Journal of Materials Processing Technology 215 (2015) 309–319

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Ceramic sanitary wares: Prediction of the deformed shape after the production process

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ARTICLE INFO

Article history:
Received 30 April 2014
Accepted 24 July 2014
Available online 1 August 2014

Keywords:
Digital manufacturing
Ceramic materials
Mould prediction
Sanitary ware
High temperatures creep
Sintering

ABSTRACT

Ceramic materials are nowadays widely used in many industrial applications, ranging from the production of sanitary wares to advanced mechanics. Despite their diffusion, their production process still involves inefficient product development procedures, often based on a trial and error approach. In particular, during drying and firing, the initial shape given by the mould undergoes significant deformations due to plastic strains and volumetric shrinkage. As a consequence, the prediction of the mould shape, needed to obtain a given final product, becomes a problem of primary importance. The first step towards the definition of an effective mould prediction procedure is to accurately simulate the whole industrial process. The aim of the present paper is to build an effective, yet simple, simulation procedure suitable for implementation in the industrial practice. In this article, the adopted modelling strategy is discussed and the results of the numerical model are compared with experimental data highlighting the effectiveness of the proposed approach. The arguments discussed in the paper have been addressed in collaboration with SACMI, a world leading company in the production of machineries for the ceramic industry.

1. Introduction

Ceramic materials are commonly used in a great variety of industrial applications ranging from the production of sanitary wares to high performances mechanical components. Thanks to their good mechanical performances, chemico-thermal stability and the impermeability developed after glazing, they have been successfully used in a variety of applications both in the production stage (i.e. as constitutive material for moulds) and as final products.

During their production process, the initial shape (given in the forming phase) undergoes significant deformations due to plastic strains and volumetric shrinkage. The effects of such deformations have to be carefully accounted for in the mould design in order to obtain the desired final shape.

The problem has been traditionally dealt with by using a trial and error approach. Such an approach strongly relies on the technicians experience and has proved to be extremely inefficient. In fact, the mould production is expensive in terms of both time and economical resources while the possibility to modify the mould after production is constraint by the piping system embedded into it. This means that, once the mould has been produced, if the final shape is not compatible with the desired one within an acceptable tolerance, the mould might be not modifiable and it has to be produced again. In the industrial practice, it is not rare to iterate mould modifications four to six times which might take several months.

During the production process, the mechanical behaviour of the material is extremely non-linear while deformations can reach up to 20% of the product characteristic length. Considering that tolerances with respect to the target shape are typically acceptable if they do not exceed 0.5% of the product dimensions, the mould prediction for sanitary wares appears to be an extremely challenging engineering problem (see Fig. 1).

As a first step towards an effective mould prediction procedure, in this paper, a numerical approach to the prediction of the deformed shape of ceramic sanitary wares during their production process is presented. The proposed methodology has been tested in collaboration with SACMI, a world leading company in the production of machineries for the ceramic industry.

The paper is organized as follows. In Section 2 the production process is described. In Section 3 the experimental tests, performed in order to characterize the material mechanical properties, are presented. In Section 4 the proposed numerical approach is discussed, while in Section 5 the numerical results are compared to experimental data in order to validate the model predictions. Finally, some conclusions are drawn in Section 6.

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http://dx.doi.org/10.1016/j.jmatprotec.2014.07.025
0924-0136/

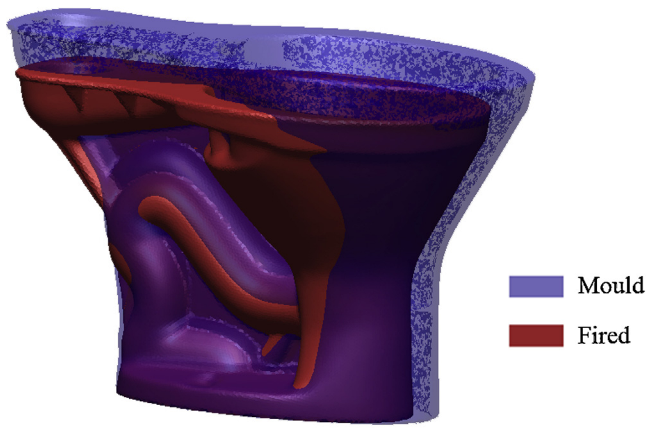

Fig. 1. Shrinkage and deformations during the production process: comparison between mould shape and fired piece.

2. The production process

The production process of sanitary wares can be ideally subdivided into three main steps: forming, drying and firing.

During the forming phase, slip composed of a mixture of ceramic powders is poured into a mould. The mould porosity allows water filtration so leading to the deposition of a clay layer in adherence to the mould surfaces. When such layer reaches the desired thickness (4–7 mm) the water is removed. Pressured air is injected, slightly desaturating the clay, so providing the minimum mechanical strength needed to extract the formed product from the mould and allowing it to support its self weight. At this stage the product is called green body.

The green body is an unsaturated normally consolidated clay and its shear strength is mainly provided by the compressive effective mean pressure developed due to suction. Some details on the effects of the degree of saturation on mechanical behaviour of unsaturated clays can be found in Sun et al. (2010), while one of the first elastoplatic models for this kind of soils is presented by Alonso et al. (1990). This is easily proved by observing that, when such material is immersed into water and reaches saturation, no residual resistance is experienced. At this stage, the material still has an high moisture content and it is extremely deformable. As a consequence, when the mould is removed, significant plastic deformations due to self weight can occur.

Subsequently, during the drying phase, pieces are exposed to environmental humidity and temperature (indicated as T in the following). This produces moisture gradients between the inner and the outer part of the clay layers and leads to water migration and, indeed, to the piece drying. The decrease in the water content strengthens suction, leading to shrinkage and to a quick improvement of the mechanical properties (see Fig. 2(a)).

Such phase is extremely delicate. In fact, if the drying is too quick and not uniform over the piece, parasite stresses arise which might lead to crack development and propagation as shown by Amorós et al. (2003). This problem has remarkable economic interest and the most convenient balance between drying speed and fracture risk is a challenging engineering problem.

Once pieces are completely dried, they are fired in a kiln following a predefined temperature profile (see Fig. 2(b)). During firing, deformations occur due to both volumetric shrinkage and creep. In fact, when the sintering temperature is reached, the melted phase fills the voids causing a complete reorganization of the ceramic microscopic structure as described by Tuncel and Ozel (2012) and an increase of deformation, as showed by Noirot and Carty (2003). In this phase, the shear strength is greatly reduced and creep controls the development of inelastic deformations.

A complete simulation of the whole production process would require a multiphysic approach able to include moisture migration and an effective-stresses based formulation (Gens et al., 2006) in the drying phase, while, during the firing phase, a model for phase transition and constitutive relations for grain and liquid-phase mixtures should be employed.

Here, aiming at obtaining a reasonably simple procedure which can be used in the industrial practice, a phenomenological approach is adopted. This is necessary also because the sanitary wares geometries are often complex and require large numerical models. In this context, the simulation time would be not compatible with the production time schedules if a fully multiphysic approach is adopted.

Furthermore, it must be noticed that, especially in the firing phase, the experimental evaluation of the mechanical properties is not straightforward. In fact the extremely high temperatures recorded in the kiln prevent from directly measuring many physical quantities by using standard procedures. In this context, only few simple measurements are possible, so that the employed models can be calibrated only with respect to a limited amount of parameters.

From this point of view, the adopted phenomenological approach is justified *a posteriori* by the fact that, once the model has been calibrated for a given material within predefined drying and firing cycles, the model proved to be robust enough to allow accurate analysis of new geometries while keeping the production process constant.

3. Material characterization

The following experimental tests have been performed in order to characterize the material mechanical properties. Indeed, they represent the minimum amount of experimental data needed to calibrate a reasonably robust numerical model. The difficulties encountered in applying standard material characterization procedures, especially during firing, are discussed.

3.1. Drying

As already introduced in Section 2, when the mould is removed, plastic deformations are almost instantaneously observed due to self weight. Such deformations increase in time and reach their final value after 10–15 min. The stabilization is due to both the weakening of the primary creep and the increase in the material strength due to drying.

It is important to notice that, although a delayed development of deformations is observed, the instantaneous ones represent the major contribution to the total amount and when this is not the case (because of secondary or tertiary creep) pieces are supported, modified or produced with more performing ceramic mixtures.

In order to characterize the material properties during this stage of the production process, several traction tests at different humidities have been performed (in the literature only a few studies have been presented concerning the tensile strength of clays, Heibrock et al., 2003). Such tests have been performed by using a bone-shaped sample obtained by cutting a flat clay layer produced with the same technology employed for the sanitary ware production. The shape of the adopted specimen is reported in Fig. 3.

Fig. 4 depicts the evolution of the $\sigma - \varepsilon$ curves with varying humidity. The humidity is calculated as the percentual weight of water considering as solid weight the fully dry piece (at ambient conditions) which is labelled as 0.0 humidity, accordingly. Tests appear to be in reasonable agreement with the results presented by Amorós et al. (2003). The rapid increase in shear strength and stiffness can be easily observed.