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Original Research Paper

Determination of the constants of cap model for compaction of three metal powders

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ABSTRACT

Cap model is a well-known model for defining the yield surface of porous materials. In this work, the constants of the model are determined by a combined experimental/numerical/optimization technique for aluminum 7075, iron and copper powder. The compaction of powder is conducted using Instron testing machine. The numerical simulation of powder compaction is performed using the Ls-Dyna hydrocode. Optimization is carried out using genetic algorithm. The objective function is defined as the difference between the experimental and numerical load–displacement curves of the compaction. The constants of the model correspond to the case when this difference is optimized. A second order Maclaurin polynomial is assumed for the objective function. The results indicate that the cap model can reasonably predict the powder compaction of iron and aluminum. The model however, proves not to be accurate for copper powder. The results also show dependency of the model's constants on strain rate.

1. Introduction

Powder compaction is an easy and cheap process which is widely used for production of material and industrial components and applications. The final microstructure and the properties of the compacts, however, depend on the choice of powder composition and selection of process parameters. The identification of these parameters usually needs extensive experimental works which are tedious, expensive and time-consuming.

The numerical simulation using finite element method has been employed as an alternative tool in powder compaction industry over the past decade. This method can predict the distribution of variables such as density, strain and stress in the powder bed prior to the actual component design and manufacturing. This gives a better understanding into the compaction process and the influence of various parameters such as compaction speed on the tools design. However, a successful simulation requires a thorough knowledge of a constitutive model or a yield criterion, friction between die and powder and well-defined initial state and conditions of the powder.

There are two approaches for characterizing the powder behavior in compacting processes; porous and granular. In the latter, known as porous media the powder is considered as a solid containing voids. In the second approach, the powder is treated as a granular media such as soil. Each approach has some advantages and some disadvantages the study of which is beyond the scopes of this investigation. However, the second approach is adopted in this work as it is easier for numerical implementation and experimental validation.

Since, the volumetric change due to voids closure in powder compaction is high, plastic deformation in compaction is also large. Various powder compaction models have been proposed by Kuhn and Downey [1], Green [2], Oyane et al. [3], Gurson [4], Corapcioglu and Uz [5] and Doraivelu et al. [6]. The details of the methods can be found in the literature. Kim et al. [7] in 2001 and Khoei et al. [8] in 2004 used new models for porous materials. Park [9] defined new constants for these categories of models. Another group of porous models can predict the powder behavior based on an equation of state. Typical models are, ε–α, P–α and P–λ. Collins et al. [10] and Borg [11] used these models in their investigations. Shima and Oyane [12] proposed a porous model which has been used by a number of researchers. Similar to porous models, granular models are also various. Typical models are cam clay [13,14], Drucker–Prager cap and Mohr–Columb cap, modified Drucker–Prager cap model [15]. Sun et al. [16] have shown that granular models are superior to porous models such as Shima and Oyane model.

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2. Drucker–Prager-cap model

Drucker–Prager-cap model, also known as kinematic hardening cap model, was initially proposed by Stojko [17] in 1990. Isenburge et al. [18] expanded the cap theory in terms of two invariants to take account of nonlinear kinematic hardening. The basics of the formulation of this model was initially introduced by Sandler and Rubin in 1979 [19] and later by Simo in 1988 [20].

Cap model consists of three surfaces in a 2-D space defined by the first and the second deviatoric stress invariants denoted by J_1 and J_{2D}, respectively. The model is shown in Fig. 1. The first surface is the fixed yield surface and is denoted by f_1 described as follows:

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

where α, θ, γ, β are the material constants and can physical be interpreted in terms of the two Prager lines geometries shown in Fig. 1(b). α is the value of $\sqrt{J_{2D}}$ at the intercept of the second Prager line (see Fig. 1(b)) which is asymptote to the surface f_1 at the point $J_1 = \infty$. θ is the slope of the first Prager line and β is the difference between the slopes of the two lines. γ is the difference between $\sqrt{J_{2D}}$ at the intercepts of the two lines with the vertical ordinate: $J_1 = 0$.

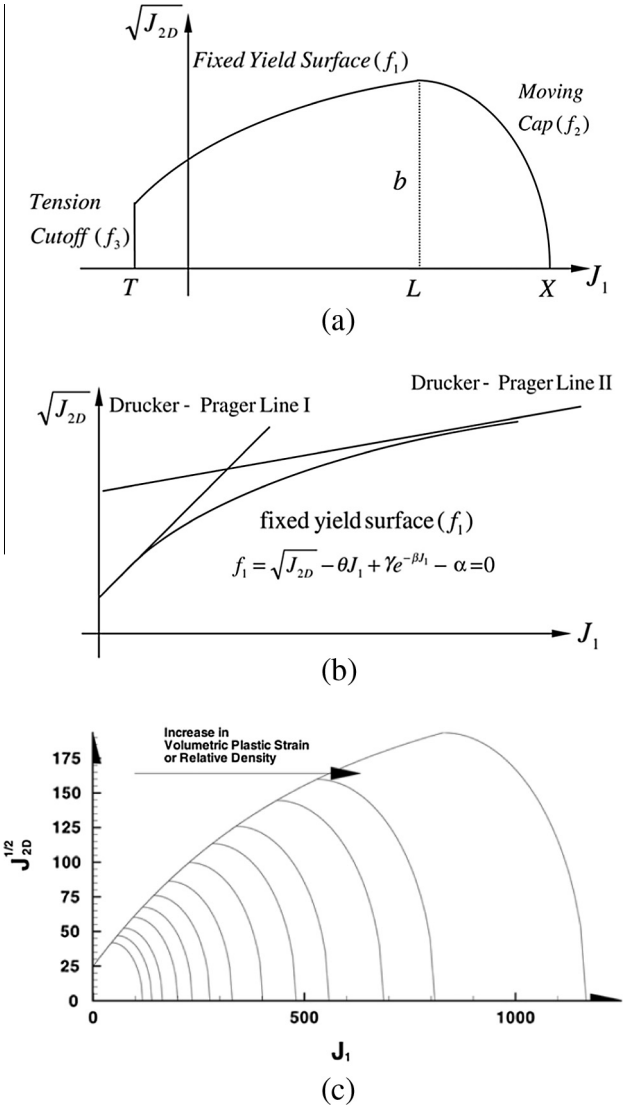

Fig. 1. (a) Definition of yield surface, (b) description of the model surfaces and (c) expansion of moving cap surface with increasing volumetric plastic strain [19].

The second moving cap surface, f_2, is defined as:

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

The constants R, L, b and X (κ) are related to each other as follows:

$$X(\kappa) = RL + b \tag{3}$$

R is the ratio of the major cap ellipse diameter to the minor one. $X(\kappa)$ represents the kinematic hardening effect as the cap surface moves because of strain hardening, κ. $X(\kappa)$ is given by the following relation:

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

where $\bar{\varepsilon}_v^p$ is the effective volumetric plastic strain, X_0 represents the initial position of the cap surface. $L(\kappa)$ is the value of J_1 at the intersection of the two surfaces f_1 and f_2. κ is the hardening parameter and is defined as [21]:

$$L(\kappa) = \begin{cases} \kappa & \kappa > 0 \\ 0 & \kappa \leqslant 0 \end{cases} \tag{5}$$

The third cap surface is defined as follows:

$$f_3 = J_1 - T = 0 \tag{6}$$

This function shows the tensile strength of the material and is 0.3 MPa for iron. As it is observed in Fig. 1(c), this parameter is too small with respect to the values of the function on the axes J_1 and is nearly negligible and thus, in the study the cap surfaces, the third surface is usually ignored. Finally, α, β, θ, γ, D, W, R are the model's constants which are determined by experiment. The two constants β and γ are usually too small and are not considered for most of metals.

The modified Drucker–Prager Cap (DPC) model has shown to be a suitable constitutive relationship for simulation of metal powder compaction. The calibration of the Drucker–Prager cap model usually involves triaxial compression test. Test equipment for conducting a triaxial compression test on metal powders is neither readily accessible nor standardized in the powder metallurgy industry.

In recent years attempts have been made to find simpler ways such as numerical simulation to calibrate the constants of the DPC. The numerical simulations usually are performed using the finite element method along with the use of an appropriate constitutive model of the powder medium. However, in order verify the numerical results reliability; they should be validated by experiment. Therefore, the main objectives of this paper are proposing a standard calibration procedure for the cap material model as well as introducing a reliable method for the experimental validation of the results of powder compaction simulation.

Sinka [17] reviewed the modeling strategies used for powder compaction focusing on the constitutive model development for finite element analysis. Hrairi et al. [22] presented the implementation of the cap constitutive model into ABAQUS FE software and proposed an inverse modeling procedure to more accurately determine the material parameters. The objective function was defined based on the discrepancy in density data between the numerical model prediction and the experimental data. Diarra et al. [23] determined the parameters of the powder in order to implement the DPC model for the simulation. They also showed that some of the parameters such as the axial transmission were well simulated. Nevertheless it was also shown that there was a disagreement between experiment and simulation for the