Simulation of powder compaction using to optimize the compaction and ejection process.

Shamasundar S*. Chidanand. G, Sachin B.M.

ProSIM R&D Center,

#4, 1St 'B' Main, 1st 'N'Block, Rajajinagar, Bangalore-560010, India

Tel: 91-80-23323020 fax: +91 80 23323304, email: shama@pro-sim.com

Compaction of powder is is used in p/m (powder metal) components, hard metals, ceramics and pharmaceutical industries. Optimisation of the punch / die / kinematics is of importance to the designer to obtain uniform density distribution. An understanding of the compaction behavior is essential to design the process and the tooling for a given component production by p/m route.

FEM analysis of p/m compaction is an useful tool to minimize the tool and die development design cycle. The designer can explore various possibilities of tool and die as well as process design using FEM simulation. A robust yield function that describes the yielding and densification of the powder, availability of a valid constitutive behavior of the powder material, incorporation of the process model in FEM simulation are critical issues.

An additional issue of importance to the industrial design engineer is the extent of elastic spring back during decompression or ejection of the green compact. The spring back and the residual stresses in the green determine the geometrical integrity of the green.

Authors have developed a procedure for simulation for the simulation of compaction and ejection process. Authors have also developed a simple procedure for delineating the material properties and yield function constants by a set of simple experimental protocol. The experiments involve uniaxial compaction of the given powder grade.

ABAQUS/Standard is used to generate the material properties from the experimental data. Once the material properties are obtained, complex geometries and processes can be simulated. Output of the FEM simulations are in the form of relative density contours, elastic spring back, and residual stress contours. Punch load at different levels of densification (at different punch displacements) are also obtained.

Key words: *hard metal, powder metal, p/m, numerical modeling, yield criteria, density gradients, decompression, elastic spring back, green compact, punch and die design.*

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* Corresponding author Dr.S.Shamasundar email: shama@pro-sim.com

1. Introduction

The die compaction process is used extensively in p/m industry for manufacturing complex shaped components. Uniform density distribution in green compact and the sintered component is required to ensure good performance and meet design specifications. Hard metal components (for example tungsten carbide) are extensively used in cutting tools, where wear resistance and high temperature resistance is required. The composition and chemistry of the powder determines the flow and densification behavior. For example, Cobalt percentage in WC-Co alters the compaction behavior. Similarly, the grain size (the powder particle size is also reported to have effect on the compaction process. It is very important to understand the behavior during compaction in order to predict the process parameters and the green compact strength. Figure 1 shows the typical uniaxial compaction process of an axisymmetric component. As the geometry of the component becomes more complex, density gradients are introduced during compaction. It is very laborious and time consuming to measure (using optical microscopy or micro hardness measurements for example) the density gradients by experiments in metallic p/m components. In case of hard metals, density measurements are not even possible experimentally. Thus, FEM simulation provides a viable alternative for quantification of density distribution during compaction.

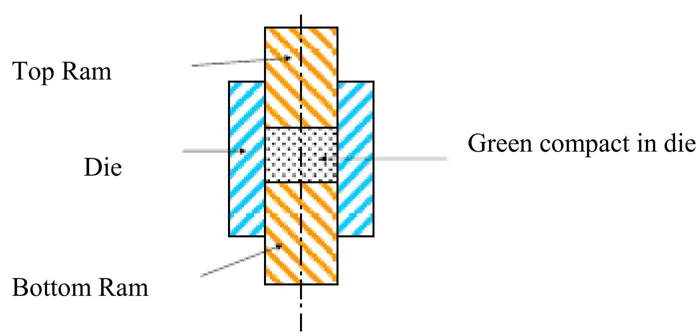

Figure 1: Pressing method

2. Constitutive models in FEM for powder compaction process

A constitutive model is a mathematical expression that describes the physical behavior of a material, and relates the stress to strain, strain rate and temperature. It simulates the mechanical response of a material when subjected to certain external conditions and boundary conditions. A constitutive law is established for a given grade of powder based on experimental observations under different stress / strain paths.

ABAQUS has got wide variety of material models in its library that are useful for analysis of p/m materials. Proper material model has to be chosen depending on the powder densification behavior. Here we are discussing Drucker -Prager Cap model and Modified Cam clay model which are available in ABAQUS, which defines the behavior of granular materials.

2.1 Drucker-Prager cap model. [1, 2, 3]

Drucker – Prager cap model consists of three surfaces, shear failure surface (Fs), cap surface (Fc) and transition surface (Ft) as shown in figure 2.

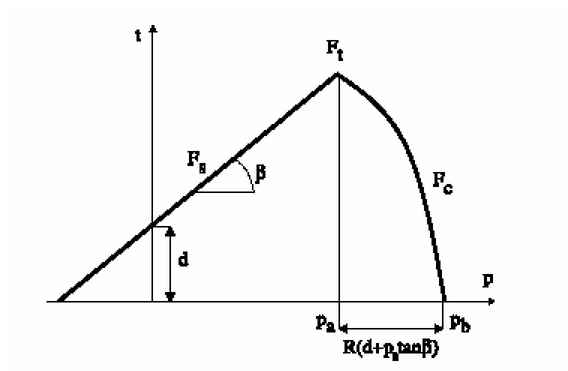

Figure 2: Parameters of the Drucker– Prager cap model.

$$F_s = t - p\tan\beta - d = 0$$ ……………………………………… Equation (1)

$$F_c = \sqrt{(p-p_a)^2 + \left[\frac{Rt}{1+\alpha-\alpha/\cos\beta}\right]^2} - R(d + p_a\tan\beta)$$ ………..Equation (2)

Where t [MPa] and p [MPa] represent the Von Mises effective stress and the hydrostatic stress, respectively; d [MPa] and β are the cohesion and friction angle respectively. R is a material parameter controlling the shape of the cap, Pa [MPa] is an evolution parameter which is related to the hydrostatic yield compression stress Pb [MPa]. In order to obtain a smooth yield surface, a transition region Ft is defined between the shear failure line and the cap surface using a small number α.

2.2 Cam-clay model [4, 5, 6, and 7]

Cam-Clay yield function model is used for the numerical modeling of compaction of the granular materials from low densities. Detailed description of the Cam-Clay model is explained below. Figure 3 shows the Cam-clay yield surface in the deviatoric (p-t) plane along with the parameters that define the yield surfaces. The Cam-clay yield surface has two bounds, namely the critical state shear surface depicted by the critical state line and the cap hardening surfaces as shown in figure 3.

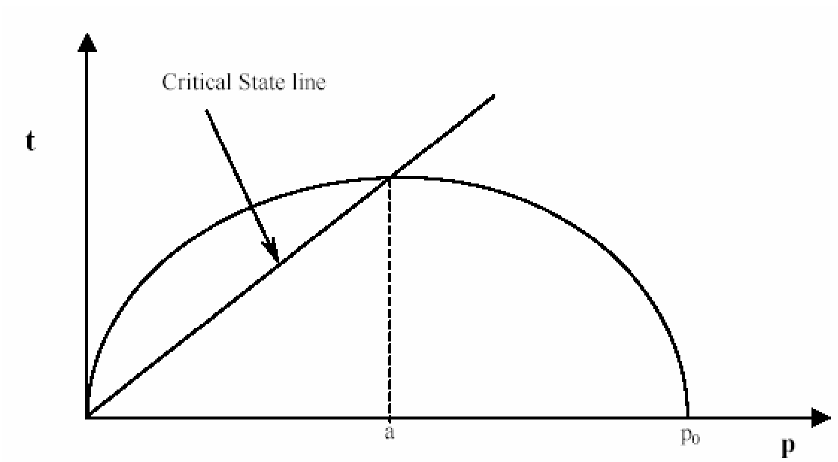

Figure 3: Cam-clay yield surface

The model is based on the yield surface as given by equation 3.

$$\frac{1}{\beta^2}\left(\frac{p}{a}-1\right)^2+\left(\frac{t}{Ma}\right)^2-1=0 \qquad \text{............ Equation (3)}$$

Where,

p is equivalent pressure
t is deviatoric stress
M is a constant that defines the slope of the critical state line
a defines the hardening of the plasticity model
β is a constant

2.2.1 Compaction modeling parameters

To model the powder compaction a non-linear FEM simulation tool ABAQUS is used in which the material parameters are incorporated.

The parameters that are needed to define these yield surfaces for Cam Clay model are given below.

1. Slope of the critical state line, M

2. Logarithmic elastic bulk modulus, k

3. Logarithmic plastic bulk modulus, λ

The relation between the applied stress/ pressure, and the model parameters are described below. Void ratio *e* is defined as,

$$e = \frac{1-\rho}{\rho} \qquad \text{.........Equation (4)}$$

Where ρ is relative density.
Under an applied pressure the total volumetric strain is divided into two parts, an elastic strain and an inelastic (plastic) strain.

$$d\varepsilon_v = d\varepsilon^e_v + d\varepsilon^p_v \qquad \text{.........Equation(5)}$$

The elastic volumetric strain is given as

$$d\varepsilon_v^e = \frac{\kappa}{1+e}\frac{dp}{p}$$

The plastic volumetric strain is given by the relationship

$$d\varepsilon_v^p = \frac{\lambda-\kappa}{1+e}\frac{dp}{p} \qquad \text{.........Equation (6)}$$

The **slope M of the critical state line** helps to define the critical shear surface. The **logarithmic elastic bulk modulus k** defines the elastic behavior of the material and plastic **logarithmic plastic bulk modulus λ** defines the plastic hardening behavior of the material or the cap surface.

2.3 Experimental Determination of Model Parameters

Following tests have to be carried out for the calibration of the model.

1. Triaxial test. (More than one experiment is required to calculate accurately)

2. Hydrostatic or isostatic test. (More than one experiment is required to calculate accurately)

The slope M of critical state line is determined experimentally from triaxial compression tests while the moduli are obtained from hydrostatic (isotropic) tests.

2.3.1 Triaxial Test to find the parameter Slope of Critical State Line (M)

Triaxial compression experiments are performed using a standard triaxial machine where a fixed confining pressure is maintained while the deviatoric stress is applied. Several tests covering the range of confining pressures of interest are usually performed. Again, the stress and strain in the direction of loading are recorded, together with the lateral strain so that the correct volume changes can be calibrated.

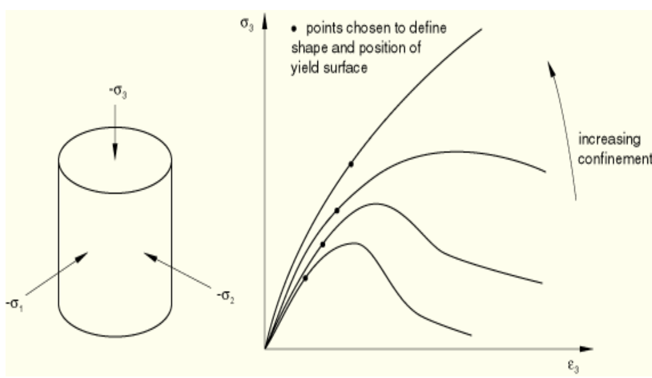

Figure 4: Triaxial tests with stress-strain curves for typical powder materials at different levels of confinement.

From triaxial experiments, we can determine the shear yield surface (Fs) by plotting the graph of deviatoric stress (σ1 - σ3) verses mean stress ((σ1+σ2+σ3)/3)

From this graph we can get the friction angle (β) as shown in figure 1.

The slope of critical state line (parameter **M**) is determined from triaxial tests and a brief description of the procedure is described here. A triaxial test device as shown in figure 4 is used for testing of cylindrical specimen. The powder is filled in a thin elastomeric jacket. A confining stress (pressure) of σ_3 (= σ_2) is applied by pressurizing the fluid in the chamber. The axial load is then applied causing the sample to shear. Continued shearing of the powder can lead to a state in which further shearing takes place without change volume. This condition is called **Critical state.** The line joining different critical states obtained by different confining pressures and applied stresses is called **critical state line.**

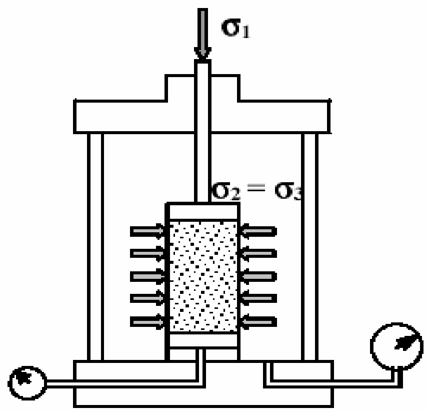

Figure 5: Schematic of cylindrical triaxial test setup

Several tests covering the range of confining pressures of interest are usually performed. Axial load and axial displacement are recorded, together with the radial displacement so that the correct volume changes can be calibrated.

The results are typically the plots of stress difference (σ_1 - σ_3) versus axial strain (ε_l) for different confining pressures as shown in Figure 6. From figure 6 we can observe that the powder will yield when it reaches certain axial stress as represented by points (A, B, C).

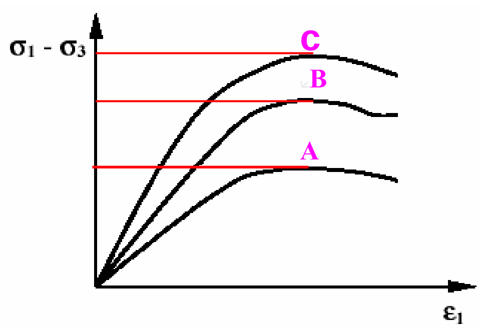

Figure 6: Deviatoric stress vs axial strain

The points A, B, C in figure 6 are plotted on p-t as shown in figure 7. These final failure points are defined as points at which the sample reaches the critical state. The slope of this critical state line, M determines material behavior.

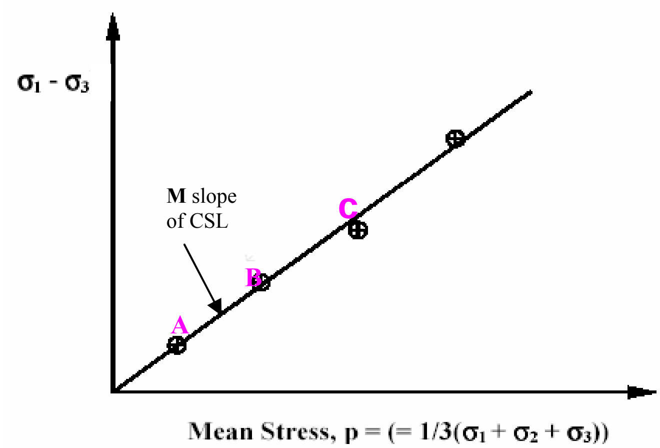

Figure 7: Critical state line in the p-t plane

2.1.2 Hydrostatic compression test

At high hydrostatic pressures, the yield surface is described by a cap surface Fc. To determine the cap yield surface, the hydrostatic compression test is performed by pressurizing the sample equally in all directions (σ1 = σ2 = σ3). The applied pressure and the volume change are recorded. From this experiment we can find the hydrostatic compression yield stress, P_b and the corresponding volumetric strain.

The evolution parameter, pa, is defined as

$$Pa = (P_b - Rd) / (1+R\tan\beta)$$

2.3.2 Determination of hardening parameters

The hardening parameters are determined from hydrostatic testing. The hydrostatic compression test is performed by pressurizing the sample equally in all directions ($\sigma_1 = \sigma_2 = \sigma_3$) as shown in figure 6. Both axial and radial displacements are recorded to determine the volumetric strain. Unloading measurements are required to determine the elastic constants. During unloading, due to the elastic properties of the green compact there will be spring back of the specimen in both radial and axial direction.

The results of hydrostatic testing are typically the plots of hydrostatic or mean stress (= $1/3(\sigma_1 + \sigma_2 + \sigma_3)$) versus volumetric strain (ε_v) .

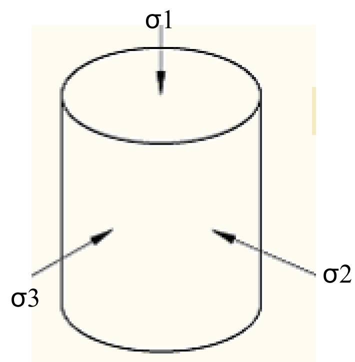

Figure 8: hydrostatic loading condition

The compression curve data gives the hydrostatic consolidation line in the **e** (void ratio**)** versus **ln (p)** plane whose slope is the logarithmic plastic bulk modulus, **λ**. The unloading curves when plotted in the **e** versus **ln (p)** plane give the hydrostatic swelling line with slope corresponding to the logarithmic elastic bulk modulus, **κ**.

2.3.2 Simulation of Compaction in ABAQUS.

In order to simulate the powder compaction behavior, one has to define initial fill density in terms of void ratio as an input in ABAQUS.

Following command lines can be used to define the void ratio in ABAQUS

*initial conditions, type=ratio

Node set, value of void ratio

Initial Void ratio can be calculated by using the relation, void ratio= (1-initial relative density)/(initial relative density)

Depending on the powder grade, a suitable material yield function has to be selected. For the standard yield functions, the material model parameters can be entered in the dialogue boxes. For advanced material models, user subroutines can be used. In this paper, authors describe the procedure directly through the ABAQUS dialogue box.

3. Case studies

3.1 case study 1: compaction of a flanged bush

The tooling setup for the compaction of flanged bush is as shown in the figure 9. Numerical modeling has been carried out according to the provided tool kinematics. Density gradients in the green compact are predicted and also the load coming on each of the punch during the process are predicted and shown in figures 10 and 11. The data for modeling was taken from DIENET modeling group presented in EPMA 2003 [16, 17]. Authors developed a damage model and implemented in a third party software, for p/m compaction. While the damage model could be implemented in the third party software, the densification simulation was difficult to be simulated. While starting from lower density levels, the simulations would often fail. Advantages of ABAQUS for p/m simulation is that, it has a variety of material models, advanced material models (for example to incorporate high temperature effects or effect of grain size) user subroutines can be effectively used.

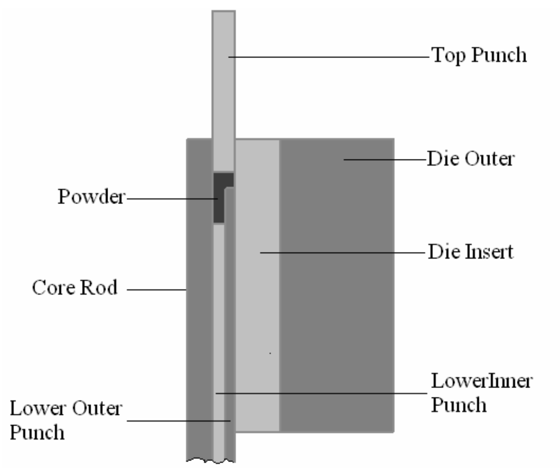

Figure 9: Tooling setup (half Symmetry, Experimental)

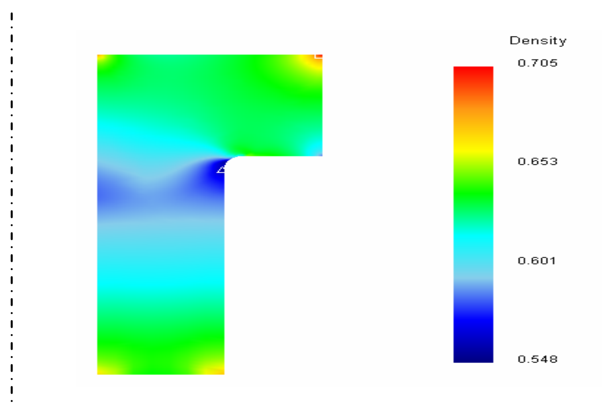

Figure 10: Density distribution in the green compact

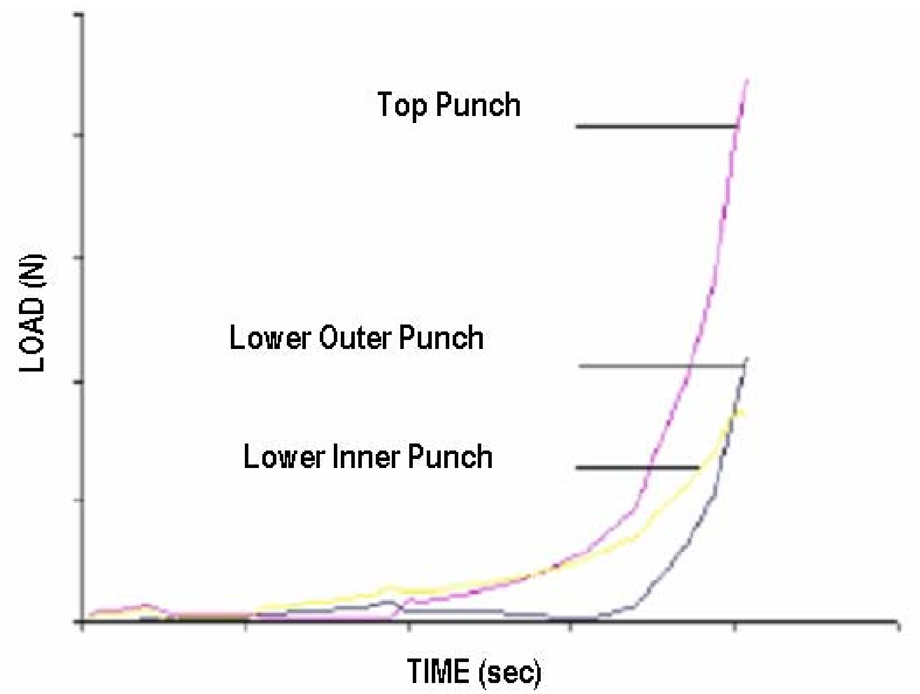

Figure11: Comparison of load coming on each punch

4. Discussion and conclusions.

The procedure developed by ProSIM can be used for the following.

- The compaction and decompression process can be simulated using appropriate material models.
- A set of simple experiments can be used to decipher the material constants for the modeling of P/M compaction process.
- The FEM model can be used for the verification of punch / die kinematics and its influence on the density distribution in the green compact.
- The procedure can be used to predict the die / tool loads and design the tooling appropriately.
- FEM simulation can also be used for the prediction of elastic springback during the ejection.
- The density distribution in green, the tool load, the springback during ejection can be used as important in the design process of the tooling and the process.

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