Journal of the European Ceramic Society 36 (2016) 2263–2275

Contents lists available at www.sciencedirect.com

Journal of the European Ceramic Society

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

Integration of CAD, CAE and CAM procedures for ceramic components undergoing sintering

Claudio Maruccio[a,*], Pasquale Bene[b], Antonio Gerardi[b], Danilo Bardaro[c]

[a] University of Salento, Via per Monteroni, 73100 Lecce, Italy
[b] Consorzio CETMA, Cittadella della ricerca, s.s. 7 Appia Km 706+030, 72100 Brindisi, Italy
[c] D'Appolonia Lecce, Via B. Ravenna, 4, 73100 Lecce, Italy

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
31 December 2015
Accepted 2 January 2016
Available online 2 March 2016

Keywords:
Ceramic materials
Sintering
Finite element analysis
CNC manufacturing

ABSTRACT

The paper discusses a new method to predict sintering deformation of complex ceramic components combining advanced nonlinear simulations and experimental results. Bending creep and dilatometric tests are used to fully characterize the complex material behavior and to determine the viscosity of vitreous china for sanitaryware as a function of relative density. The material model is then implemented into a USERMAT subroutine for the Ansys finite element program and the deformation of ceramic components of complex shapes during sintering is numerically simulated. Finally a method is developed and implemented in Ansys using the APDL language aiming to apply a subdivision algorithm to the final deformed mesh predicted through the finite element analysis. After the application of the subdivision algorithm, a smooth surface geometry of the ceramic component is obtained in a format suitable for manufacturing.

1. Introduction

Today, optimization of industrial processes is a central topic in any production field. Since a sintering step is always included in each production facility of ceramic parts understanding sintering is very important. Huge efforts were invested since the late 1940s from the scientific community to develop theoretical, experimental and numerical strategies to describe sintering, see [1–7] for a review. Different researchers developed theoretical models for the early, intermediate and late sintering stages, see [8–22]. The mechanisms of neck growth and shrinkage in the early sintering were successfully described by the two-sphere model of Frenkel [8] and Kuczynski [9]. The intermediate shrinkage state can be understood based on the cylindrical pore channel model of Coble [10] and the extrapolated two-particle model of Kingery and Berg [11] while late sintering stages can be described by the spherical pore model of MacKenzie and Shuttleworth [12]. Reviews on liquid phase sintering are available in [13–15]. Special effects affecting sintering such as gravity, particle orientation, anisotropic shrinkage or superposition of external loads were analyzed in [16,17].

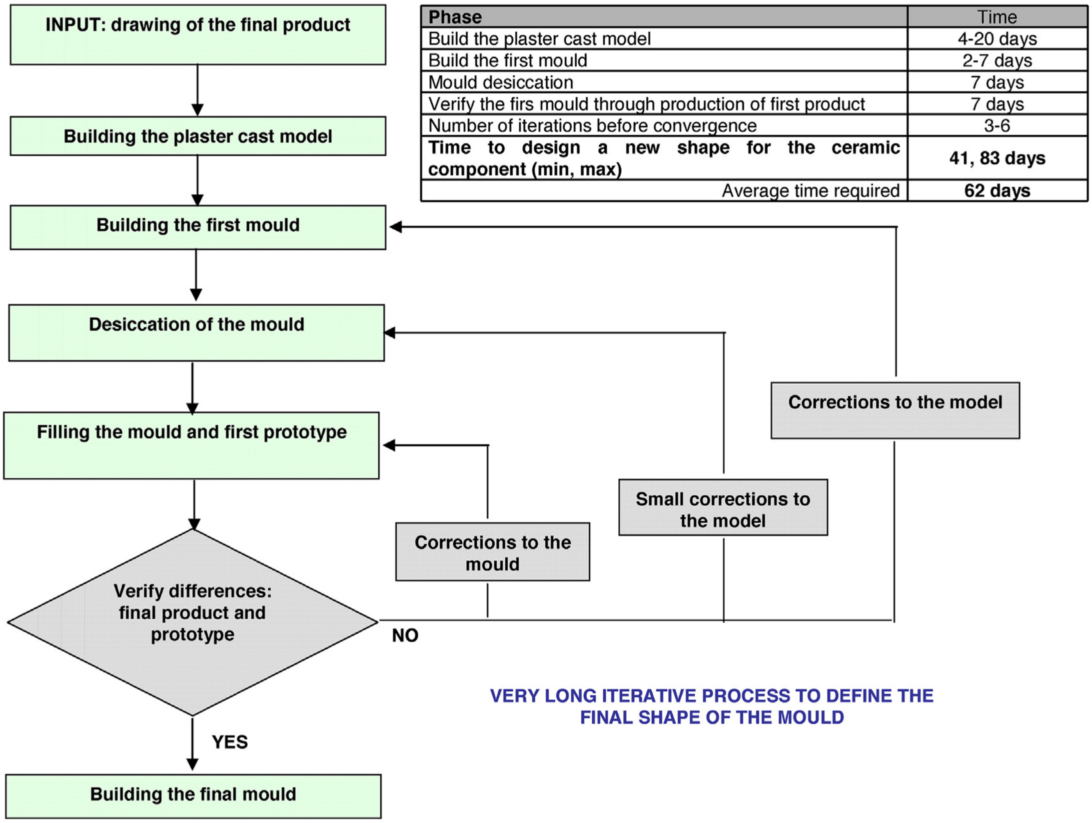
Several experimental approaches were also developed to experimentally measure the viscosity of ceramic materials undergoing sintering. This is in general possible using a compressive or tensile test which generates creep deformations. To avoid gripping or alignment problems, bending creep test were also proposed, see [23–27]. The viscosity of materials during sintering was demonstrated to depend strongly from the relative density and temperature, see [28–37]. Moreover further experimental work demonstrated that a porous material undergoing densification can be treated as a linear viscous material at low stresses (about 1 MPa).

The introduction of numerical methods helped to deal with more realistic situations and enables investigations of relevant technical applications [17]. Recent studies deal with numerical modeling of developing warpage during sintering of a graded cemented carbide [38], porosity distribution in bi-layered structures [39], viscoplastic constitutive model and simulation results on the warpage of graded powder compacts [40,41], deformation of sintering for several parts made of FE-based, WC-Co or aluminium powders [42,43], etc. Distortion during liquid phase sintering due to the viscous flow [44], or shape changes due to gravity [45] can also be predicted. Temperature gradients may also play a role in developing distortions and have to be considered in sintering simulations to get realistic results, see [45,46]. Several authors emphasize the importance of coupling sintering simulation with heat transfer analysis with the aim to investigate the final shape of the part, see [47–52]. In general, predicting sintering distortions to minimize them by appropriate process control is one of the main aspects in the application of sintering simulations [17].

---

* Corresponding author.
E-mail address: claudio.maruccio@unisalento.it (C. Maruccio).

http://dx.doi.org/10.1016/j.jeurceramsoc.2016.01.001
0955-2219/



Phase	Time
Build the plaster cast model	4-20 days
Build the first mould	2-7 days
Mould desiccation	7 days
Verify the firs mould through production of first product	7 days
Number of iterations before convergence	3-6
Time to design a new shape for the ceramic component (min, max)	**41, 83 days**
Average time required	**62 days**

Fig. 1. Flow chart: traditional method to design the mold.

This paper discusses a new method to predict sintering deformation of complex ceramic components combining advanced nonlinear simulations and experimental results. Bending creep and dilatometric tests are used to fully characterize the complex material behavior and to determine the viscosity of vitreous china for sanitaryware as a function of relative density. Equations based on beam deflection theory and the linear elastic to linear viscous analogy are used to determine the viscosity during the entire heating cycle by measuring the deflection in the center of the specimen using an optical instrument. In addition, dilatometric analyses are performed to measure the sintering shrinkage and the specimen density during the sintering process. The material model is then implemented into a USERMAT subroutine for the Ansys finite element program [53]. The deformations of ceramic components of complex shapes during sintering are numerically simulated based on the material model implemented. Due to material and geometrical non linearities in the finite element analysis, computing time is very high even if parallel algorithms are used. Therefore a coarse mesh and an advanced material model is needed during the finite element analysis. However high mesh resolution is required to allow the manufacturing process through CNC machines. Therefore a method is developed and implemented in Ansys using the APDL language [54], aiming to apply a subdivision algorithm to the final deformed mesh predicted through the finite element analysis. After the application of the subdivision algorithm, a smooth surface geometry of the ceramic component is obtained in a format suitable for manufacturing.

2. Traditional ceramic products: fabrication process

The steps required to fabricate traditional ceramic components are well known. The process starts preparing the slurry used to fill the mold. Then the cast is formed and after draining and partial drying it is possible to separate the two parts of the mold and extract the final product. A final drying process is necessary to achieve the final mechanical properties of the product. The traditional approach to design new ceramic components requires several weeks before to get the target geometry and it is based on a trial and error approach mainly influenced from the experience of the people involved in each production stage, see Fig. 1. Aiming to optimize the industrial process and reduce the time to market for new design, an innovative method is proposed in this paper that allows to automatize several steps based on finite element simulations of the production process. The new approach reduce drastically the iterations needed to pass from the first prototype to the final shape of the product, see Fig. 2. Starting from the target geometry provided in a CAD format from the designers, the main objective of this work is the development of a coupled experimental numerical procedure that allows to predict the green model geometry in such a way that the final product geometry after the sintering step can be achieved with minimum errors, see Fig. 3.

3. Experimental characterization

During sintering processes a traditional ceramic material undergoes several physical and chemical transformations. From a macroscopic mechanical point of view the main interests are the shrinkage prediction and the estimation of the pyroplastic deformation under material self weight. During firing, the ceramic material undergoing densification exhibits a linear viscous behavior. For a two point bending creep test, see Fig. 4, using the beam deflection theory and the linear elastic to linear viscous behavior analogy, it is possible to derive a relationship where the material viscosity η is a function of the density ρ, the specimen thickness h (or the equivalent specimen thickness h^*), the gravity acceleration g, the span length L (or the equivalent specimen length L^*) and the deflection rate at beam center $\dot{\delta}$ (or the equivalent deflection rate