Finite element simulation of ceramic powder isostatic pressing process using material parameters of a uniaxial compaction

R. B. Canto, V. Tita, J. de Carvalho and B. de M. Purquerio

Universidade de São Paulo, Escola de Engenharia de São Carlos, Depto de Engenharia Mecânica
Av. Trabalhador São Carlense, 400 - Cx. P. 359 - CEP 13566-590 - São Carlos, SP, Brasil
Fax: +55 16 273 94 02. E-mail: canto@sc.usp.br

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Abstract: This paper presents the results of finite element simulations of isostatic pressing process using material parameters of a uniaxial compaction. For this study, it is simulated the isostatic pressing of ceramic spheres for hip implant stem. This has been done through the use of a Drucker-Prager/cap model within the commercial finite element code ABAQUS®. The simulations yield to a good agreement with measured manufactured components.

Introduction

Isostatic pressing of ceramic powders is a process commonly used for the production of high quality green ceramic components. The process consists of filling an elastomeric bag with ceramic powder, sealing it, and then subjecting it to an external hydrostatic pressure. In this process, components are usually pressed with excess of material for further machining. When the excess of material is large, the final product cost is significantly increased due to material waste and necessity of additional machining processes. However, it is still difficult to predict the final shape and dimensions of a pressed component that depend of the bag design. In current industrial practice, the elastomeric bag shape is chosen either by trial and error, with the aid of simple compaction calculations, or based upon past experience [1].

Therefore, finite element simulations of the isostatic pressing process are carried out to predict the final shape and dimension of the pressed component. These simulations are required to adjust the bag design in order to minimize the amount of material in excess before the green machining. The isostatic pressing process of alumina ceramic spheres for hip implant stem is simulated as a case study.

For simulation analysis of powder materials, material parameters are most commonly available from triaxial testing [2]. However, to perform these triaxial tests complex experiment apparatus is needed. In order to find an easier and reliable way to perform this simulation, in this study the required material parameters were obtained by a uniaxial compaction of the ceramic powder. The numeric results are further validated through comparison with the final shapes of the pressed spheres.

Material model for powder consolidation

The most notable feature of powder materials is their ability to undergo permanent volume reduction as a result of hydrostatic pressure. This volume reduction can be enhanced by the application of shear loads [1]. However, the mechanism developed during the compaction is typically a non-linear process. This behavior can be approached by using models developed in soil mechanics. For modeling powder materials (like soils) a continuum view is necessary and valid for an application of mathematical theories of elasticity, plasticity and viscosity [3].
The modified Drucker-Prager/cap plasticity model intended for geological materials is appropriate to represent the behavior of powder material when loaded. The yield surface includes two main segments: a shear failure surface ($F_s$), dominantly shearing flow, and a “cap” ($F_c$), which intersects the equivalent pressure stress axis $p$. The cap serves to two main purposes: it bounds the yield surface in hydrostatic compression, thus providing an inelastic hardening mechanism to represent plastic compaction, and it helps to control volume dilatancy when the material yields in shear. This is possible by providing softening as a function of the inelastic volume increase created as the material yields on the Drucker-Prager shear failure and transition yield surfaces [2].

The yield surfaces are plotted in the stress space showed in the Fig. 1, where the coordinates are the equivalent pressure (Eq. 1) and the square root of second invariant of the deviatoric stress (Eq. 2). The stresses $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the principal stresses.

![Figure 1 - Modified Drucker-Prager/Cap model [2]](image)

\[ p = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \]  
\[ J'_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] \]  

The Drucker-Prager shear failure surface function is written in Eq. 3 and the cap yield surface function is written in Eq. 4.

\[ F_s = \sqrt{J'_2} - p \tan \beta - d = 0 \]  
\[ F_c = \left\{ (p - p_a)^2 + \left[ \frac{R \sqrt{J'_2}}{(1 + \alpha - \alpha/\cos \beta)} \right]^2 \right\}^{\frac{1}{7}} - R (d + p_a \tan \beta) = 0 \]  

where $\beta$ is the internal angle of friction, $d$ is the cohesion, $R$ is a material parameter that controls the shape of the cap and $\alpha$ is a small number (typically 0.01 to 0.05) used to define a transition yield surface. The evolution parameter $p_a$ represents the hardening/softening driven by volumetric inelastic strain. The hardening/softening law is a function relating the hydrostatic compression, the yield stress, $p_b$, and volumetric plastic strain $\varepsilon_{pl}^{vol}$. 

Experimental Procedures

The isostatic pressing process of alumina ceramic spheres for hip implant stem is simulated as a case study. This component was pressed by 200 MPa. The mould used to obtain this component, showed in Fig. 2, was developed by Wrege [4] and it is formed basically by three parts: metallic container, elastomeric bag and metallic mandrel.

In the present work, the alumina powder used in uniaxial tests and manufacture of ceramic spheres was an alumina 99.5% with the following formulation: 99.90% in weight of alumina S5G (ALCAN) and 0.25% in weight of MgO [5].

For the determination of material parameters of alumina powder an apparatus was developed to be used with a universal testing machine (Instron 5500 R). The apparatus (Fig. 3) itself is a punch assembled in a cylinder and it was made of steel tool, with inner diameter cylinder equal to 20 mm. Zinc Stearate powder was used as a lubricant. Many other authors [6,7,8] have used the same apparatus to study powder material parameters.

For the tests, firstly the cavity is filled with the alumina powder (assembly phase in Fig. 3), then the apparatus is placed in the test machine where a displacement is applied at a constant rate of 5 mm/min (compaction phase in Fig. 3) until an ultimate uniaxial stress of 210 MPa is achieved. Finally the punch is used to extract the specimen of the cylinder (extraction phase in Fig. 3) aided by a support ring.

\[ p_a = \frac{p_b - R \, d}{1 + R \, \tan \beta} \]  

(5)

For uniaxial compaction (\(z\) is the axial direction), the following relations are assumed:

\[ \sigma_z = \sigma_z \]  

(6)

\[ \sigma_1 = \sigma_3 = \rho \sigma_z = \sigma_r \]  

(7)

where \(\rho\) is a factor that establishes a linear relation between axial stress and radial stress during loading. Then:

\[ p = \frac{1}{3} \left( \sigma_z + 2 \sigma_r \right) \]  

(8)
The compaction curve obtained in the uniaxial test is showed in Fig. 4. Both phases, loading and unloading are indicated and the main points used to obtain the material parameters are indicated by A, B, C, D and E. The stress states A, B and D were obtained from Fig. 4 (The stress state D is considered the elastic limit of the unloading curve).

The slope of region BD in the unloading curve in Fig. 4, is equal to the constrained modulus, \(M\), given by Eq. 10 [9], while the slope of the corresponding stress path in Fig. 5 is equal to \(m\) given by Eq. 13. The values of the bulk modulus, \(K\), and the shear modulus, \(G\), were found from Eq. 10 and Eq. 11, which relates de Poisson Ratio with \(G\) and \(K\). At this stage, the Young’s modulus, \(E\), for the powder system can be calculated from Eq. 12.

By using the graph of the stress space in Fig. 5 it is possible to obtain: \(\beta\), that is the tangent of the slope from AB; the stress state in the point C from Eq.13; the shear failure surface, \(F_s\) (and directly the value of the cohesion, \(d\)), which is obtained when the unloading curve reaches the stress state of the point D, where the unloading curve can no longer proceed elastically and, finally, the stress state of the point E, which is obtained by making DE parallel to \(F_s\) and the axial stress equal to zero.

\[
M = K + \frac{4}{3}G \tag{10}
\]

\[
\nu = \frac{3K - 2G}{2(3K + G)} \tag{11}
\]

\[
E = \frac{9GK}{3K + G} \tag{12}
\]

\[
m = \frac{2G}{\sqrt{3}K} = \frac{\left(\sqrt{J'_2}\right)_B}{(p)_B - (p)_C} \tag{13}
\]
Assuming values extracted from the literature for $\nu$, $\alpha$, $\rho \in \mathbb{R}$ [6], the following parameters $\beta$, $E$ and $d$ are obtained and presented in Table 1.

Table 1. Parameters of alumina powder used in this work

<table>
<thead>
<tr>
<th>$\nu$</th>
<th>$\alpha$</th>
<th>$\rho$</th>
<th>$R$</th>
<th>$\beta$</th>
<th>$E$ [MPa]</th>
<th>$d$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.278</td>
<td>0.03</td>
<td>1.617</td>
<td>0.558</td>
<td>16.5°</td>
<td>2850</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Assuming the procedure used by Aydin [6], the hardening part of the model was approximated from Fig. 4 by considering that the unloading response would be identical at every stage of compaction. In other words, the unloading curves from the points $B_1$, $B_2$, $B_3$, $B_4$, $B_5$ and $B_6$, have the same slope value of BD curve, and it can be possible to obtain the correspondent strain plastic values for each value of equivalent stress, $p$, for $B_n$ points. Fitting these pairs $(p, \varepsilon_{\text{vol}}^{pl})_{B_n}$ it is possible to write the Eq. 14. Now the hardening part of the Drucker-Prager/cap model can be obtained from Eq. 15 that relates Eq. 5 and Eq. 14.

\[
P = 0.060 \times 10^{4.786 \varepsilon_{\text{vol}}^{pl}} \quad (14)
\]

\[
P_b = 1.562 + 0.070 \times 10^{4.786 \varepsilon_{\text{vol}}^{pl}} \quad (15)
\]

**Finite element analysis of isostatic pressing process**

For the simulation of the isostatic pressing process, the ceramic powder is modeled in contact with the metallic mandrel. The contact interaction was modeled with Coulomb friction and the coefficient of friction between the metallic mandrel and the powder was assumed to be 0.2 [8]. The elastomeric bag was not considered in the analysis in order to simplify it. However it should be noted that the presence of this bag has influence in the prediction of possible distortions in the component [1]. Thus, the pressure of 200 MPa was applied directly to the powder. An axysimmetric model was used to simulate the spherical component. Elements type CAX4 (4 nodes) were used in ABAQUS®. The parameters for the material model have been previously presented in Table 1.
As showed in Fig. 9, the simulations have a good agreement with measured manufactured components. The maximum error (2.9 %) happened in the upper region of the component. This error can be due to the absence of elastomeric bag in analysis and the fact that the real coefficient of friction may be different from the assumed value.

Conclusions

The good agreement between theoretical and experimental results prove the viability of using the parameters of uniaxial compaction test in the Drucker-Prager/cap model implemented in commercial finite element code ABAQUS®. Additional simulations must be performed in more complex geometry components to validate the predictive capability of the overall numerical procedure. This would allow the adjustment of the mold to the requirements of shape and dimensions of the desired ceramic pressed component. It is also an advantageous technique to optimize the amount of ceramic material to be removed during the green machining process.

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References