) and in the process.

This paper describes the studies carried out to predict the final geometry of three-dimensional pieces of the sheet type obtained by conventional pressing techniques, from the Da distribution in each point of the piece. For this purpose, pieces were modelled using finite element (FEM) techniques, applying simulation processes to obtain the strain at each point of the piece as a function of its Da. The experimental validation was performed using the X-ray absorption method for Da and a CMM (coordinate measuring machine) for the geometry.

1. INTRODUCTION

During the firing of a dry-pressed tile, shrinkage takes place with relation to its green geometry, which mainly depends on the material and its bulk density (Da). Each material is known to have a corresponding vitrification diagram, which provides its shrinkage values as a function of Da, and variations of Da (ΔDa) between pieces are known to lead to different dimensions, while such variations in different areas of the same piece produce geometric errors.

In order to reduce ΔDa and thus variability, enhancing precision, isostatic punches are used in addition to die cavity filling control. However, these techniques, envisaged for quasi-flat pieces, are difficult to apply in three-dimensional pieces (differences in profile altitude ≥ 15 mm); this is even more so when high-dimensional precision is required.

In addition, after-pressing expansion and post-firing shrinkage materialise in a non-linear form in curved sheets, requiring models that allow what the green geometry should be for a given final fired geometry to be estimated. The linear model used for a flat sheet (a simple zoom) is inapplicable for obtaining precise three-dimensional geometries.

The methods of executing flat ceramics need to be adapted. Thus, if the die cavity filling is flat, the obtainment of three-dimensional pieces of quasi-uniform thickness (sheets) requires large displacements of the deposited powder. In addition, the spray-dried powder grains are hollow and, when pressed, they deform plastically instead of just moving, in contrast to what would occur with solid granules. As a result, the obtainment of three-dimensional pieces by dry pressing, using current techniques, is a complex issue.

2. UNIAXIAL PRESSING WITH CURVED PUNCHES

In uniaxial pressing with punches that have a curved surface, once the powder has entered into contact with the surface, a shear component appears that materialises in a radial movement of the powder (in relation to the normal to the punch surface) and lower effective pressure (Pe, component normal to the curve surface), both of which depend on the curvature and, therefore, on the position (see Illustration 1). This affects the compaction and Da of the green piece.

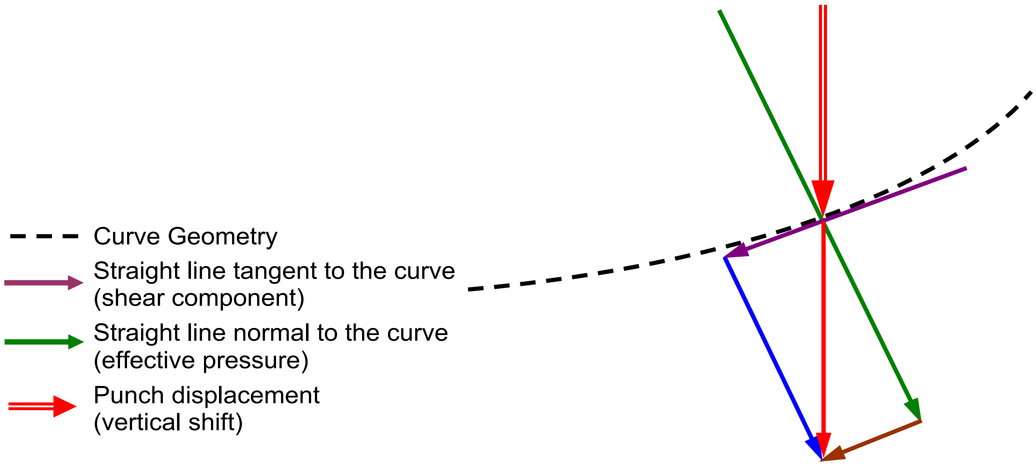

Illustration 1. Components of the pressing force in curved surfaces.

In order to offset this, it is necessary to operate with the usual instruments in industry. Thus, knowing the coefficient of shrinkage in each point, the noble surface curve can be compensated. However, since the geometry of the die introduces constraints regarding the expected movement of the powder, compensation is no simple matter.

Another possibility is modifying the geometry of the rear with elements that limit the undesired movement of the body, or by putting in place reservoirs that accept the displaced mass so that this does not affect the ΔDa too much in the volume of the piece. The adjustment of these procedures entails a laborious process of trial and error.

In any event, there is a significant radial movement of the powder (with respect to the punch axis), which induces a great quantity of residual stress-strain, thus increasing the possibilities of mechanical failure.

2.1. Experimental results

Porcelain tiles were pressed in a SACMI 980 press, with Arciblansa ESM70 powder, loading the cavity in the traditional form, flush with the frame. The profile was curved for the noble surface on the bottom punch, as shown in Illustration 2, varying that of the back (top, moving punch). During the first pressing trials, it was observed that the profile of the support ridges needed to be smoothened, or that they even needed to be removed, to assure fabricability.

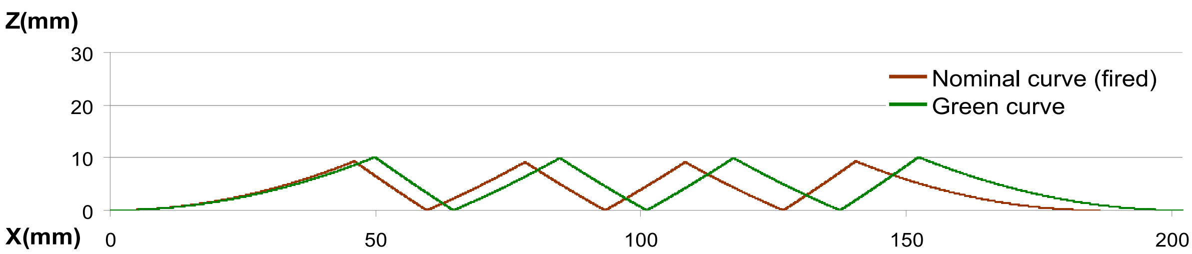

Illustration 2. Noble surface curve: nominal and green (it is not to scale)

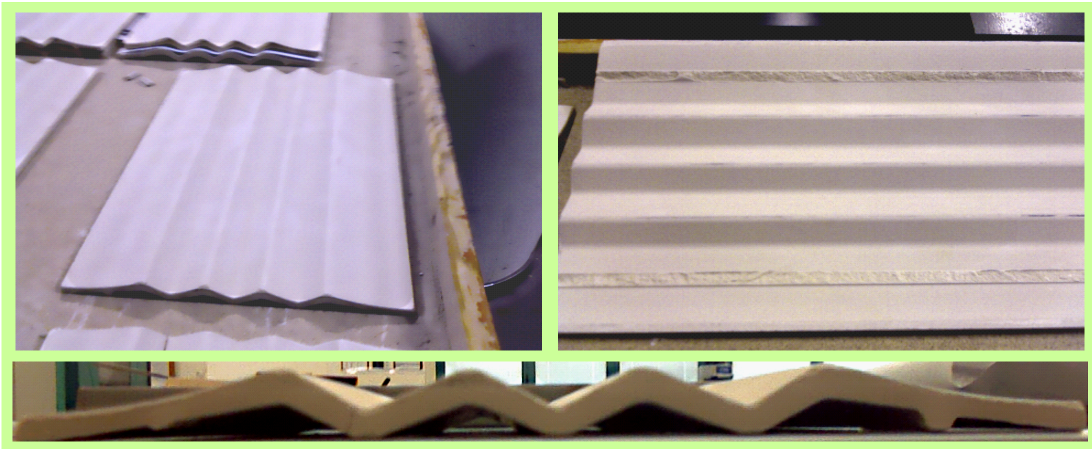

Illustration 3. Pressed prototypes of the piece with compensated back (reservoir)

The Da (vertical average) was then measured by X-rays with the ITC Densexplorer (1) in several cross-sectional cuts, to study its scatter and how the geometry of the back affected its distribution. The use of X-ray axial computed tomography for the study of Da in the volume of pharmaceutical tablets is described in (2), which provides information on its space distribution. Although the studied pieces may be basically considered flat, it would be very useful to verify the Da distribution in height to study the effect of powder friction with the die and punch. Illustrations 4, 5, and 6 show some results obtained in the measurement of Da with the Densexplorer for two configurations.

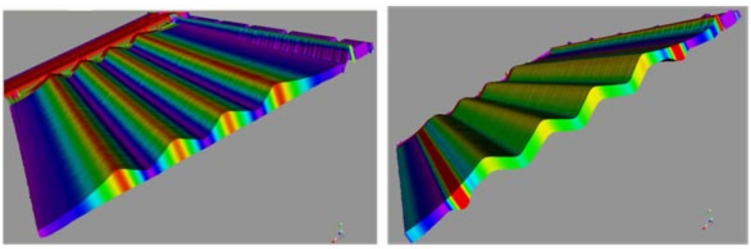

Illustration 4. Measurement of green thickness. Flat back and with reservoir

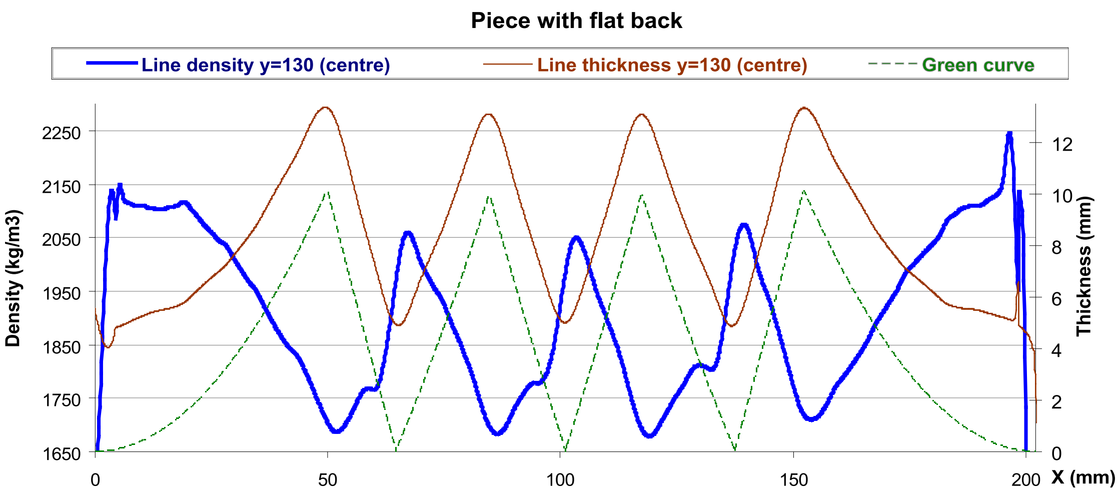

Illustration 5. Da and thickness in a piece with flat back

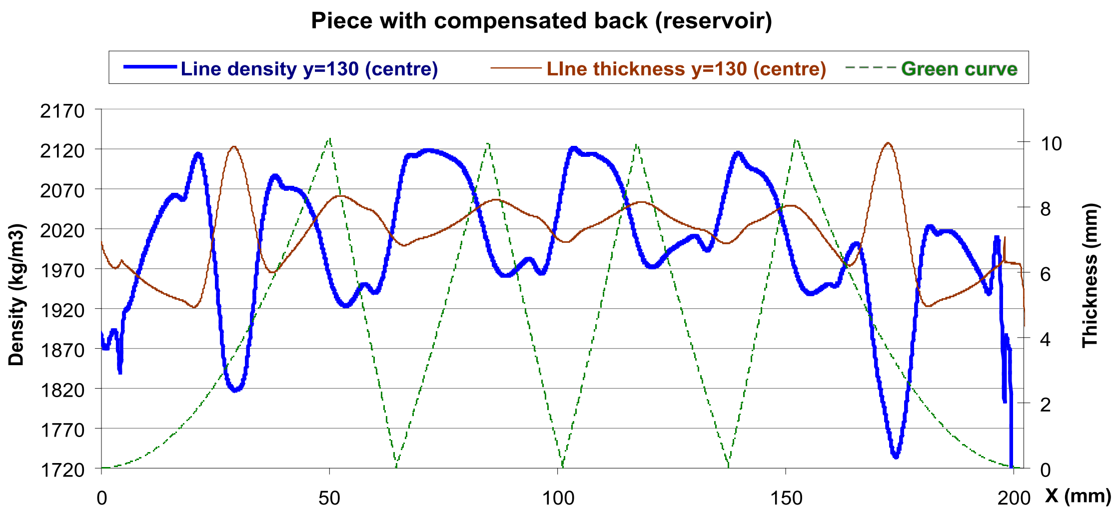

Illustration 6. Da and thickness in a piece with compensated back (reservoir)

The distribution of Da in the plane for the studied specimens enabled significant information to be obtained for the pressing process:

1. There was movement of the body in the cavity. This was noted by comparing the variation of Da in the series pressed with a flat back with the series made with a compensated back. The differences in Da were about 400 kg/m^3 for the non-compensated pieces. The punch compensation was designed with the movement of the clay in mind, which yielded an improvement in the differences, which went to 200 kg/m^3. On again modifying the geometry of the back, a ΔDa of the order of 130 kg/m^3 was achieved, and the green pieces matched well the theoretical geometry.

2. The experimental observation that the peaks were pressed less than the troughs (cracking in the troughs) was confirmed. Note that pressing occurred with the noble surface facing down and in that situation (peak in bottom position):

   a) In the case of pressing with the compensated back, it was to be expected that the wedge-shaped top punch would shift the body of the peak (at the bottom) towards the trough, where it was confined, increasing the bulk density as a result of that build-up.

   b) For the flat back, the thickness displayed a maximum in the peak, so that the compaction ratio (Rc) was greater in the peaks than in the troughs[1] (at higher Rc, lower compaction).

3. The difference in Da appeared to be related to the difference in thickness. For that reason, it appeared convenient to equalise thicknesses, i.e. for the piece to have a moderately uniform sheet thickness. There was a reasonable correlation between thickness and bulk density (Da); with greater thickness, lower Da. See Illustrations 7 and 8.

1 Rc=final thickness/(final thickness+charge height{a, which is constant and greater than 0}) V->final thickness in trough, C->final thickness in peak, C>V>0 & a>0 ->Ca>Va>0, a+C>0, a+V>0, Ca+CV>Va+CV>CV>0 ->C(a+V)>V(a+C)>0 ->C>V(a+C)/(a+V)>0 ->C/(a+C)>V/(a+V)>0

2.2. Relationship between Da and thickness

Analysing the experimental data obtained by the Densexplorer, the existence was determined, at a given pressure and ceramic body, of a linear relationship between the resulting Da and the height of the ceramic body charge. In view of the risk of lack of reliability of the obtained values of Da in the up-flanks owing to the possible problems of alignment of the Densexplorer telemeters, only the data of the down-flanks were selected, good coefficients of linear correlation being obtained.

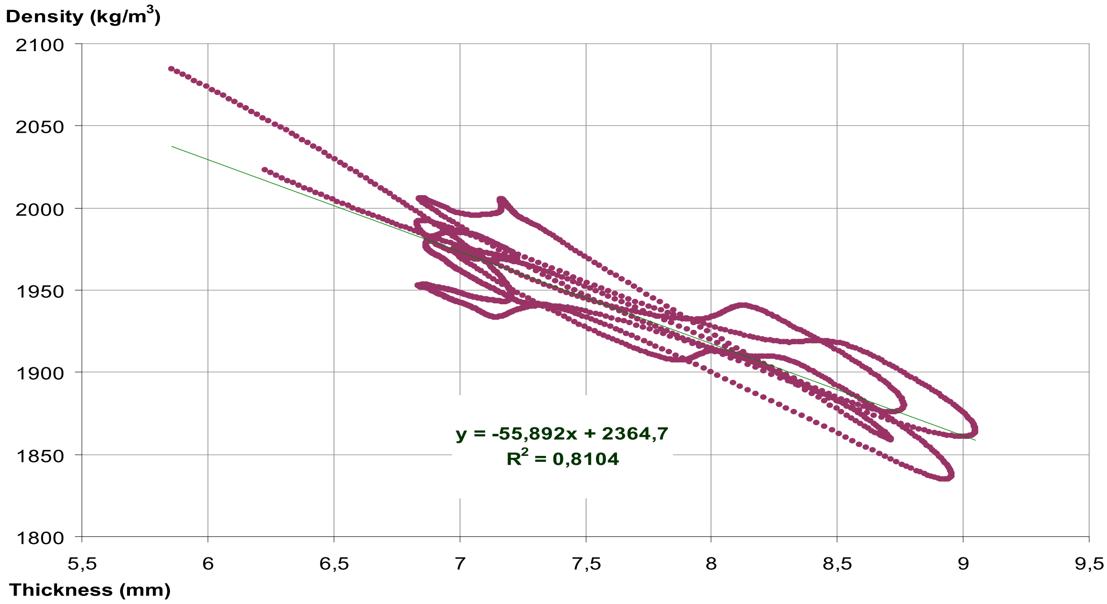

Illustration 7. Da vs. thickness for shaped back (reservoir) (all points) line 17

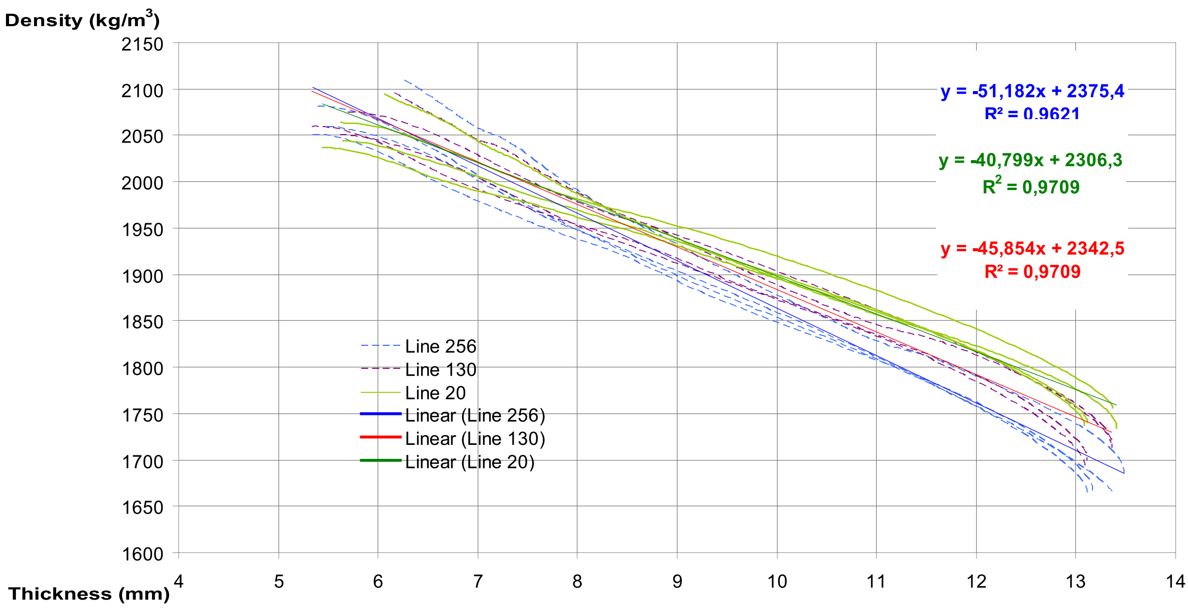

Illustration 8. Da vs. thickness for flat back (only up-flanks)

3. RESULTS AND DISCUSSION

Similar situations have been described for convex punches in the pharmaceutical industry. Certain important differences are to be noted, however, in the studied compact:

- The aspect ratio (specimen height divided by width) of the tablets is greater. Volume vs. sheet (space vs. plane).
- The deflection of the curves (difference in height between the peak and the trough) in relation to the overall height is greater for the tiles.
- The slope of the curves is greater for the tiles.

In (3) it is noted that the friction between the powder and the die and between the powder and the punch has a pronounced effect on the space distribution of Da: 'When the material at the boundary is initially pressed by the external part of the punch, it begins to densify. A region of high Da forms in the top corner of the compact, which tends to propagate radially and vertically. If the friction is high, the radial movement is restricted and the densification that follows is limited to the boundary. The central part of the tablet only begins to densify when the top punch totally contacts the material. With low friction, the tendency of the initially densified regions to move radially towards the centre of the tablet is facilitated by slipping on the curved face of the die, producing higher Da in the centre of the specimen. In general, the extent of this movement will be affected by the geometry of the punch and the local friction conditions. The results show that it is possible to optimise the lubrication in order to minimise the gradient of Da in the tablet, avoiding areas of low density …'.

In the studied case, friction alone does not explain the results, because the top punch begins to contact the powder in the peak area and this area has the lowest Da (the greater travel of the punch in the powder does not appear to have any effect). Therefore, as stated in 2)-b) of point 2.1, the mechanical drag by the `wedge' exceeds the effect of the powder–punch friction. It is necessary to consider the slope of the curve as an additional factor. In contrast, friction does indeed explain the relationship between Da and thickness, because with greater thickness, there is more dissipation energy and, therefore, lower compaction.

In (2) the study is extended and the main factors are described that influence the distribution of Da in tablet pressing: `basic powder behaviour during compaction; friction between the powder and the die wall; die and punch geometry; the sequence of the punch movement; starting conditions, which are related to the state of the powder in the die after filling. When it comes to fixing the target Da, a rule has been established in the pharmaceutical industry: `maximum heterogeneity is reached when the ratio between average target Da and powder maximum density is about 0.8'.

In (4) the distribution of Da and the movement of the powder (microcrystalline cellulose) in pressing cylindrical tablets, with both flat and convex faces, at 97.2 MPa are studied, using the Train Explanation (5) for the development of the stress/density patterns, which allowed him to plot the evolution of the pressure pattern in the compacts. He concludes that `friction is the main factor that explains the distribution of Da, so that, when this is reduced, a more uniform distribution can be achieved; if the pressure is increased, the range of Da also increases, for both flat and curved surfaces, but more for the curved ones, because the friction has a greater effect; in the case of flat surfaces, the high density regions occur in the top corners and at the heart, with low density regions in the middle of the top part and in the bottom corners; in the curved surfaces the high density region occurs at the side of the tablet, where the powder is in contact with the die and the friction effect is greater'. However, when the height/width ratio is low, the importance of friction decreases.

In addition in (6) the effect of the lateral movement of the powder from the ends towards the centre is studied in depth, since this plays an important role in density distribution (if this did not occur, the density at the ends in contact with the moving punch would be much greater than the observed density). To measure this, an arrangement of metal balls instead of coloured layers is used. The study concludes that the radial movement is greater by at least a factor of 3 for the curved tablets compared to the flat ones.

Studies are also available on ΔDa in the ceramic industry, but only for flat punches, (7) relating this to the friction between the body and the die wall, the regions with high Da being attributed to the relatively high displacement of the powder near the moving punch next to the die wall. In (8), a study is performed of the effect of the pressing method and die geometry, and it concludes that for a cylindrical die and a single moving punch, the range of Da is greater than in the case of pressing with a double effect. The opposite occurs for a die in the form of a block, which would be more similar to the case studied here.

4. NEW STRATEGIES

Beyond the simple analytical compensation [in the X–Z plane] of the quadratic effect, on dealing with curved profiles, of the typically anisotropic shrinkage, in this study the effect of the punch profile on the distribution of Da has been examined. As stated in section 2, this has a direct and inevitable influence on the variation of compaction (result of ΔPe), albeit with the advantage of being mathematically predictable and which can, therefore, be compensated. In the experiments conducted, another phenomenon, which is much more difficult to anticipate, has been described, namely powder movement during pressing, which generates ΔDa. This occurs basically by two mechanisms[2]:

2 In the pharmaceutical industry, the two mechanisms are not differentiated, though drag by the curved punch is implicitly (6) assumed.

a) Mechanical drag, owing to the wedge effect of the punch, during the first pressing phase (until the moving punch totally contacts the material).

b) Diffusion, by similarity with cellular transport, owing to the effective pressure gradient, generated in both flat and curved punches. In the latter, the effect is greater. This diffusion is limited by friction, because the force of the punch is dissipated and the powder, moving away from this, is less compacted.

From the foregoing one can infer the practical impossibility of obtaining a rigorously uniform Da throughout the body of the piece, which entails differential post-firing shrinkage to a greater or lesser degree depending on the Da values, in different points of the piece. This phenomenon, in flat pieces and in slightly three-dimensional ones results in small strains that are generally allowable as they lie within the tolerance ranges customarily used in the ceramic sector. However, in the case of notably three-dimensional pieces in which, in addition, a high degree of precision in the final geometric shape is demanded, the final geometric variabilities can be clearly inadmissible.

One strategy aimed at minimising this problem, deriving from hardly correctable variations of ∆Da, is to help reduce geometric strains by compensating the corresponding green geometry. To this end, an analysis was performed of the shrinkage of the pieces with a heterogeneous Da distribution in the bodies by using finite element (FEM) simulation techniques, assigning different coefficients of shrinkage to each region of the piece according to the expected and/or measured Da.

The simulation results were compared with the experimental values measured with a coordinate measuring machine (CMM), Brown & Sharpe (DEA), Mistral model, and a significant correlation was observed. This tool allows the level of the effect on the geometry by the difference in Da to be evaluated, so that a prediction can be made that allows the geometry in the die to be compensated, as well as the maximum level of heterogeneity of the allowable Da and its distribution to be evaluated.

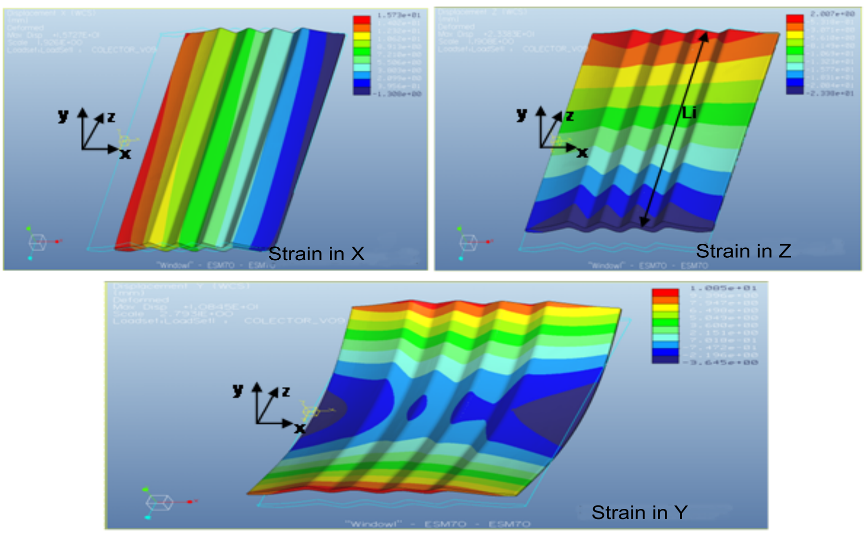

Illustration 9. Values of the strains in each axis with strain in simulated pieces.

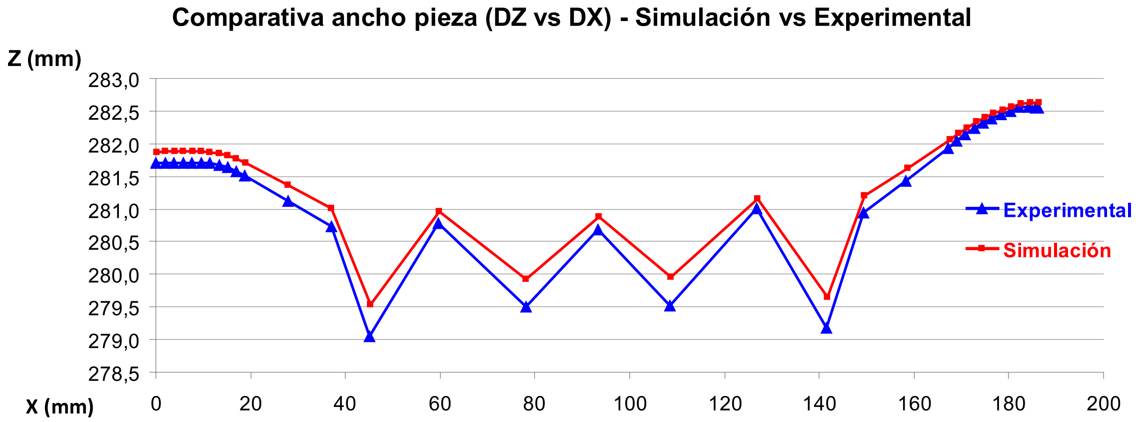

Illustration 10. Final dimensions of the pieces in width (Li values in Illustration 9) real/simulation

The pharmaceutical industry, together with that of powder metallurgy, uses finite element modelling (FEM) techniques to study the differences in density that develop during the powder pressing process and the subsequent effect of the release of stored stress–strain. It interests these sectors to study, at a lower cost and more quickly, the effect of a given geometry on the error rate.

5. CONCLUSIONS

The described methodology can be applied to the design of dies and technical punches to offset strains. The approach can be used in cases of anisotropic shrinkage and non-linear geometries (quadratic, splines, etc.), anticipating the compensations needed in the green geometry in order to achieve the targeted final geometry, opening up a wide field of application in engineering and architecture.

It is feasible to obtain pieces with a marked curved profile by uniaxial pressing, observing a maximum slope limit.

The strategy used reduces the ΔDa range introduced by the movement of the body and the variation of thickness. The mere suppression of the mechanical movement of the body, as occurs in the case of a flat back, is insufficient. The modification of the back geometry to form a reservoir is promising, but it needs a results evaluation procedure that is less expensive than trial and error, such as computer simulation. The ΔDa introduced by the geometry remains to be solved.

Any attempt to achieve very small values of ΔDa in these types of pieces, minimising differentials strains, is very complicated. When it is sought to obtain complex fired geometries with a high level of precision, this feature is critical. Analysis by finite element (FEM) simulation, taking into account the Da in each region of the piece, led to very satisfactory results with regard to the prediction of the final geometry of a fired piece and, therefore, of the differential strains produced by the heterogeneity of Da. This opens up a field of work that, using these techniques, enables the applicable compensations to be calculated and established for the green geometry so that, after firing, the final geometry will indeed be the targeted geometry. In addition, such work allows it to be established what the maximum variations of Da and their distribution in a piece might be for the resulting residual strains in the final geometry to be within functionally acceptable limits.

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