Contact impingement in packings of elastic–plastic spheres, application to powder compaction

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ABSTRACT

High-density compaction of ductile powder particles is characterized by a sharp increase of the inter-particle normal contact force. This is due to both complex contact interactions and plastic incompressibility of the particle constitutive material. A DEM model (OPEN-DEM YADE) using an interaction force-law reproducing this increase has been developed to simulate high-density compaction of ductile powders. Its formulation is derived from a Finite Element Method model (ABAQUS). Macroscopic stresses resulting from compaction tests carried out on a random assembly of spherical grains were computed with both models and then compared. A good agreement between the stress–density curves confirmed the accuracy of the DEM formulation. However, the role of the grain deformation may not be well described using DEM since it is based on an assumption of overlapping rigid particles but allows low calculation costs. To highlight the role of this deformation process, a detailed FEM-based analysis of the influence of contact impingement on the normal contact force is thus presented. It explores the mechanisms of stress transmission between contact zones and quantifies the appearance of contact interactions in terms of both indentation depth and relative density. Results show that contact impingement cannot be neglected at a relative density as low as 0.7 if a local, contact-scale analysis is aimed for (such as density distribution for instance). In such a case, previous models like the one proposed by Storåkers and co-authors, should be used with care. The local solid fraction provides a correct local description of both contact interactions and plastic incompressibility of the constitutive material of the grains up to the maximum density. This would allow the DEM to be successfully applied to large-scale simulations of high-density compaction.

1. Introduction

Powder metallurgy has long been an attractive technology for both advanced and conventional materials. The material properties can be obtained by mixing different powder materials and producing near net shape parts which is the major advantage of this method. In many applications, powder parts are compacted up to a relative density as high as possible (more than 0.95), for strength and homogeneity. A numerical tool which would properly predict the mechanical constitutive behavior of the powder during all the forming process is a key issue for manufacturers. With this in mind, plasticity and elasticity phenomena, internal friction of the porous medium and frictional effects between the die walls must be considered. Continuum models based on

Drucker Prager Cap model [12,11] are currently used by industrials, but they are limited for several basic applications, such as the calculation of stresses during compaction [14]. Such models are based on complex and expensive experimental devices, which only give information on few loading paths. As a result, they fail to describe the material's behavior for other loadings or complex loading histories. To overcome this problem, and to further understand the complex relations between the grains behavior and the aggregates behavior, the problem of the mechanical behavior of powders has been addressed from a micromechanical perspective. Arzt [3], for instance, studied the influence of the coordination number on the compaction and sintering of powders. A micromechanical model is then proposed by Fischmeister and Artz [15] by assuming that the movement of the particles can be described as an isotropic homogeneous densification. Fleck et al. [17], then Fleck [16] and Storåkers et al. [44] proposed a model for the first part of compaction (stage I compaction), by applying a homogeneous strain field to the particles. This model has been compared with experiments by Akisanya et al. [2],

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Sridhar and Fleck [42] and Cocks [8]. Cocks and Sinka [9] and Sinka and Cocks [40] carried out investigations on similar bases, while presenting a framework for the modeling and the experimental calibration of powder compaction.

Over the last decade, the Discrete Element Method (DEM) [10] has been applied to the compaction of powders. Heyliger and McMeeking [24] and Martin [32] compared results from the DEM to a homogeneous strain field model. Several studies have been carried out, such as those of Martin and Bouvard [33], Martin et al. [34], Skrinjar and Larsson [41], Pizette et al. [36]. The core of the DEM is the contact law, which describes the relationship between the contact force and the relative displacement of two particles in contact. For cold compaction of metal powders, it is commonly assumed that the main phenomenon to be studied at the contact scale is plasticity. Therefore, the right contact laws to be used have to describe correctly the plastic indentation of two solid particles. Vu-Quoc and Zhang [46] and Vu-Quoc et al. [47] proposed a contact model accounting for plasticity, but their model is valid in the context of granular flows, where the deformations involved remain very small. However, the problem of plastic indentation of two particles is to be put together with the Brinell or Vickers indentation problem [28,25]. In this context, Storåkers et al. [43] have developed a plastic contact law for power-law strain-hardening solids, which has been intensively applied in DEM simulations and homogeneous strain field modeling of powder compaction by most of the previously cited authors. But the modeling of powder compaction by the discrete element method up to a relative density higher than 0.8–0.85 is not yet valid, because the implementation of such contact laws in micromechanical models has the major inconvenient of considering the mechanical and geometrical independence of contacts during the densification. Preliminary studies by Harthong et al. [23] introduced a high-density contact law for the DEM based on finite element simulations.

In parallel, another discrete numerical approach based on the finite-element method has emerged. Here, this method will be referred to as the Multi-Particle Finite Element Method (MPFEM) [21,20,48,38]. It has the significant advantage of describing very accurately the deformation and the movement of the particles, and to be usable with classical and well-known constitutive laws to describe the particle material. The main limitation of the method is the calculation time needed when considering assemblies of numerous meshed particles. First developed for two-dimensional particles, it has been applied recently to 3D particles by Chen [6,7] and Frenning [18,19]. Using this method, Schmidt et al. [39] and Harthong et al. [22] derived yield surfaces from an assembly of 3D elastic–plastic meshed particles.

Both DEM and MPFEM may be powerful tools to understand the microstructural phenomena which lead to the well-known or less-known macroscopic aspects of powder compaction. Both methods consist in representing the powder by discrete particles (assumed spherical in most cases) and modeling the interaction between the particles. However, the computational cost of the MPFEM remains too high to perform simulations on a realistic number of particles, even though it gives more information and it appears more accurate and reliable. This is the reason why the DEM appears as the best practical compromise between accuracy and calculation efficiency.

The new contact law for the DEM presented in Harthong et al. [23] was validated on the basis of DEM and MPFEM frictionless simulations on a 32-sphere assembly. The aim of the present paper is to present an analysis of the mechanisms of complex interactions at contact zones between grains in the context of high-density compaction. This analysis is focused on a DEM application, and thus underlines and explains the limits of a previous model [43] in an application such as powder metallurgy,

which have never been discussed before. This is the reason why, after a short description of the main features of DEM and MPFEM in Section 2, the first part of this paper details, in Section 3, the DEM implementation of a contact model based on Harthong et al. [23]. These DEM simulations are used as a basis to understand the relations between contact models and overall or macroscopic behavior. Section 4 finally discusses the results of the contact models using MPFEM results as a reference.

2. MPFEM and DEM approaches

2.1. Multi-particle finite element method

The multi-particle finite element method (MPFEM) consists in performing classical finite element simulations on an assembly of discrete particles. These particles are meshed and their interactions are ruled by classical finite-element contact conditions. In the present work, the method has been applied by using the finite element code ABAQUS. The interactions are modeled by a penalty contact algorithm, where the nodal forces are proportional to the penetration between the surfaces, and by a Coulomb friction with a friction coefficient f (with the same value for both sphere/sphere and sphere/wall contacts). The details of the contact modeling and finite element implementation can be found in ABAQUS [1]. No contact cohesion was considered here.

The constitutive law of individual particles corresponds to a Von-Mises type, elastic–plastic material with strain hardening. The evolution of the yield surface is calculated through a power-law:

$$\sigma = \sigma_0 \varepsilon^{1/m} \tag{1}$$

where σ and ε are respectively the Von Mises equivalent stress and strain, σ_0 is the hardening modulus, and $1/m$ is the plastic exponent. The elastic part is assumed linear and isotropic, with elastic modulus E and Poisson's coefficient v.

Previous studies by Chen et al. [6,7], comparing experimental and numerical results, involved lead alloy as the constitutive material of the particles. We chose the same material, with the following numerical values of E, v, σ_0 and m:

$$\begin{cases} E = 10,000 \text{ MPa} \\ v = 0.435 \\ \sigma_0 = 20.5 \text{ MPa} \\ m = 4.16 \end{cases} \tag{2}$$

The same authors [6,7] also determined the value of the friction coefficient between lead spheres to be $f = 0.1$ on the basis of numerical simulation and literature search ([4] for instance). Moreover, the choice of such a low value was very convenient to reduce the calculation time required for the MPFEM simulations.

The mesh was designed to provide a correct description of the contact forces at the local scale. It includes 2600 quadratic tetrahedral elements per sphere (Fig. 2).

2.2. Discrete element method

In DEM, spherical particles are not meshed and can be defined only with the coordinates of their center, their radius and mass. For each increment of time, the center-to-center distances are calculated. Usually, deformation is supposed to occur only in a small contact zone so that the relative displacement h_{ij} between particles i and j is enough to represent the deformation, and to evaluate a force F_{ij} from a so-called *force-law*; see Fig. 1. In other words, particles are rigid but contact deformation is modeled anyway, with the help of the overlap h_{ij}. At a given time step, the total force and moment acting on the mass center of each particle