

Finite Element Analysis of Friction-Assisted Powder Compaction Process

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ABSTRACT

The major disadvantage of powder metallurgy (PM) is the density gradient throughout the green powder compacts. During the compaction process, due to the existence of friction at powder-tool interfaces, the contact surfaces experience a non-uniform stress distribution having to do with variable friction coefficient and tool kinematics, consequently resulting in density gradient throughout the powder compacts. This represents a serious problem in terms of the reliability and performance of a final product, as the density gradient may contribute to a crack-defect generation during the compaction cycle, and more importantly a non-uniform compact shrinkage during the sintering process. Simulation analyses were conducted using the finite element software, MSC.Marc Mentat, and Shima and Oyane powder constitutive model, to study and suppress the causes of density gradient in the cylindrically shaped green powder compacts. A newly proposed friction-assisted compaction technique was employed, consisting of a moving upper-punch and a die, which uses friction force at the powder-die interface to assist in the compaction of powder. Numerical results are presented and compared with the literature and experimental tests. The simulation analyses had shown that the overall heterogeneity of the corresponding green powder compacts may be considerably reduced by using the proposed friction-assisted compaction technique.

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INTRODUCTION

The major disadvantage of powder metallurgy (PM) is the density gradient throughout the green powder compacts, primarily due to the existence of friction at powder-tool interfaces. This causes the contact surfaces to experience a non-uniform stress distribution, mainly having to do with a variable friction coefficient and tool kinematics of a press system [1,2,3,4], consequently resulting in density variation throughout the green powder compacts [5, 6, 7, 8, 9, 10, 11]. Density variation in a green powder compact poses a serious problem in terms of reliability and performance of a final product, as it may contribute to a crack-defect generation during the compaction cycle [9, 12], and more importantly a non-uniform powder compact shrinkage during the sintering process [13]. The resultant geometrical distortion caused by a non-uniform shrinkage may require secondary operations,

such as machining, thus, compromising the competitiveness of PM technology. For this reason friction in PM is seen as an undesirable factor, which degrades the effectiveness of a press system to produce homogenous green compacts.

Until now, the research on reducing frictional effects has led to the development and implementation of enhanced powder and tool lubricants. However, excessive addition of lubricants undermines the mechanical properties of a final product, due to increased porosity upon sintering [14]. Moreover, a double-action compaction has generally been put into practice, and different isostatic pressing methods have been introduced to further reduce the effects of friction. However, the problem of heterogeneity cannot be eliminated just by reducing the accumulative density gradient with a double-action compaction or by isostatic pressing alone, as for most practical cases a desired shape cannot be achieved

with a uniform pressure due to the imposed geometrical constraints [9, 12, 15, 16]. Ultimately, the key to further reduction of heterogeneity in green powder compacts lies in an efficient design of a press system. In their studies, Canta and Frunza [5], Know et al. [16], and Doremus et al. [12], have demonstrated that the most influential practices that improve the efficiency of a press system consist of optimization of the compaction cycle, i.e., pressing-tools kinematics, such that the resultant green compacts have the least density variation throughout their corresponding bodies.

As explained above, friction is seen as an undesirable factor in PM. Nevertheless, a newly proposed powder compaction technique, as presented by Canta and Frunza [5] and Sas-Boca [14], has demonstrated that friction can actually assist as opposed to undermine the compaction process. The proposed friction-assisted compaction technique is applicable to uniaxial compaction, which utilizes friction as an active pressing force at the powder-die interface. Unlike the traditional cold-die compaction process, which consists of a stationary die, the proposed method uses a moving die, parallel to both punches; see Fig. 1. By displacing the die in the same direction and at specific speed with respect to the moving upper-punch, the opposing friction force at the powder-die interface tends to change its sense and reverses into an assistive force, ultimately aiding as opposed to resisting in the compaction of powder. Using this technique in their experimental studies, Canta and Frunza [5] have shown that by varying the die-to-upper-punch velocity ratio, v_{die}/v_{u-p} , density gradient over the compact height can be considerably reduced. In addition, Sas-Boca [14] has demonstrated that a higher overall average density level can be achieved. Thus, even though the friction force cannot be eliminated in PM, changing its sense may prove to be beneficial in to compaction process.

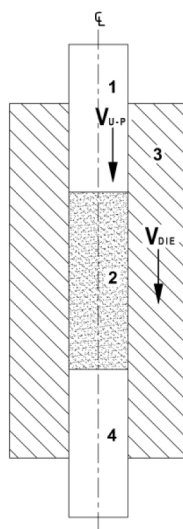


Figure 1. Friction-assisted press system consisting of: (1) upper-punch, (2) powder, (3) movable die, and (4) lower-punch.

Using the finite element analysis, the focus of this study was to investigate the proposed friction-assisted powder compaction technique, and accordingly, to establish optimal tool kinematics during the compaction cycle to minimize the overall density gradient in cylindrically shaped green powder compacts, by studying the effect of die-to-upper-punch velocity ratio on powder density. To do this, a nonlinear finite element (FE) software, MSC.Marc Mentat, was used. The Shima and Oyane powder yield criterion was utilized for this study. A set of experimentally derived material properties was employed to assimilate a realistic material behavior. To better reproduce process associated conditions, both a constant friction coefficient value and experimentally derived variable relation were employed, and their results were compared. The corresponding material properties and the variable friction coefficient relation were derived using identical iron-based powder composition. All results were compared to experimental data reported by Canta and Frunza [5].

THEORY

POWDER CONSTITUTIVE MODEL

The Shima and Oyane model, first introduced by Shima and Oyane [17], was adopted for the present study. Initially developed as a yield criterion for porous metals (i.e., sintered powder compacts), it has been successfully adopted in numerous numerical compaction analyses studies of different powder materials, yielding consistent results for various compact geometries in comparison to the experimental data [7, 10, 11, 13, 16, 18, 19]. The Shima and Oyane yield criterion, Φ , is based on the von-Mises criterion with implemented influence of hydrostatic stress on yielding. Unlike other powder constitutive models, its main advantage is that the yield surface is expressed using a single function [17]

$$\Phi = \frac{1}{\gamma} \left[q^2 + \left(\frac{p}{\beta} \right)^2 \right]^{1/2} - \bar{\sigma} \quad (1)$$

where $\bar{\sigma}$ is yield stress, $q (= \sqrt{3\sigma_{ij}\sigma_{ij}/2})$ is deviatoric stress tensor, $p (= \sigma_{kk}/3)$ is hydrostatic (mean) stress tensor, and β and γ are material parameters and are both function of relative density, $\bar{\rho}$, expressed as

$$\bar{\rho} = \rho / \rho_0 \quad (2)$$

where ρ is powder density, and ρ_0 is theoretical density of powder constitutive material.

As expressed in the works of Shima and Oyane [17] and Oyane et al. [20], the yielding of powder is caused by both deviatoric and hydrostatic stress tensors. Consequently, material parameter β represents the degree of influence of hydrostatic stress component on the yielding onset, whereas γ

represents the ratio of the apparent stress applied to the powder body and the effective stress applied to the powder particles. For iron-based powder, the expressions of β and γ were experimentally derived as [17]

$$\beta = \frac{1}{2.49(1-\bar{\rho})^{0.514}} \quad (3)$$

$$\gamma = \bar{\rho}^{2.5} \quad (4)$$

CONSTITUTIVE EQUATIONS

The strain rate tensor for elastic-plastic deformation of powder material is expressed as

$$\dot{\epsilon}_{ij} = \dot{\epsilon}_{ij}^e + \dot{\epsilon}_{ij}^p \quad (5)$$

where $\dot{\epsilon}_{ij}^e$ and $\dot{\epsilon}_{ij}^p$ are elastic and plastic strain rate tensors, respectively, with

$$\dot{\epsilon}_{ij}^p = \dot{\lambda} \frac{\partial \Phi}{\partial \sigma_{ij}} \quad \text{or} \quad \dot{\epsilon}_{ij}^p = \frac{1}{\eta} \left(\frac{\Phi}{\bar{\sigma}} \right) \quad (6)$$

where $\dot{\lambda}$ is a positive proportionality constant, Φ is Shima and Oyane's yield function, and η is shear viscosity for powder constitutive (or matrix of sintered porous) material [7, 11].

Assuming that the constitutive material is incompressible, the rate of relative density, $\dot{\bar{\rho}}$ is expressed as

$$\dot{\bar{\rho}} = -\bar{\rho} \dot{\epsilon}_{kk}^p \quad (7)$$

and the stress tensor can be written in the form of Hooke's law as

$$\sigma_{ij} = D_{ijkl}^e \epsilon_{kl}^e \quad (8)$$

where D_{ijkl}^e is a fourth-order elastic modulus tensor [7, 11]. Further, it is assumed that plastic work done on powder (or porous) body is equivalent to that of the powder constitutive (or matrix of sintered porous) material, such that

$$\bar{\rho} \bar{\sigma} \dot{\bar{\epsilon}} = \sigma_{ij} \dot{\epsilon}_{ij}^p \quad (9)$$

where again $\bar{\sigma}$ is the yield stress and $\dot{\bar{\epsilon}}$ is the effective plastic strain rate of powder body [7, 11]. In the rate form, the effective plastic strain, $\bar{\epsilon}$, is defined as [21, 22]

$$\dot{\bar{\epsilon}} = \sqrt{\frac{2}{3} \dot{\epsilon}_{ij}^p \dot{\epsilon}_{ij}^p} \quad (10)$$

where $\dot{\epsilon}_{ij}^p$ is the plastic strain rate tensor expressed by Eq. (6).

EXPERIMENTAL DATA

POWDER

The powder used for the present study is an atomised iron-based powder, composed of 4% nickel, 1.5% copper, 0.5% molybdenum, 0.5% graphite, and 1% Hoechst wax (as internal lubricant), with the balance made up of iron [23]. The apparent and theoretical densities for this powder are 3.04 and 7.33 g/cm³, respectively.

MATERIAL PROPERTIES

The material properties for the corresponding powder were adopted from experimental studies reported by Pavier and Doremus [24] and Riera et al. [25], derived using the triaxial cell apparatus, based on which the elastic modulus was derived as a function of density, ρ , as

$$E = (E_0 + E_1 \rho) \exp \left(\left(\frac{\rho}{\rho_0} \right)^a \right) \quad (11)$$

with $E_0 = -28000$ MPa, $E_1 = 10020$ MPa, $a = 6$, and $\rho_0 = 6.8$ g/cm³; bulk modulus, as

$$K = (K_0 + K_1 \rho) \exp \left(\left(\frac{\rho}{\rho_0} \right)^b \right) \quad (12)$$

with $K_0 = -10500$ MPa, $K_1 = 3750$ MPa, $b = 6$, and $\rho_0 = 6.55$ g/cm³; and Poisson's ratio, as

$$\nu = 0.5 - \frac{E}{6K} \quad (13)$$

where E and K are elastic and bulk moduli, given by Eqs. (11) and (12), respectively.

The compressive yield stress limit, $\bar{\sigma}$, of 370 MPa was employed based on the data provided by Pavier and Doremus [24, 26, 27]. Further, for shear viscosity, η , a value of $2 \cdot 10^6$ Pa·s was used, which was experimentally derived by Polyakov and Alekseev [28] for iron-based powder material, using the Voigt rheological model.

FRICTION IN POWDER METALLURGY

In powder compaction, friction coefficient at the powder-tool interface is a function of various physical and material parameters, and is nonlinear in nature [2, 3, 4, 29]. Generally, for simulation analysis, a mean value of friction coefficient is employed, where for an iron-based powder typically a value of 0.1 is assigned [6, 30, 31]. Nonetheless, a constant friction coefficient does not provide a true representation of operational conditions. Traditionally, this approach is adopted because of inconsistent or incomplete experimental data, or due to imposed FEA software limitations. To account for this,

a modified version of experimentally derived variable friction coefficient relation, reported by Doremus et al. [32, 33, 34], expressed as

$$\mu(\sigma_n, v_r) = (0.224) \times \exp\left(\frac{-\sigma_n}{1169}\right) \times \dots \times \left(1.437 \times \tanh\left(\frac{v_r}{12.6} + 0.886\right)\right) \quad (14)$$

was used in the analyses, where σ_n (MPa) and v_r (mm/s) are normal stress and relative sliding velocity between powder and tool surface, respectively.

Just like material properties, the friction coefficient is dependent on powder constitutive material, and thus, when derived for a specific powder composition it cannot be directly adopted for the analysis of powder composed of different constitutive material, or for the case of identical powder, but with different amount or type of lubricant. For this reason, all experiments must be conducted using identical powder and lubricant composition. The experimental data presented above, were specifically chosen due to their consistency and completeness, where both the material properties and the variable friction coefficient relation, Eq. (14), were derived by the same researchers using identical iron-based powder composition, thus, providing a consistent database for simulation analysis.

FINITE ELEMENT APPROACH

For the present study, a nonlinear FE software, MSC.Marc Mentat, was utilized, with an implicit integration method and full Newton-Raphson iterative scheme. Due to the circumferential symmetry, all cylindrical powder fills were modeled as 2-D axisymmetric models; see Fig. 2. In total, three separate case studies were conducted, consisting of three FE models with different dimensional sets. The corresponding FE models, representing the uncompressed powder-fill state, were compacted to a final height, h_f , of one-half of their initial height, h_i . Consequently, depending on the initial height, the compacted cylindrical parts had accordingly resulted in the final compact height-to-diameter ratio, h/d , of 1.50, 1.00, and 0.50; see Table 1. The use of different compact height-to-diameter ratio was employed to study the influence of compact height on final density distribution. The details of all corresponding models are presented in Table 2.

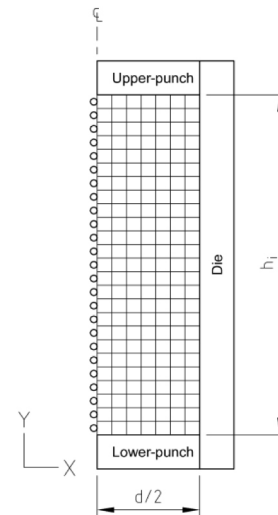


Figure 2. Axisymmetric FE model representing the uncompressed powder-fill state.

Table 1. Data for all FE models used.

Case study	(1)	(2)	(3)
Compact Height-to-Diameter Ratio, h/d	1.50	1.00	0.50
Initial height, h_i [mm]	36	24	12
Compacted height, h_f [mm]	18	12	6
Diameter, d [mm]	12	12	12
Total number of elements	864	576	288
Total number of nodes	949	637	325

Table 2. Summary of tool kinematics for all case studies.

Tool:	Upper-punch (1)			Die (3)		
Case Study	(1)	(2)	(3)	(1)	(2)	(3)
Compact h/d	1.50	1.00	0.50	1.50	1.00	0.50
Velocity [mm/s]	5	5	5	0 to 2.5	0 to 2.5	0 to 2.5
Displacement [mm]	18	12	6	0 to 18	0 to 12	0 to 6
Total Load Time [s]	3.6	2.4	1.2	3.6	2.4	1.2

All simulations were carried out using compaction speeds representative of the industrial practices, which typically range from 1 to 5 mm/s [31]. The displacement-driven method was employed for all case studies, by prescribing velocity to the specified pressing-tools. Accordingly, the die-to-upper-punch velocity ratio, v_{die}/v_{u-p} , was varied from 0 to 0.5, in increments of 0.1, to study the effect of die motion on density gradient over green compact's height. Specifically, the velocity of an upper-punch was kept constant at 5 mm/s at all times, while the velocity of the die corresponded to the specified v_{die}/v_{u-p} , varying from 0 to 2.5 mm/s; see Table 2. The lower-punch was kept stationary at all times.

A quadrilateral isoparametric element was employed, consisting of four nodes per element. The reason for not utilizing a higher-order element type was due to the ability of the selected element to better represent large distortion in a