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MODELLING AND SIMULATION OF POWDER COMPACTION PROCESSES

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RINGKASAN: *Model dan teknik pengiraan bagi menerangkan proses pemadatan dipersembahkan. Gabungan Model Alah Mohr-Coulomb dan Elliptical Cap digunakan sebagai mewakili kelakuan sifat bahan serbuk semasa pemadatan. Kaedah unsur terhingga digunakan, bersama dengan model alah yang dicadangkan, untuk simulasi komponen sesendal. Isian kedalaman yang berbeza bagi serbuk besi boleh disimulasikan dengan model ini dan menunjukan keputusan yang menggalakan dengan data ujikaji. Kebolehgunaan teknik pengiraan juga membolehkan simulasi perkakas dengan gerakan yang berbeza-beza.*

ABSTRACT: A model and computational technique to describe the complete compaction process is presented. A combination Mohr-Coulomb and Elliptical Cap Yield Model is used to represent the material behaviour of powder under compaction. The finite element method is utilised, incorporating the suggested yield model, for simulating the bush component. Different fill depth of iron powder can be simulated with this model and shows good agreement with the experimental data. The versatility of the computational technique also allows the different motions of tooling simulation.

KEYWORDS: powder compaction, yield criteria, finite element model.

INTRODUCTION

Powder metallurgy covers a diversity of processing which includes metal stream atomisation, spray forming, compaction, injection moulding and sintering. These topics have been considered by many researchers focusing on modelling, experimental work or their combination. A brief review of the compaction models for powder metallurgy processes can be found in Ferguson and Lawley (1993) from which it may be considered that they are relatively primitive in comparison with application in other forming fields.

Densification modelling has provided an understanding of the basic mechanisms of the compaction process and the nature of green strength (Cytermann and Geva, 1987). Over the last 70 years, using this type of study, empirical models have been extracted from experimental results expressing pressure-density relationships for different powder types and mixtures. This has led to theoretical compaction equations for powder materials, which describes the relationship between the compact green density and the applied external pressure (Kim, 1988; Carol and Kim, 1984; Li *et al,* 1994).

The limitations of this category of model is that it cannot predict, with any accuracy, the local density, stress state and shape of compacts. Also, there is no general equation, which is suitable for every condition, especially where the load applied starts at a very low level and increases to a high compacting pressure. However, this type of investigation is still needed especially to understand the micro-level densification and more importantly, to compare compaction performance of various powders. The limitation of this approach has led to the need for a more comprehensive modelling to represent the compact powder, especially for the more complex parts.

In powder compaction, two basic methods have been developed in modelling the material behaviour. One is based on a micro-mechanical representation and the other is on a macro-mechanical or continuum basis. The former approach focuses on powder particles, which practically have a variety of size, hardness, shape and arrangement in the compact. The method may be used to investigate the effect of particle characteristics on the compact. It is believed that micro-mechanical studies still have an important role to play in providing intricate micro-mechanical characteristics to describe a powder. However, for application to the simulation of more real problems, this model is impractical since it is not capable of representing the global behaviour.

The macro-mechanical approach idealises the powder as a continuum. This type of method is believed to be the most reliable to simulate the powder compaction process since it has the capability to provide useful information on the macroscopic behaviour of the powder assembly such as density distribution, stress state and compact shape during and after the process (Biarez and Hicher, 1989). The knowledge fo this macroscopic behaviour is of primary importance because the current techniques of powder forming, especially die

compaction, produces heterogeneous densification which can cause failure or fracture in subsequent processes.

MATERIAL MODEL

Powder materials possess fractional and compressible characteristics and during compaction the volume reduces and the material becomes harder. Table 1 shows the physical aspects of powder and the modelling part which may be relevent. The physical aspects of the compaction process together with the basic laws used show to be a highly non-linear problem. Therefore, the behaviour of the powder during the compaction process suggests certain requirements for the constitutive relationships to model the process. Basically, two approaches have been developed which describe the effect of stress states on the response of the powder material. One has been based on a porous material model and the other on a particulate or granular material model. These are also generally well known as modified Von Mises and Coulomb (Tresca) criteria respectively because of their origination (Corapcioglu and Uz, 1978). Both material model approaches originate from the same classical plasticity theory.

Table 1. Relevent Aspects in Modelling

Powder Physical Aspect	Modelling Aspect
large height reduction	large displacement based formulation
compressible and frictional material	yield criterion
strain hardening	elastoplastic material

In porous material model, it has always been assumed that the yield stress values under compression or tension may be treated in the same way. However, for a green compact this is not correct since it cannot sustain significant levels of tensile stress. Also comparison of the yield stress values at the same density for a green compact and sintered powder have been found to be different (Brown and Weber, 1988). This model is therefore more applicable to precompacted, sintered powder or secondary compaction process. It was concluded in Gollion *et al* (1989) that the use of yield criterion for a porous material was not suitable for loose metal powder and the authors suggested the adoption of a model which represents a frictional granular material.

The second approach which has been used is based on the modelling of fractional granular materials such as soil and other particulate materials which are loose in nature. A description of the behaviour of fractional granular materials under loading was initially proposed by Drucker and Prager (1952). The application of this model to describe the behaviour of soil or rock has been well established and examples can be found in Prevost (1978), Sandler *et al* (1976) and Lade and Kim (1988). Metal powder has also been assumed to behave

as a granular material and examples which adopt this assumption can also be found in the literature (Doremus *et al,* 1994; Riero and Prado, 1994; Oldenburg and Haggblad, 1994).

In this paper, the macro-mechanical approach with particulate material model is considered in the determination of powder material behaviour under die compaction. It is believed that this will be most feasible for deformation simulation of powder or particulate media despite the discrete nature of such materials. The significance of this treatment of powders is that the constitutive model can cover full range of compaction from loose powder settlement, to the achievement of the desired densified mass.

CONSTITUTIVE LAWS

During compaction, the strain can be decomposed into elastic and plastic components, i.e.,

$$d\varepsilon = d\varepsilon^e + d\varepsilon^p \tag{1}$$

In terms of elastic increment

$$d\varepsilon^e = \mathbf{D}_e^{-1}\, d\sigma \tag{2}$$

And the component of plastic strain increment can be written as

$$d\varepsilon^p = d\gamma \frac{\partial Q}{\partial \sigma} \tag{3}$$

Therefore, the strain increment can be written as

$$d\varepsilon = \mathbf{D}_e^{-1}\, d\sigma + d\gamma \frac{\partial Q}{\partial \sigma} \tag{4}$$

Incorporating the hardening and the associated flow rule, the stress and strain relationship can be written as

$$d\sigma = \left[\mathbf{D}^e - \frac{\mathbf{D}^e \left\{ \frac{\partial Q}{\partial \sigma} \right\} \left\{ \frac{\partial F}{\partial \sigma} \right\}^{\mathrm{T}} \mathbf{D}^e}{H + \left\{ \frac{\partial F}{\partial \sigma} \right\}^{\mathrm{T}} \mathbf{D}^e \left\{ \frac{\partial Q}{\partial \sigma} \right\}} \right] d\varepsilon \tag{5}$$

where H represent a hardening modulus and equation (5) can be written as

$$d\sigma = \mathbf{D}_{ep}\, d\varepsilon \tag{6}$$

where $\mathbf{D}_{ep}$ is the elastoplastic constitutive relation between stress and strain. This term is highly non-linear where this matrix is dependent on many functions. The elasticity matrix $\mathbf{D}_e$ is a function of Young modulus which is dependent on the density level of powder (Ariffin, 1995). The yield function and hardening function will be discussed below.

A yield criterion is also defined as a yield function in mathematical terms where it represents a yield surface in *n*-dimensional stress space, which divides the elastic state from the plastic state.

The yield function can be written as (Ariffin, 1995)

$$F = 3J_{2D} + M^2 \left((J_1 + \sigma_c)^2 - \left(\sigma_c + \frac{c}{\tan \phi} \right)^2 \right) = 0 \tag{7}$$

The size of the ellipse is governed by the initial hydrostatic stress of compaction, σ_{co} and the hardening is the function of the plastic volumetric strain, ε_v^p (Naylor and Pande, 1981). Therefore the major axis of the ellipse can be expressed as

$$\sigma_c = f(\varepsilon_v^p) = \sigma_{co}\, e^{\frac{\varepsilon_v^p}{\chi}} \tag{8}$$

where χ is the plastic compressibility given by

$$\chi = \frac{\lambda - \kappa}{1 + \bar{e}_o} \tag{9}$$

where λ is the compaction index, κ is the elastic index and $\bar{e}_o$ is the initial void ratio.

FINITE ELEMENT APPROXIMATIONS

Six-noded isoparametric triangular elements have been used in the finite element discretization procedures since these elements have the ability to approximate any boundary shape (Zienkiewicz, 1989). The domain is discretized into a number of finite elements.

$$\Omega = \sum_{e=1}^{n_{el}} \Omega_e \tag{10}$$

At any point within an element, displacement and strain can be calculated as

$$u = \sum_{i=1}^{6} N_i a_i \quad ; \quad \varepsilon = \sum_{i=1}^{6} B_i a_i \tag{11}$$

where a_i is virtual displacement at the nodes, N_i is the shape function and the matrix B_i is the discrete strain operator. The linearization from the virtual work principle leads to the element stiffness formulation

$$[K]\ \{\Delta a\} = \{R\} \tag{12}$$

where [K] is the tangential stiffness matrix, {Δa} is the prescribed incremental displacement at the boundary condition or the unknown incremental nodal displacement vector and {R} is the force vector including the body force.

Equation (12) is non-linear due to the elastoplastic material constitutive laws. There is no direct solution to the problem and therefore, it requires the application of an incremental-iterative technique. The elastoplastic incremental solution used the strategy which integrates the constitutive equation and iterative scheme to solve the equilibrium equation. Two issues have to be focused on the solution procedure for the powder materials and the powder-die interface, namely, the incremental-iterative procedures and the computation of the stress increment.

In the present work, a standard incremental-iterative solution was used where the total prescribed displacement is divided into small increment, with each increment requiring an iterative procedure to reach its solution. After the incremental displacements are obtained by equation (12), the incremental strain vector can be calculated. In this work, the direct iterative method is used which is more economical and sufficient since the stress computation is incorporated with a direct integration procedure to improve the accuracy. In the direct integration, the strain increment, $\Delta\varepsilon$ is subdivided into k intervals in which equation (5) is replaced by

$$\Delta\sigma = \sum_{l=0}^{k} \frac{{}^{l\text{-}1}\mathbf{D}_{ep}\Delta\varepsilon}{k} \tag{13}$$

where l-1 implies the evolution of $\mathbf{D}_{ep}$ is explicit and is taken from the previous increment. However, the k value needs to be determined and suitable for a particular problem. In engineering applications, a typical value of k is 12.5% (Owen and Hinton, 1980) and this value was used throughout this work.

RESULTS AND DISCUSSIONS

Using an axisymmetric representation, the geometry of a plain bush component is shown in Figure 1. The mesh is an example which is typical for the 20 mm fill depth bush. The simulations were also done for 40 mm and 80 mm fill depth. The mesh shown in Figure 1 consists of 38 elements and 101 nodes to represent the powder material and 20 elements and 84 nodes to represent the powder-tooling interface.

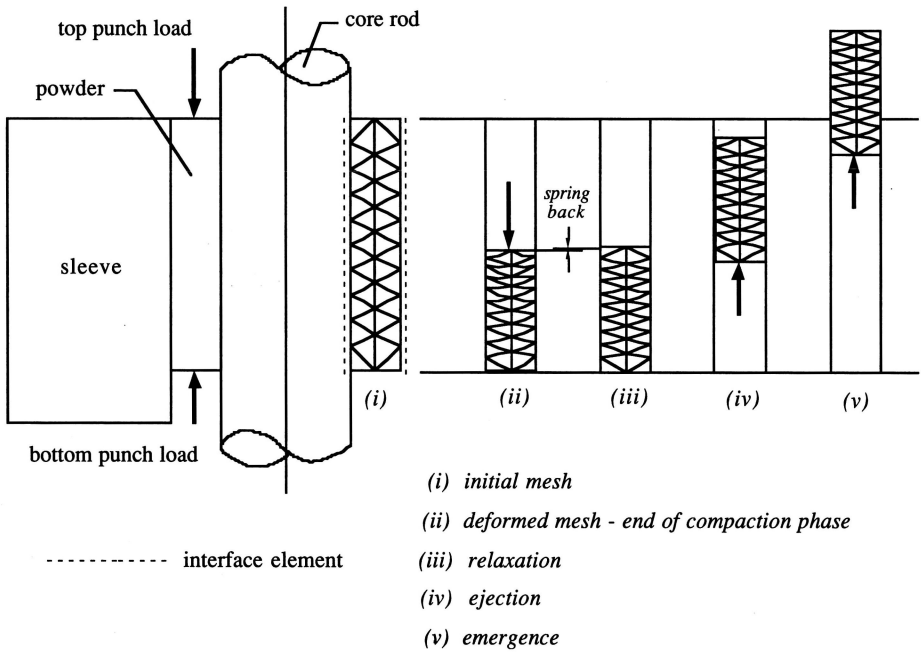


Figure 1. *Initial and deformed mesh for a complete compaction process*

The direction of the top most nodes displacement are always in a vertical plane which represents the axial punch load. Fixed nodal values were employed to represent the fixed bottom punch. These infer an assumption that there is no relative movement between the punch and the powder. At places where relative movement occurs, the interface element was used which in this case was along the sleeve and core rod surface. This is to reflect the shear movement at the powder-tooling interface during the compaction process.

Table 2. Summary of material parameters

Cohesion, c	2.5 N/mm^2
Internal friction angle, ϕ	33.0°
Initial relative density, d_o	0.4
Plastic hardening constant, χ	0.161
Initial stress, σ_{co}	0.2 N/mm^2

The simulation was performed to mimic the experiment where the complete process cycle was simulated for iron powder. Main material parameters in the model are itemised in Table 2 (Gethin *et al,* 1994). The loading or the movement of the punches was modelled by incrementally

prescribed displacements, which are summarised in Table 3. The top punch was moved 20 steps to give a 50% height reduction of the powder. This large movement needs the large deformation solution. At every incremental step, all the variables were referred to the configuration at the previous step. Therefore, the mesh, stress, strain and density were updated at each time step to reflect the updated Lagrangian solution strategy.

Table 3. Summary of displacement increments

Phase	Displacement increment (mm) at compact length of 20 mm	40 mm	80 mm	steps	Punch movement
compaction	0.5	1.0	2.0	20	top
relaxation	0.05	0.05	0.05	7	top
ejection	1.0	2.0	4.0	10	bottom
emergence	1.0	2.0	4.0	10	bottom

Figure 2 presents the contours density, stress and displacement at the end of the four stages for a complete cycle for iron powder. Clearly, the figures shows redistribution especially for the density and stress contours. In addition, the relaxation phase legend indicates the spring-back mechanism.

In the ejection phase, the compact was pushed out from the die by means of the bottom punch where a small amount of redensification may occur at the bottom region of the compact. Figure 2 shows an increase in density as a result of secondary densification during this phase. Table 4 presents the extreme values and the range in density in the process for the three compact lengths. This table show clearly that for a particular compact length, at the end of ejection and emergence, the density increases at the bottom due to secondary densification and decreases at the top due to spring-back. The results also show the density range is largest for the longer component.

Table 4. Density range between bottom to top punch

Phase	20mm	40 mm	80 mm
end of compaction	0.76-1.00 (range 0.24)	0.65-1.00 (range 0.35)	0.48-1.00 (range 0.52)
fully merged	0.80-0.90 (range 0.10)	0.75-0.86 (range 0.11)	0.70-0.86 (range 0.16)

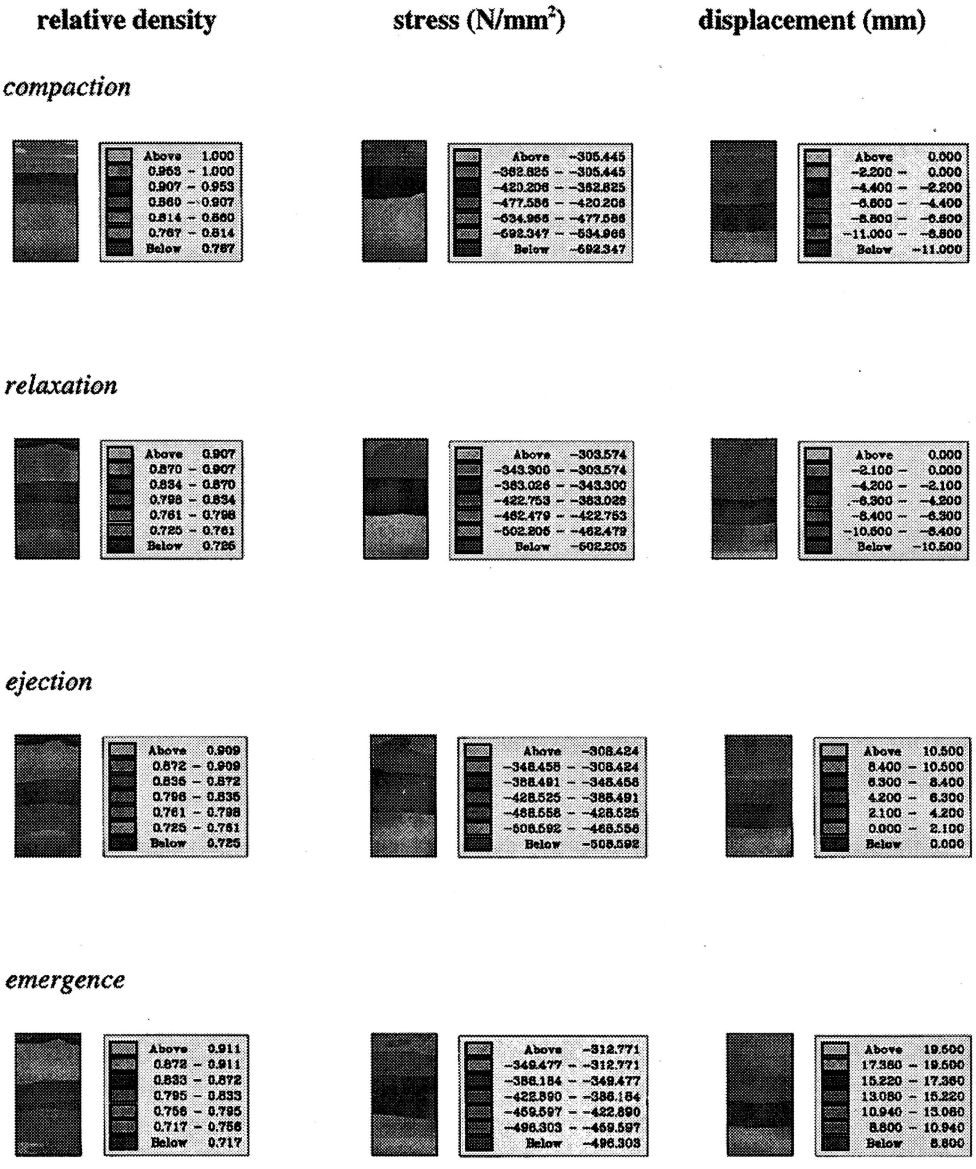


Figure 2. *Powder density, principal stress and displacement during compaction process*

Figure 3 shows the evolution of the compact density during compaction of 80 mm fill depth of the iron powder. In general, the density decreases towards the bottom. The highest gradient occurs at the end of the compaction phase. The axial movement during relaxation causes a decrease in density, particularly at the top of the compact. They indicate a bigger density range as depicted in Table 4 and a clear evident change in density gradient at the bottom end of the largest compact. At the end of the cycle, the predicted density are in a very close agreement with the experimental data measured in Gethin *et al,* 1994.

Figure 4 shows three different motions for the punches and tooling which are alternatives to the single-ended punch compaction and represent combinations of double punch movement.

The first motion to be considered is where the top punch completes its downward motion and stops as in Figure 4 (a.I). This is followed by the bottom punch moving upward to finish the compaction in Figure 4 (a.II). The final product still exhibits a density gradient, however the maximum density is now at the bottom punch surface and decreases to the top.

In this case, the density variation was found to be slightly smaller when compared with the single-ended compaction.

The second motion features simultaneous top and bottom punch movement as indicated in Figure 4 (b). The result shows that the density and flow pattern are symmetric and centred about the mid-height of the compact. This gives the lowest density variation over the compact height.

In the third motion, the die and core rod moves simultaneously in the same direction as the top punch and in this case the bottom punch remains fixed. Figure 4(c) shows the results when the tooling speed is half of the top punch speed. This type of motion is identical to that shown in Figure 4(b) and gives identical results, thereby confirming the ability of the model to represent different motion combinations.

From the above punch and tooling motion, a different powder density result can be obtained. In the production of this simple plain bush, even when double punch action is used, a density variation still exists. However the density gradient is minimised.

CONCLUSIONS

A model and simulation of a complete bush compact from a die have been presented. The conclusions which may be drawn from this work are that the Combination Mohr-Coulomb and Elliptical Cap Yield Model may be suitable to represent the mechanical behaviour such as density, stresses, flow, springback and redensification of powder under compaction. The computational work also allows the other combiantion of punches movement, which may give clear understanding of different motion of punch and tooling.

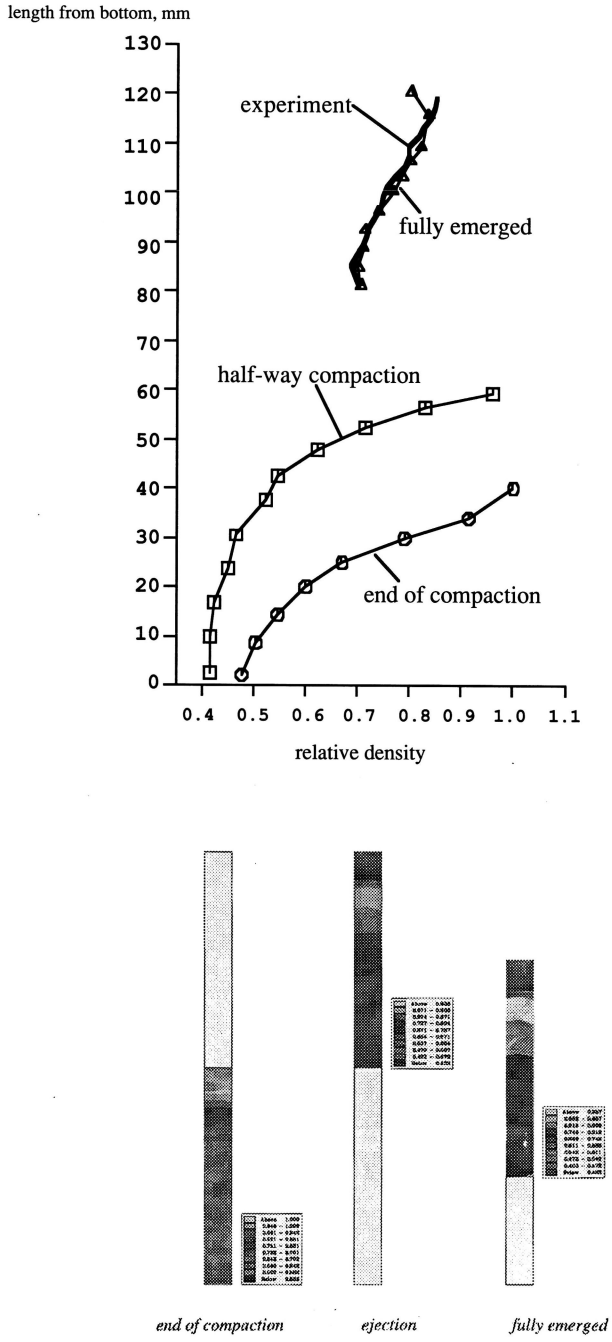
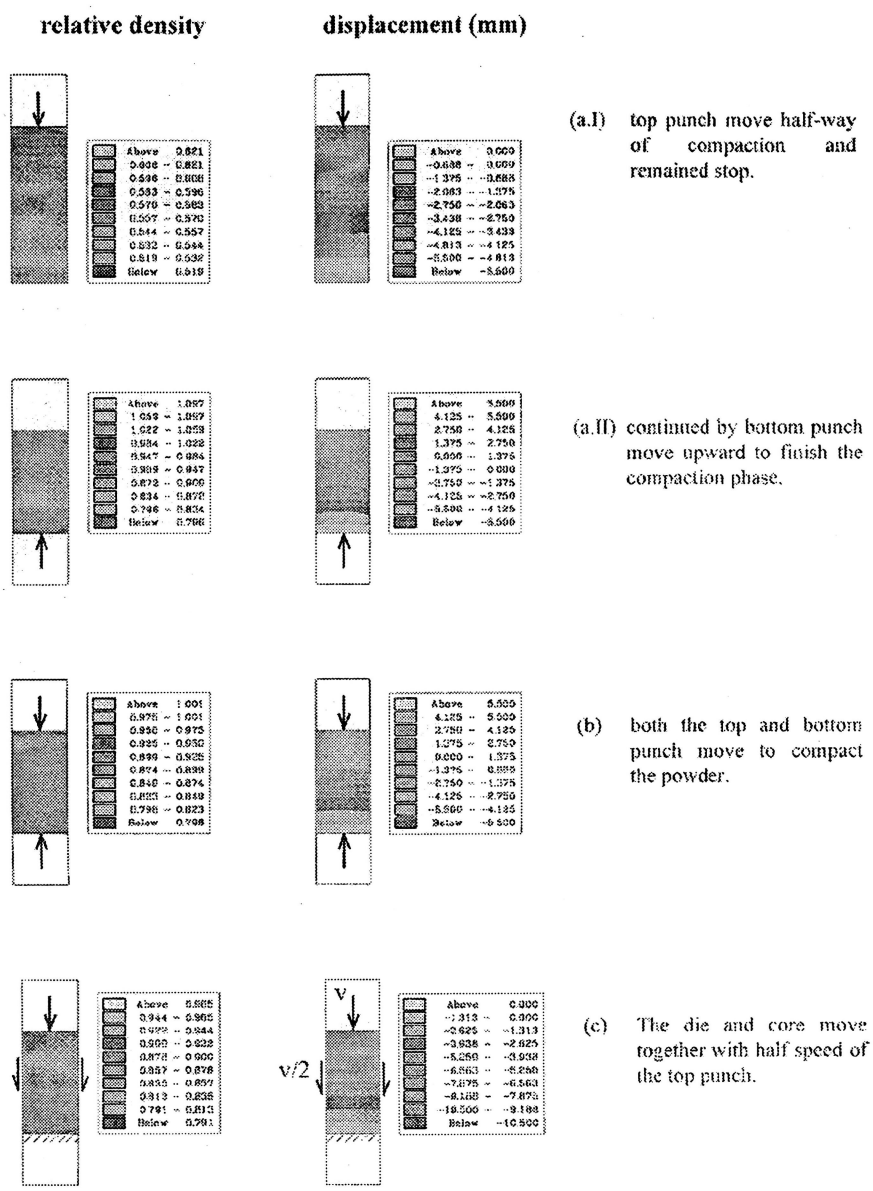


Figure 3. *Density distribution during compaction, ejection and fully emerged*



(a.I) top punch move half-way of compaction and remained stop.

(a.II) continued by bottom punch move upward to finish the compaction phase.

(b) both the top and bottom punch move to compact the powder.

(c) The die and core move together with half speed of the top punch.

Figure 4. *Examples of other punch motion for a plain bush*

NOTATIONS

$\mathbf{D}_e$,$\mathbf{D}_{ep}$	Elasticity and elastoplastic matrix
$\bar{e}$	Average void ratio
F	Yield function
H	Hardening modulus
J_1	First invariant of deviatoric stress
J_{2D}	Second invariant of deviatoric stress
M	Critical state line
Q	Potential function
χ	Plastic hardening constant
ε	Strain tensor
ε_v	Volumetric strain
σ	Stress tensor
σ_c	Critical mean pressure
σ_{co}	Initial critical mean pressure

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