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3D numerical modeling of powder compaction processes using a cap plasticity theory

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In this paper, the numerical simulation of powder compaction processes is presented using a cap plasticity theory. A cone-cap plasticity model based on a combination of a convex yield surface consisting of a failure envelope and a hardening elliptical cap is developed for nonlinear behavior of powder materials in the concept of the generalized plasticity formulation for the description of cyclic loading. A general algorithm for the cap plasticity from the viewpoint of efficient numerical modeling is presented. The numerical simulation is illustrated in the modeling of a 3D multi-level component.

1. INTRODUCTION

The knowledge of the behavior of powder material undergoing cold compaction is necessary for predicting the final shape and the density distribution within the parts, and for preventing the failures that can occur during the subsequent sintering. Such components vary from simple bush families, which are appropriate for bearing applications, through to complex multilevel parts, which are used in automatic transmission systems. The powder compaction process transforms the loose powder into a compacted sample with a density increase. Design of a compaction process consists, essentially, in determining the sequence and relative displacements of die and punches in order to achieve this goal. The design process, which has to be done for any new type of piece to be manufactured, could be effectively improved by using a simulation tool, able to predict the mechanical response of the compact along the process.

The numerical simulation of the compaction process is central to an understanding of the mechanics of powder behavior and when it is coupled with experimental inputs the simulation can be considered as an alternative tool to achieve a more economic enterprise. A successful numerical simulation needs a reliable constitutive model that allow us to predict the behavior of the powder and a computational framework to make use of it. The geological and frictional material models are employed to capture the major features of the response of initially loose metal powders to complex deformation processing histories encountered in the manufacture of engineering components by powder metallurgy techniques. The cone-cap plasticity models, which reflects the yielding, frictional and densification characteristics of powder along with strain and geometrical hardening, have been developed by Haggblad and Oldenburg [1], Khoei and Lewis [2, 3] and Gu *et al.*[4].

2. CONE-CAP PLASTICITY MODEL

The cone-cap plasticity models are based on the concept of continuous yielding of materials expressed in terms of a three-dimensional state of stress and formulated on the basis of consistent mechanics principles. A generalized cap model, based on classical plasticity theory, developed by Hofstetter *et al*. [5] allows the control of dilatancy by means of a hardening cap that intersects a fixed failure envelope in a non-smooth fashion. The model assumes a one-to-one correspondence between the hardening of the cap and the plastic volume change. However, if a one-to-one hardening law is postulated, softening response may occur when the stress point is located at the compressive corner region.

The yield surface of the model has a moving cap, intersecting the hydrostatic loading line, whose position is a function of plastic volumetric strain, as shown in Figure 1. The main features of the cap model include a failure surface and an elliptical yield cap which closes the open space between the failure surface and the hydrostatic axis. The yield cap expands in the stress space according to a specified hardening rule. The functional forms for these surfaces are as follows

$$f_1 = \sqrt{J_{2D}} - \theta J_1 + \gamma e^{-\beta J_1} - \alpha = 0 \tag{1}$$

$$f_2 = R^2 J_{2D} + (J_1 - L)^2 - R^2 b^2 = 0 \tag{2}$$

$$f_3 = J_1 - T = 0 \tag{3}$$

where J_1 and J_{2D} are the first invariant of effective stress tensor and second invariant of deviatoric effective stress tensor, respectively. α, β, γ and θ are the parameters of fixed yield surface f_1, which controls the deviatoric stress limits. The fixed yield surface f_1 is defined by an exponential function and in reality is consist of two different Drucker-Prager yield surfaces. The cap yield surface f_2 is an elliptical function, with R denoting the ratio of two elliptical cap's diameters. The function f_3 indicates the tension cutoff zone, with T denoting the material's tension limit.

The hardening rule for moving cap is related to the volumetric plastic strain ε_v^p as

$$X(\kappa) = X(\varepsilon_v^p) = \frac{-1}{D} \ln\left(\frac{1-\varepsilon_v^p}{W}\right) + X_0 \tag{4}$$

where D and W are material parameters and X_0 refers to the position of initial cap surface. The plastic hardening/softening modulus H is zero for f_1 and f_3.

3. GENERALIZED PLASTICITY THEORY

In generalized plasticity theory, the constitutive tensor in loading $\mathbf{C}_L$ (inverse of $\mathbf{D}_L$) differs from constitutive tensor in unloading $\mathbf{C}_U$ (inverse of $\mathbf{D}_U$), i.e.

$$d\boldsymbol{\varepsilon}_L = \mathbf{C}_L . d\boldsymbol{\sigma}', \quad d\boldsymbol{\varepsilon}_U = \mathbf{C}_U . d\boldsymbol{\sigma}' \tag{5}$$

In fact, at each point of the stress space, a direction tensor is specified to distinguish between loading and unloading. A loading direction vector $\mathbf{n}$ is introduced to discriminate between loading and unloading, as

$$\mathbf{n}^T \, d\boldsymbol{\sigma}'_e > 0 \qquad \text{for loading}$$

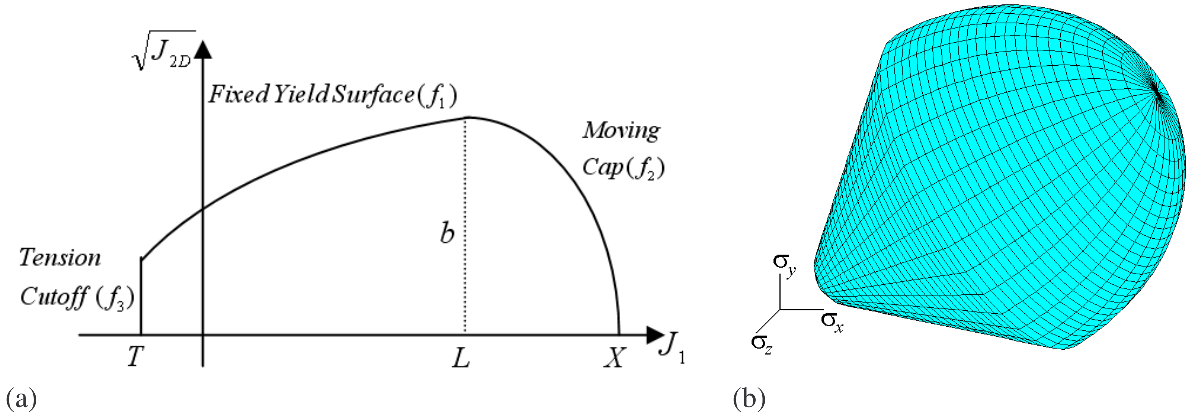

Figure 1. The cone-cap plasticity model; a) 2D model, b) 3D model

$$\mathbf{n}^T\, d\boldsymbol{\sigma}'_e < 0 \qquad \text{for unloading} \tag{6}$$
$$\mathbf{n}^T\, d\boldsymbol{\sigma}'_e = 0 \qquad \text{for neutral loading}$$

where $d\boldsymbol{\sigma}'_e = \mathbf{D}_e d\boldsymbol{\varepsilon}$. The constitutive matrix can be defined as

$$\mathbf{C}_L = \mathbf{C}^e + \frac{1}{H_L}\mathbf{n}_{gL}.\mathbf{n}^T, \qquad \mathbf{C}_U = \mathbf{C}^e + \frac{1}{H_U}\mathbf{n}_{gU}.\mathbf{n}^T \tag{7}$$

or in reverse form

$$\mathbf{D}_L = \mathbf{D}_e - \frac{\mathbf{D}_e.\mathbf{n}_{gL}.\mathbf{n}^T.\mathbf{D}_e}{H_L + \mathbf{n}^T.\mathbf{D}_e.\mathbf{n}_{gL}}, \qquad \mathbf{D}_U = \mathbf{D}_e - \frac{\mathbf{D}_e.\mathbf{n}_{gU}.\mathbf{n}^T.\mathbf{D}_e}{H_U + \mathbf{n}^T.\mathbf{D}_e.\mathbf{n}_{gU}} \tag{8}$$

where H_L and H_U are the plastic hardening/softening modulus in loading and unloading and $\mathbf{n}_{gL}$ and $\mathbf{n}_{gU}$ are the normal vector to plastic potential in loading and unloading conditions. In this frame work, all necessary components of elasto-plastic constitutive matrix depend on the current state of stress and loading/unloading condition.

4. NUMERICAL SIMULATION RESULTS

In order to illustrate the applicability of the cap plasticity model in 3D modeling of powder forming process, the frictionless compaction of a multi-level component is analysed numerically. The hard metal powder properties in term of cap model parameters are given in references [2, 3]. A rotational flanged component is modelled by an axisymmetric representation as illustrated in Figure 2. The loading characteristics are achieved by the use of prescribed nodal displacements for the top and bottom punches. The finite element modeling of this flanged component is performed using eight-noded brick element. The simulation has been performed using the remaining pressing distance of 6.06 mm from above and an under-pressing of 7.07 mm.

In the simulation presented here the friction effects are neglected. Therefore, the results are a qualitative approximation to the real compaction process, where the friction effects have to be taken into account [2]. In Figure 3, the relative density contours at the half and final stages of compaction are presented for one quarter of component, which can be compared with those given in reference [2]. It can be seen that the proposed cap plasticity model is capable of simulating metal powder compaction processes in an efficient and accurate manner.

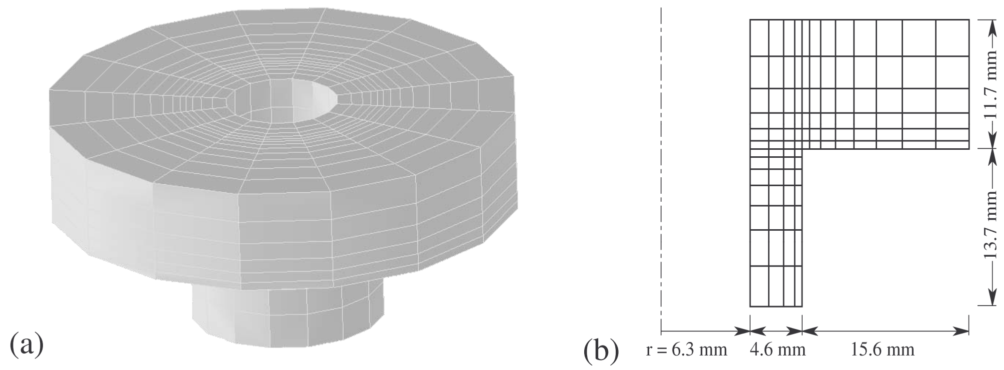

Figure 2. A rotational flanged component, a) 3D finite element mesh, b) Geometry

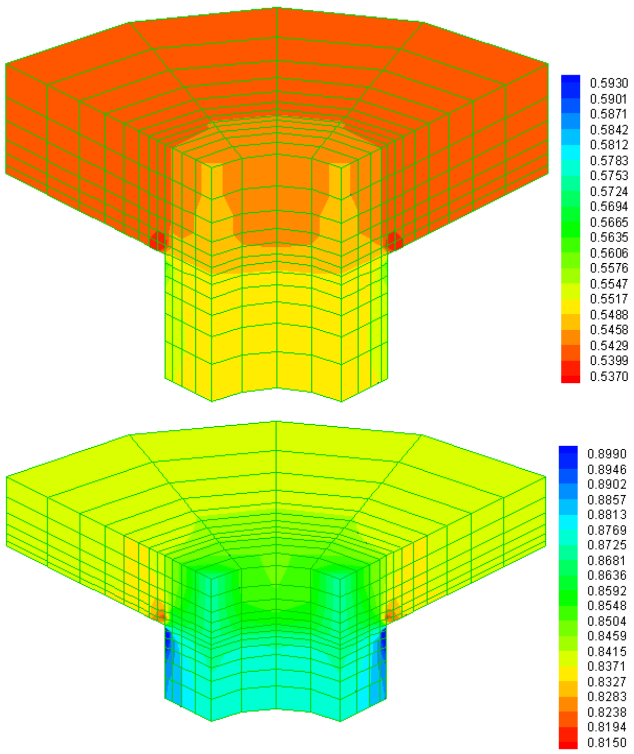

Figure 3. Relative density contours at different stages of compaction for one quarter of component

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