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# Numerical study of hard-metal powder compaction

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**Abstract.** Powder compacting is a widely used process for both metallurgy and pharmaceutical production. The mathematical simulation of the powder compaction process is a promising tool for its study. The compacting of WC/Co powder by a punch in a cylindrical die is simulated in this work. The use of the Drucker-Prager Cap constitutive model is made. Results on stress distribution and volume plastic deformation during compaction are obtained. Relative density distribution in the powder compact can also be estimated from volume plastic strain. The severe influence of frictional contact between powder and die wall on the results is noted.

## 1. Introduction

Powder compaction is an easy and cheap process that is widely used for the production of materials and industrial components [1]. In the manufacturing technologies of powder metallurgy (PM) products, cold and hot isostatic pressing and die compaction are widely used. One of the main problems in such technologies is that PM parts formed by die compaction have inhomogeneous density distributions due to the friction between the powder and the die wall. Inhomogeneity in density leads to non-uniform shrinkage or distortion during the powder compact sintering, which may lead to cracking of the obtained products [2].

PM is a fast-growing segment of the industry as, for example, automotive manufacturers look to reduce the overall weight of vehicles by replacing a range of ferrous components with PM products and thus increase car fuel efficiency. PM products are looked to as feasible substitutes in the place of both die-cast aluminum and iron materials for moving engine components [3].

Active users of powder compacting technology are pharmaceutical companies. The compressing of dry powder mixtures is one of the most significant operational processes in the pharmaceutical industry. With the use of this technology, pills are usually made. A critical step in the manufacture of tablets is the compaction of a loose powder/granule formulation between two punches within a die. Among other qualities, the resulting compact should have nearly uniform properties with sufficient mechanical strength to avoid breakage and attrition [4].

Concerning hard metal components, they are widely used in different industries as cutting tool elements. For example, cutting inserts that are used as the cutting element in a lathe, especially in a situation where space is limited, are produced by powder metallurgy technology [5].

However, the final microstructure and the properties of the compacts depend on not only the choice of the powder composition. The choice of the parameters of the compaction process influences them as well. The identification of these parameters usually needs extensive experimental works that are tedious, expensive, and time-consuming.



Therefore, the numerical simulation using the finite element method has been employed as an alternative tool to investigate powder compacting processes over the past decades. This method can predict the distribution of variables such as density, strain, and stress in the powder mixture before the actual component design and manufacturing. This gives a better understanding of the compaction process and the influence of various parameters. However, the 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 [1]. Moreover, simulation of the process compaction can also help to understand the influence of tooling properties, lubrication, and compaction kinematics, such as speed compaction and compaction sequences, and provide guidance for the optimization of tooling design and the improvement of the powder mixture [6].

The aim of this work is to study the process of compacting the mixture of hard-metal powders, as well as the distribution of stresses and bulk plastic deformations in the resulting compact.

## 2. Mathematical model of compaction

The phenomenological models, such as critical state plasticity models like Cam-Clay and Drucker-Prager Cap (DPC), which were originally developed for geological materials in soil mechanics, turned out to be well suited for modeling powder compaction, especially in PM. Recently, the DPC plasticity model has been widely used for powder compacting analysis of different powders as it can describe powder compaction and hardening.

The DPC model is one of the continuum mechanical models, in which the powder is considered as a porous medium. The DPC model can represent the densification and hardening of the powder, as well as the inter-particle friction. This model can also reasonably represent both the shear failure and the plastic yielding of the powder and can be readily characterized via experiments on real powders. Therefore, the DPC model is used frequently to analyze the strain, relative-density changes, and stress distribution of compacts during the compacting process. Finally, the DPC model is characterized by parameters that are mainly related to the internal friction angle, elastic modulus, and plastic deformation, among other parameters, that change through the hardening law [7].

Although the DPC model is a subset of the extended Drucker-Prager material, the Cap model should be viewed as a separate constitutive model. It has been proposed to enable users to describe the plastic volume compression of porous bodies when pores are collapsed and the subsequent hardening of the compressible material. With the regular Drucker-Prager models, the yield strength would increase indefinitely if the hydrostatic compressive stresses kept increasing in magnitude. A compaction cap allows users to define a hydrostatic pressure at which compaction occurs—hence, instead of yielding on the shear envelope, yielding can also occur from compaction or expansion [8].

Here, the ANSYS LS-DYNA software package was used to model the powder compacting process. In this software package, the model of Drucker-Prager Cap material is already implemented under the name `*MAT_025/*MAT_GEOLOGIC_CAP_MODEL`.

### 2.1. Geometry model

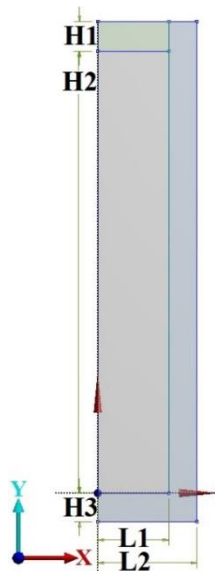
The geometry of the punch, the die, and the powder was constructed using Ansys DM in a two-dimensional axisymmetric description. It is assumed that both the punch and the die are rigid cylindrical bodies made of steel, and the powder is an elastic-plastic solid described by the DPC model. The cylindrical die has the inner radius of  $L1 = 7.5$  mm and the outer radius of  $L2 = 10.5$  mm (see the notations in figure 1). The initial filling height of the powder is  $H2 = 46.87$  mm. The other values of geometry schematic depicted in figure 1 were as follows,  $H1 = H3 = 3$  mm. The mathematical model was solved using axially symmetric quadrangular finite elements. The number of elements in the model was equal to 2241.

### 2.2. Material model parameters

In our work, we focus on modeling the process of compacting hard-metal powders. The composition of hard-metal powder varies depending on its application. For a cemented carbide a normal

composition is about 90 % of WC and about 10 % of cobalt, though other materials could also be included.

The parameters presented in table 1 were used to describe the material model. They were determined based on the data of Reference [9] for a precompacted powder of 15 MPa. The author of [9] derived the parameters from experimental data on three-axis loading.



**Figure 1.** The geometry schematic.

**Table 1.** The Drucker-Prager Cap model parameters.

Parameter (Units)	Value
Initial density ( $\text{kg/m}^3$ )	6700
Initial bulk modulus (MPa)	701.1
Initial shear modulus (MPa)	593.2
Failure envelope parameter, $\alpha$ (MPa)	929.2
Failure envelope linear coefficient, $\theta$	0.0
Failure envelope exponential coefficient, $\gamma$ (MPa)	928.8
Failure envelope exponent, $\beta$ ( $\text{GPa}^{-1}$ )	0.051
Cap surface axis ratio, $R$	17.1
Hardening law exponent, $D$ ( $\text{MPa}^{-1}$ )	0.0074
Hardening law coefficient, $W$	0.3015

### 2.3. Boundary condition

The die is fixed in both the axial and the radial direction, while the punch is fixed only in the radial direction but free to move in the axial direction. The punch is loaded by smoothly increasing force to simulate the hydraulic press up to the pressure of 50 MPa. The contact between the die, the punch, and the powder is simulated by the algorithm of surface-to-surface contact in LS-DYNA and uses Coulomb friction with the value 0.16 taken from the literature [2, 9].

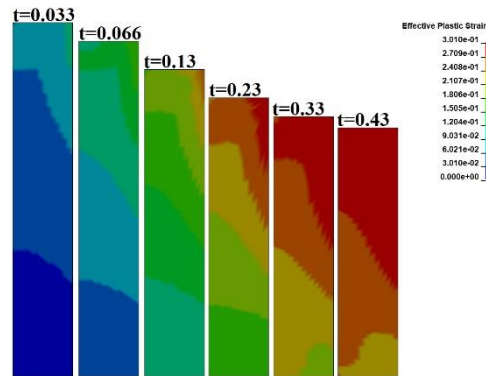
## 3. Results and discussion

In the phenomenological approach used, a pre-compacted powder mixture is considered as a continuous medium. The task of the study is to determine the distribution of stresses and plastic strains of this medium at different stages of the process, which allows assessing the quality of the resulting compact and the reasons for its deterioration.

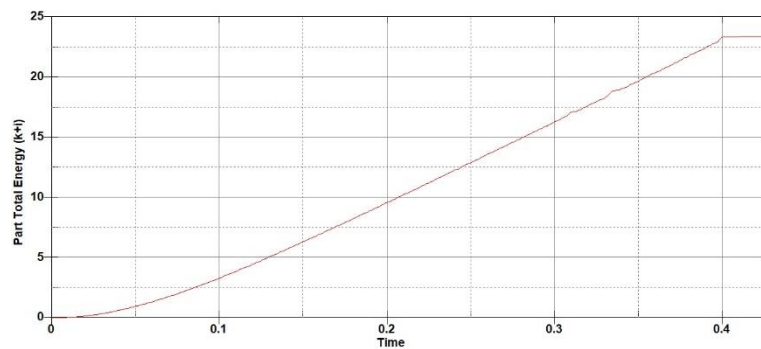
In the model, the highest stresses are localized in the corner where all three elements of the model—the punch, die, and powder—contact each other, while the lowest stresses are in the opposite corner along the vertical axis. Stress gradients, as a rule, are the highest near the sidewall boundaries due to the resistance to powder movement resulting from friction with the wall.

The distributions of effective plastic strain during the process are presented in figure 2. It may be noted that starting the initial stage of compacting the plastic strains are distributed non-uniformly throughout the powder. As the time of the process increases, also increases the localization of strains at the right top angle near the punch. The finite elements along the die are found to be distorted especially near the punch, which is evidently caused by friction between the powder and the die wall. This effect is related to the interaction energy of powder particles in the model. The change of the total energy in the powder mixture is shown in figure 3. The results obtained are qualitatively consistent with the works of the authors [2, 9].

Knowing the volume plastic strain, the relative powder density can be calculated via  $\rho = \rho_0 \cdot \varepsilon_v^{pl}$ .



**Figure 2.** Effective plastic strain in the model during compaction.



**Figure 3.** Total energy change during compaction.

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