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EFFECT OF FRICTION FOR DENSITY DISTRIBUTION IN DIE COMPACTION OF POWDERS

Summary. The results of simulation of density distribution in die compaction were described in this paper. There were compared two different types of powder compacts formed under two lubrication conditions. Analysis of powders compaction were implemented for Drucker-Prager Cap model into finite element program ABAQUS. This model was calibrated from experimental work by using simple test, such as cylindrical die compaction of the sample of steel powder material. It was shown, that modifying the lubrication conditions between powder and die wall results in opposing relative density distribution trends in the compact. The predictions of the model in terms of relative density distribution show good agreement of used model and matching with experimental results of research work in die compaction.

Key words: simulation, forming, compact, density, friction.

INTRODUCTION

Powder compaction is an attractive process technology for conventional and waste materials as well. In a forming operation powder is consolidated into a desired shape, normally by applying pressure. The forming process can either be performed in a cold or heated state. Excellent mechanical, physical and chemical properties are important for the quality of the final component.

The mechanical properties of the compacts depends on the powder mix, tool kinematics, material response, the friction effects in the contact between the powder and the tool walls, etc. Mechanical properties of the compacts are also important after performed. This requires a no defect and high strength [1].

The designing of powder parts is develop with a numerical simulation. Numerical analysis of tool kinematics, tool force, tool stresses, tool design, density distribution, residual stresses and crack initiation etc., might reduce time consuming trial and error methods. In many cases numerical methods could improve the product properties, reduce cost and increase implementation of powder components. Finite Element Method (FEM) for simulations can establish theoretical and practical knowledge of stress, fracture and mechanical properties of powder compacts.

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CONSTITUTIVE MODELS FOR POWDER PRESSING

The pressing process is highly nonlinear due to the material response, large deformations and strains, contact boundary conditions and friction behaviour. To capture the event of pressing it is important to use appropriate models. The numerical solution of the highly nonlinear problem often demands small time steps, giving explicit methods a computational time advantage compared to implicit methods [5].

An ideal mathematical model for powder pressing should be based on elements of individual particles including different sizes, shapes and their interaction. Discrete element modelling (DEM) takes into account the individual particles and has been used to model powder compaction [3]. The motion of each particle and its interaction with neighbouring particles is taken into account using DEM. Often large spherical particles or clusters of spherical particles are used. A short-coming with DEM is that the method is time consuming for realistic simulations [6].

Another model is the combined FKM-Gurson model [4]. This model consists of macroscopic constitutive law for the plastic yielding of a random aggregate of perfectly plastic spherical metal particles. The Gurson model is based on the assumption that a porous material contains separated spherical voids. The micromechanical basis is appropriate for high porosity, but at lower porosity the Gurson model is more applicable. A combination of the two models can cover the whole porosity range during powder compaction.

The most common models used today are based on the Drucker-Prager Cap (DPC) model. The DPC model is an extended and modified version of the Mohr-Coulomb model. It is a multi-surface elastic-plasticity model permitting the representation of densification hardening as well as interparticle friction and was first developed in soil mechanics. It was then adopted and used to simulate the cold die compaction of tungsten carbide powder and other metallic and pharmaceutical powders [9]. In this model,

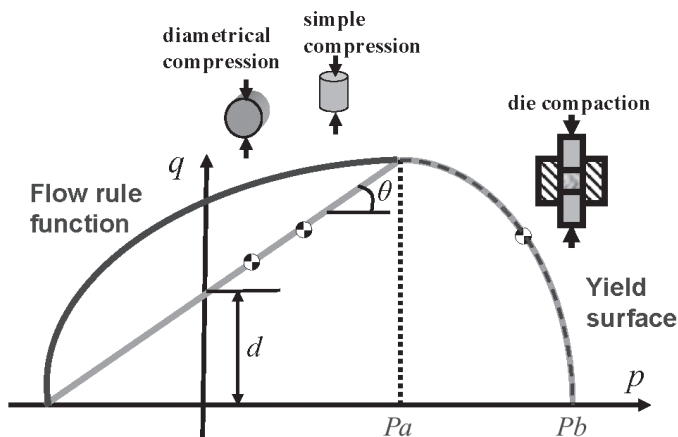


Fig. 1. Schematic representation of Drucker-Prager Cap model [9]

the yield locus is the function of relative density. Its shape will shrink or expand as the relative density decreases or increases. Therefore, a complete yield criterion can be represented as a series of yield loci space. Figure 1 shows the schematic diagram of DPC model.

The DPC model consists of two parts: one associated and one non-associated as discussed below. The yield locus is described using two parts: a cap surface F_C and a shear failure line F_S . The cap yield surface has an elliptical shape. It addresses the plastic deformation of powders under highly confined stress conditions (high hydrostatic pressure):

$$F_C = \sqrt{(p - P_a)^2 + (Rq)^2} - R(d + P_a \tan(\theta)) = 0 \quad (1)$$

where: p – hydrostatic pressure,
 q – Mises equivalent stress,
 P_a – material compression parameter,
 R – cap eccentricity parameter ($0.0 < R < 1.0$),
 d – pure shear (cohesion) yield stress,
 θ – friction angle of the materials.

The parameter P_a can be calculated based on the following equations:

$$P_a = \frac{P_b - Rd}{1 + R \tan(\theta)} \quad (2)$$

where: P_b – hydrostatic compression yield stress.

In the shear region (at low hydrostatic pressure), the yield surface can be represented by a straight line, which is also known as the Mohr-Coulomb shear failure line F_S :

$$F_S = q - p \tan(\theta) - d \quad (3)$$

There are a four of independent parameters in the DPC model. Normally, these four independent parameters are calibrated from experiments [7, 8].

Galen and Zavaliangos have shown that the mechanical strength of powder compacts produced by closed die compaction is anisotropic [4]. The cylindrical samples were prepared by means of closed die compaction for both ductile and brittle powders. Diametrical compression tests were conducted to obtain the compact strength in two orientations: perpendicular to and parallel to the direction of compaction. Information regarding strength anisotropy was collected. It was shown that in ductile powders the tensile strength in the prior-compaction direction is lower than in the transverse direction. In brittle powders, the opposite behaviour was observed. In both cases, strength anisotropy is a function of density and the trends are opposite, with the ductile materials becoming increasingly anisotropic and the brittle material becoming increasing isotropic as density increases.

Based on these understanding, anisotropy and path dependence of compacts are essentially different manifestations of the directionality of microstructure. Figure 2 schematically shows these two concepts – loading path dependence and strength anisotropy. Path dependence reflects the fact that the processing history can affect significantly the resulting microstructure and in turn the properties.

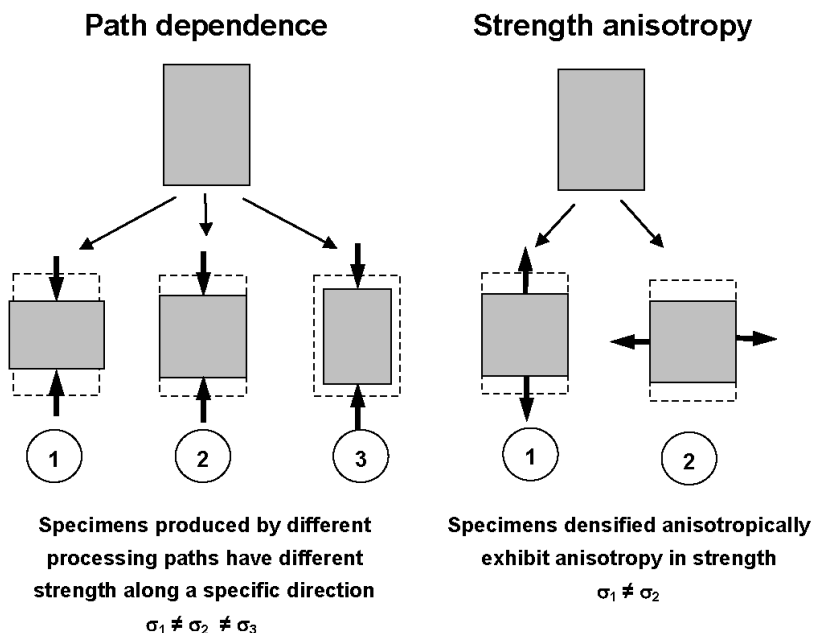


Fig. 2. Schematic illustration of loading path dependence and strength anisotropy [7]

The recently developed Multi-Particle Finite Element Method (MPFEM) relaxes the assumptions in other computational models discussed above [9]. The only assumed constitutive behaviours are the material properties of the particle and the interparticle friction interaction. In this model, the individual particles were discretized by using finite elements. This model offers great flexibility in terms of the shape, mechanical behaviour of particles and interaction at the contact, and has the ability to have large contact deformation and to simulate compaction to high relative densities.

MATCHING A MODEL PARAMETERS

The simulations were conducted by using finite element software – ABAQUS ver. 6.6. The library of ABAQUS contains several constitutive models including a version of Drucker Prager Cap model.

The finite element analysis of many compaction problems faces often difficulties due to the strongly non-linear material behaviour including friction which makes convergence difficult in implicit finite element schemes. Such problems can be better addressed within the framework of explicit schemes (such as ABAQUS/Explicit) especially when coupled with a remeshing strategy.

The initial relative density was set as 0.3 (porosity = 0.7). On the Table 1 parameters used in Drucker-Prager Cap model for the powder of 100Cr6 (AISI 52100) bearing steel were shown.

Table 1. Parameters used in Drucker-Prager Cap model

Relative Density	Young's Modulus E (Pa)	Poisson ratio ν	d (Pa)	θ (degree)	R	P_b (Pa)
0.30	4.50E+07	0.016	2.68E+04	54.4	0.270	6.09E+05
0.40	1.77E+08	0.035	7.23E+05	68.8	0.312	4.03E+06
0.50	4.82E+08	0.061	1.16E+06	68.3	0.586	1.07E+07
0.60	1.05E+09	0.094	3.12E+06	68.0	0.640	2.05E+07
0.70	2.06E+09	0.136	5.85E+06	68.1	0.690	3.58E+07
0.80	3.71E+09	0.187	1.05E+07	67.4	0.789	6.47E+07
0.90	6.32E+09	0.250	1.86E+07	66.5	0.907	1.28E+08

The die compaction analysis was performed in 3D test. The geometry of the model was set up for a 30-mm-diameter tablet. The punches and die were implemented as rigid surfaces. The bottom punch was stationary. The initial punch separation was 40 mm and the simulation was considered to terminate after the top punch moved down by a 20 mm distance that corresponded to a predetermined average relative density, as listed in Table 2.

The friction interaction between powder and die wall and punches is described using Coulomb's law of friction. The two friction conditions were considered in the simulations. High friction in a die cleaned by acetone before the experiment and a low friction in a die in which a powder was compressed to apply lubrication at all tool surfaces. In each case, the coefficient of friction varies with the contact pressure. As shown in Figure 3, as the contact pressure increases, the friction coefficient decreases.

Compaction test simulation was modelled using element mesh type of C3D8R (8-node linear brick, reduced integration 3D continuum elements). Due to symmetry, only 1/2 of the geometry was modelled. The platen that compresses the tablet on its side was implemented as a flat rigid surface. The interface between platen and tablet was assumed to be frictionless.

Table 2. Displacement boundary conditions of samples used in compaction simulation

Item No.	Top punch displacement (mm)	Final relative density	Die condition
1.	20.4	0.59	no lubrication
2.	19.7	0.56	no lubrication
3.	18.9	0.51	no lubrication
4.	18.1	0.46	no lubrication
5.	17.6	0.42	no lubrication
6.	20,6	0.61	lubricated
7.	19,7	0.56	lubricated
8.	18,9	0.51	lubricated
9.	18,2	0.47	lubricated
10.	17,6	0.42	lubricated

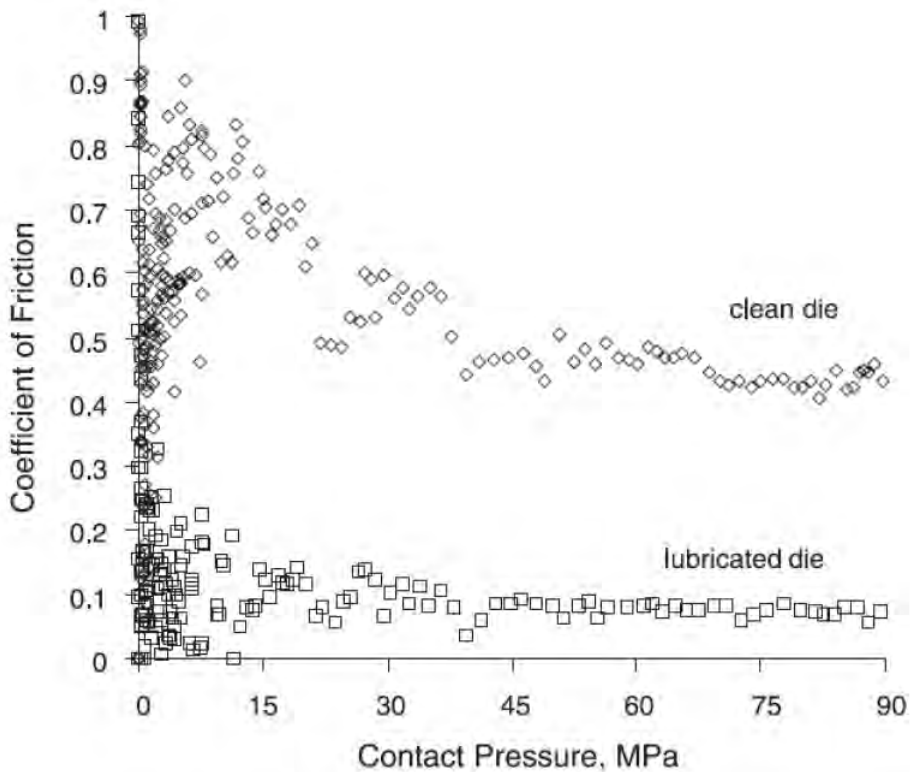


Fig. 3. Variation of the coefficient of friction with applied forces

A vertical displacement was prescribed on the top punch. The compaction behaviour of material was modelled using of the DPC model described before. During the calculation, a constant velocity boundary condition is applied at the top rigid punch with a value of $1 \text{ mm}\cdot\text{s}^{-1}$. Mass scaled density of $1000 \text{ kg}\cdot\text{m}^{-3}$ is employed in ABAQUS calculation to improve computational efficiency. Since the application of mass scaling technique will artificially magnify the effect of inertia effect. It was monitored and the value of mass scaling factor is limited so that the ratio of kinetic to internal energy is less than 1.5% for the steady state conditions.

RESULTS AND DISCUSSION

Two types of compacts (unlubricated vs. lubricated) showed significant different results during die compaction test simulation. Figure 4 shows a different levels of the average relative density.

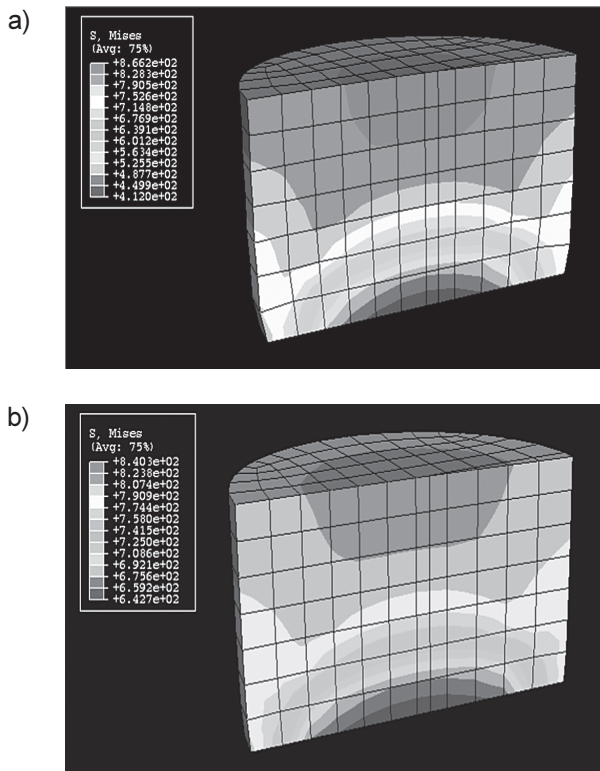


Fig. 4. Density distributions in compaction simulation: a) high friction condition (unlubricated die and punch), b) low friction condition (lubricated die and punch)

The results showed that the lubrication conditions induced strong gradients in density inside the compact. Briquettes compacted under high friction (unlubricated) have a higher density in the centre, while the others compacted under low friction (lubricated) have a lower density. In the unlubricated body density highly decrease from the centre of the material to the periphery. The lubricated samples exhibit an more uniform pattern. The material in the centre as well as in the periphery of the sample show good densification.

The relative density predictions were validated with experimental density maps obtained from surface hardness tests carried out on cross sections of the compacts [1]. The agreement between the experimental and numerical results gives confidence in the predictive capabilities of the model. Figures 5a and 5b show the comparison of simulation and experimental results of the density distribution, where it can be seen that numerical predictions and experimental data match very well.

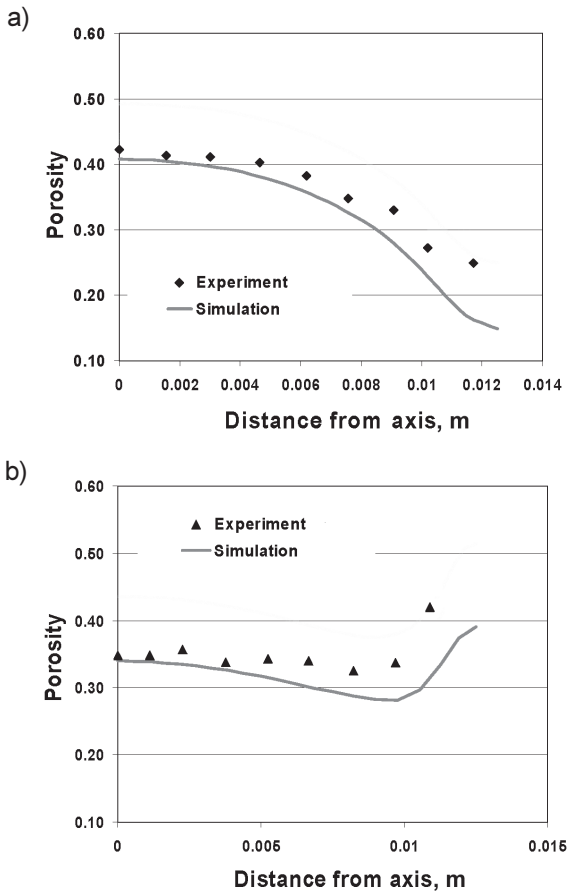


Fig. 5. Density distribution along centre line of the body: a) under high friction condition, b) under low friction condition

There were confirmed that the unlubricated body required a larger load to achieve the same overall density as lubricated, but were a not so big difference of force-displacement during compaction between the two lubrication conditions.

As a result, the material in the periphery densities more. On the other hand, under lubricated conditions, the tendency of the material flowing was observed – from the periphery to move toward to the centre. Due to the material flow, the final density at the edge of compact is lower than in the centre.

CONCLUSIONS

FEM simulation of powder compaction involves many challenges. During pressing large deformations are induced into the material and the increase in density effects mechanical properties significantly. The major concern in the development of numerical modelling of powder pressing is to understand the different phenomena that occur during shaping to different geometries and reproduce them numerically as close as possible.

The difficulty of the DPC model to predict body strength is due to its isotropic nature. In the other hand DPC model has some limitations. There were used 200 particles model, witch may not well represent the actual microstructure of waste powders. Therefore, the parameters used in the degrading material model need experimental calibration.

There were compared two compacts formed under two different lubrication conditions. The friction between material and die or punch has a major effect during compaction and reverses the radial density distribution were confirmed. The results obtained in the simulations agree well with the experimental measurements.

Further systematically analyses of powder compaction and prediction of strength and anisotropy are possible. Studies can be taken into account in the framework of FEM simulation, such as the compaction of porous particles, effect of material hardening, effect of particle fragmentation and other important factors. These studies would help to build a more comprehensive picture of the strength of cold compacted powders.

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WPŁYW TARCIA NA ROZKŁAD GĘSTOŚCI MATERIAŁÓW DROBNOZIARNISTYCH W PROCESIE FORMOWANIA

Streszczenie

W publikacji przedstawiono wyniki symulacji komputerowej rozkładu gęstości podczas scalania materiałów drobnoziarnistych w matrycy zamkniętej. Porównano dwa typy wyprasek z drobnoziarnistych frakcji formowane w różnych warunkach tarcia zewnętrznego. Do symulacji metodą elementów skończonych wykorzystano model Drucker-Prager Cap zaimplementowany w programie obliczeniowym ABAQUS. Model ten skalibrowano wykorzystując wyniki badań doświadczalnych uzyskane przy scalaniu w walcowej matrycy zamkniętej próbek materiałów poszlifierskich z obróbki stali. Stwierdzono, że modyfikacja warunków smarowania powierzchni wewnętrznej matrycy oddziałuje na rozkład gęstości materiału w wypraskach. Wyniki analizy numerycznej rozkładu gęstości wykazały dobre dopasowanie zastosowanego modelu oraz dużą zgodność z wynikami wcześniejszych badań doświadczalnych scalania materiałów drobnoziarnistych.

Słowa kluczowe: symulacja, formowanie, wypraska, gęstość, tarcie.