ELASTOPLASTIC SIMULATION OF CONTACTS AMONG PARTICLES IN GRANULAR MATERIALS

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Abstract

The mechanisms governing the densification of powdered materials under compaction are highly dependent on the deformation and the state of stress in the contact among particles. Therefore, a micromechanical model can be very useful in studying the phenomena involved in the compaction process. In this work numerical simulations showing the distributions of strain and stress in models containing two and four particles are presented. The evolution of the deformation in the contact area among particles, the residual stresses appeared after releasing the compressive load and their consequences on the macroscopic mechanical behaviour of powder compacts are here analysed

Introduction

As in the case of many other industrial processes computer simulation of metal powder compaction is having a growing attention from researchers in the last years. Mechanical properties of powder parts depend on the homogeneity of their internal density distribution that can change with the relative motion of the compacting punches. Dimensional tolerances of the parts after die ejection are dependent on the magnitude of the elastic spring-back, which can vary with the geometry of the part and die material. Therefore, undisputable economic benefits can be obtained from computer simulation during the design stage of new powder metallurgical parts.

In the case of Powder Metallurgy, the simulation of the process is in an initial developing stage due to the lack of knowledge of an elasto-plastic model that could explain the mechanical behaviour of porous sintered components. The lack of mechanical models is even greater when the initial stage of powder die compaction is the one to be simulated. For this reason geological models such as Cam-Clay and Cap [1,2,3,4] have initially been used to represent the plastic behaviour of the metal particles inside the die during compaction. The validity of these models, in spite of giving good qualitative results in certain cases, is inevitably limited due to the different nature and, consequently, mechanical behaviour of the geological and metal particles.

Another approach is the micromechanical study of the contact among metal particles [5,6,7]. The complexity of this kind of study limits its applicability, but valuable information can be obtained about the mechanisms of softening and hardening involved during compaction and uniaxial compression tests[8,9]. In spite that finite element modelling seems very appropriated for this kind of study it has been scarcely used.

In this work the elastoplastic behaviour in the contact among particles is studied by means of finite element modelling. Conclusions are derived about the type of elastic law followed by granular

materials and also about the residual stresses generated in local contacts during their plastic deformation.

Simulation

Uniaxial compression of different geometrical arrays of spheres, under elastic and elastoplastic conditions, is simulated by means of finite element modelling. The studied geometries are shown in Fig.1 (a, b and c for the elastic case and d for the elastoplastic) corresponding to sphere packing of simple cubic, body centred cubic and face centred cubic (giving densities of 0.52, 0.68 and 0.74 respectively) for the elastic case and simple cubic when the elastoplastic study is carried out.

The aim of the elastic simulation is to find the constitutive law governing this behaviour, meanwhile the elastoplastic simulation gives information about the residual stresses developed around local contacts between particles. Tetragonal 3-D elements allowing great deflections and deformations have been used. The contact areas have been finely meshed to make sure a detailed
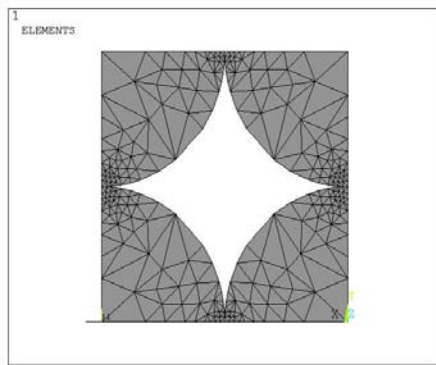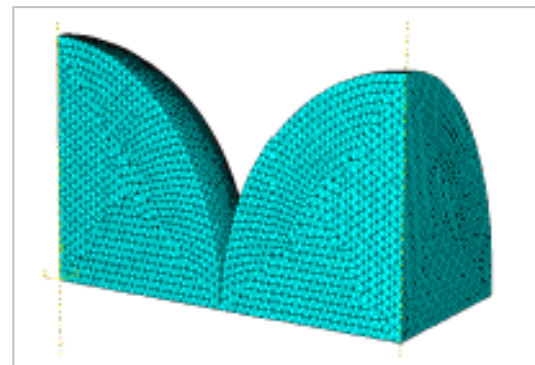

(a)
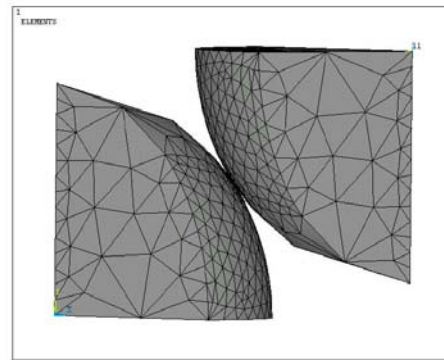
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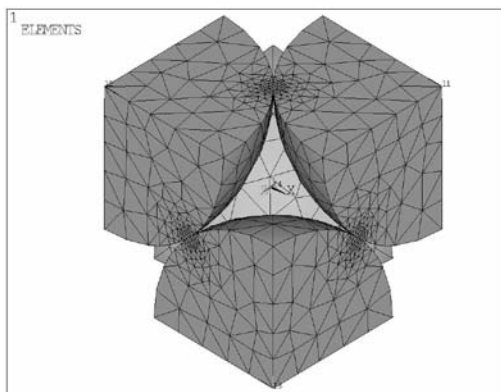
(c)

(d)

Fig.1. Meshed geometric arrays. Elastic case: a) Simple cubic, b) body centred cubic, c) Face centred cubic. Elastoplastic case d) Simple cubic

and correct study of this zone. In the elastic case, sliding between particles was prevented by coupling the nodes initially in contact.

Particles are supposed isotropic and homogeneous; spheres are of equal nature and size with the mechanical properties of pure iron: Elastic limit 170 MPa, Young modulus 196 GPa and Poisson's coefficient 0.33.

The FEM programs used has been ANSYS 6.0 for the elastic case and ABAQUS 6.3 for the elastoplastic.

Results and Discussion

a) Elastic case

The numerical simulation allows find the curves relating the axial stress and strain for each geometrical configuration. They are shown in Fig. 2.
In the three cases the equation followed by the curves is of the type:

$$\sigma_{ax} \; K \; (\varepsilon^{el}_{ax})^n \tag{1}$$

where K and n are two material parameters that take the values given in Table I for each of the different configurations.

TABLE I

Geometrical array	Relative density	K	n
Simple cubic	0.52	82386	1.5
Body centred cubic	0.68	36073	1.5
Face centred cubic	0.74	302602	1.5

Riera et al. [10] have found, for the elastic behaviour, the same type of law during cyclic compression tests of metal powder compacts. They find that the value of n evolves, with load cycling, from high values of 2 towards 1.5, which is the value predicted in this work. However, the behaviour of the parameter K is different in both cases: simulation and experiment. In this latter

.   (a)

                                                                    (b)

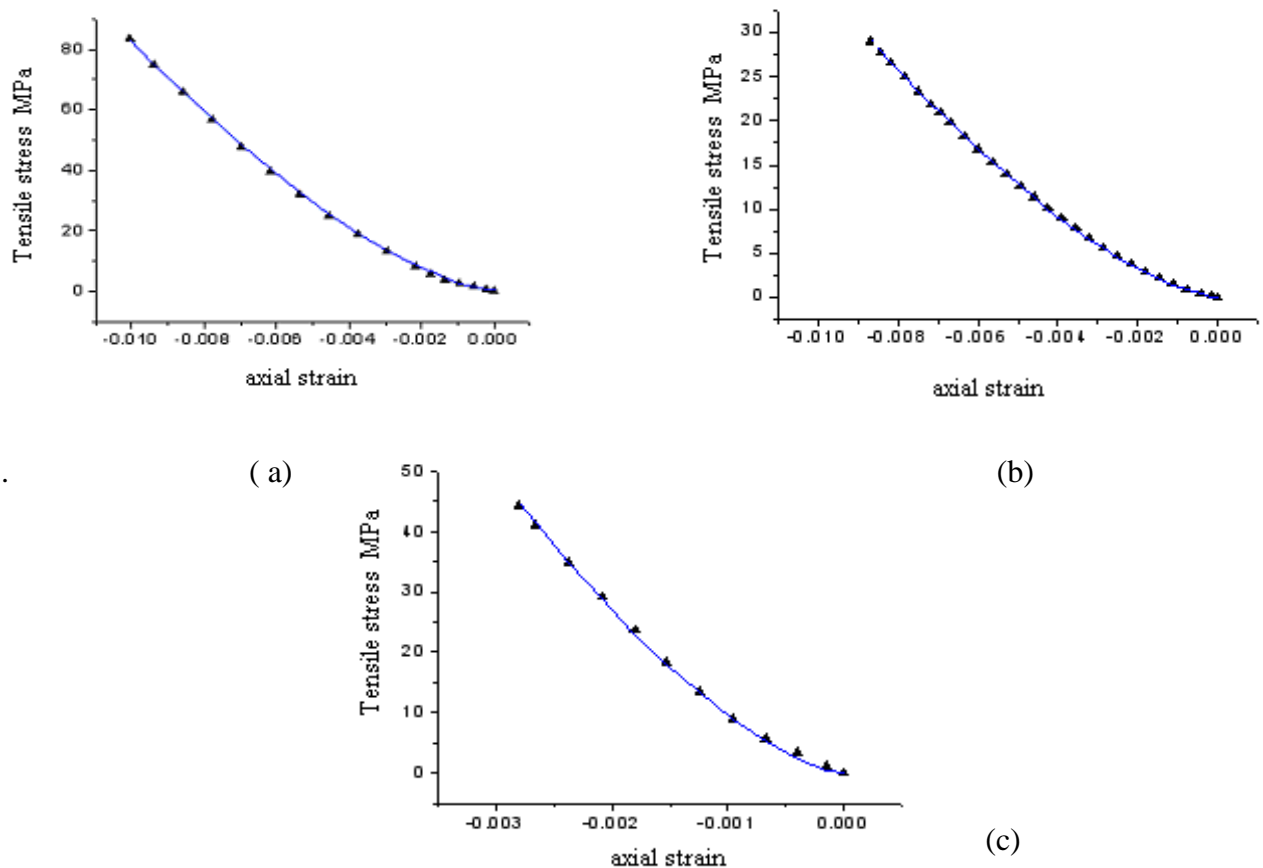   (c)

Fig.2. Curves relating axial tensile stress versus axial elastic strain. a) Simple cubic. b) Body centred cubic. c) Face centred cubic.

case, metal powder is disorderly arrange being only the coordination number the parameter typifying the packing at different densities. In the simulation study the spheres are orderly placed in crystallographic like structures for which elasticity is highly anisotropic. Therefore, the main conclusion that can be derived from the FEM simulation is the non linearity of the elastic behaviour, which follows a potential law of the type of equation (1). Even the value of 1.5 for the exponential parameter n corresponds only to an ideally elastic case.

b) **Elastoplastic case**

Plastic material models normally used to simulate the compaction behaviour of metal powders are based on geological models. However, metal and geological particles are, from a plastic point of view, of a very different nature. Ceramic (geological) particles are hard and brittle and, consequently, they do not strain harden with applied stress; on the other hand, metal particles are ductile and strain harden strongly when deformed. Hence, geological materials have only volumetric hardening when compacted meanwhile metallic powders combine both volumetric and particle strain hardening. Another aspect that has not been taken into account previously is the heterogeneous plastic deformation occurring in the compaction of metal powders. Local plastic deformation of the contact areas takes place while the rest of the particle remains unaffected. This
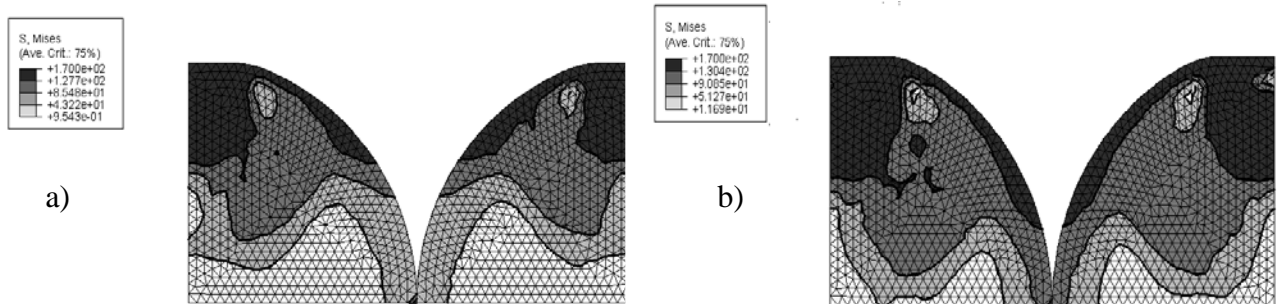

Fig.3. Distribution of Von Mises stress (black areas) after two loading cycles with maximum applied stresses of a) 44 MPa, b) 82 MPa.

behaviour can be appreciated in Fig.3 that shows the type of Von Mises stress distribution developed around the contacts when two increasing loads, 44 and 82 MPa, are applied. Inside the black areas the equivalent stresses are higher than the elastic limit of the material and, then, are fully plastified. It can be also observed that in spite that the stress field, inside the particles, increases with the applied external stress, the extension of the plastified areas remain practically constant. This simulation also shows that during uniaxial compression the contacts between lateral spheres are hardly developed, meaning that forces are transmitted mainly vertically.

A direct consequence of the localized plastification is the development of residual stresses around the contact areas what, in turn, can influence the mechanical response of the granular aggregate mainly of parameters such as the elastic and bulk modulus.
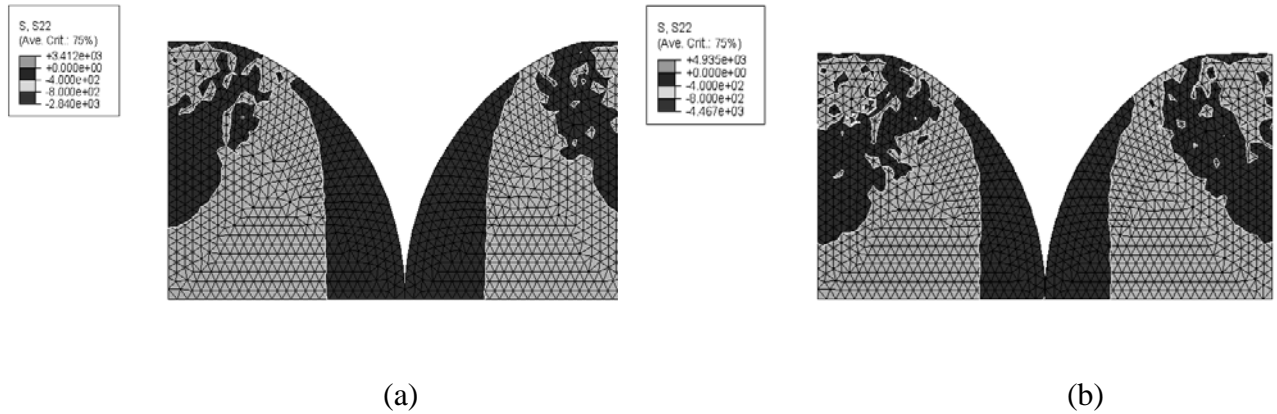
Fig.4. Distribution of the residual σ_y stress after two loading cycles. a) 44 MPa, b) 82 MPa. Grey areas are in traction and black in compression.

The state of residual stresses developed during plastic deformation is quite complex. Fig.4 shows the distribution of the residual σ_y stresses around the local contact areas once the external stress has been retired. There is a narrow zone just on the contact area in which residual stresses are of compressive nature, below it exists a broader tensile band followed by another again of compressive kind. The lateral contacts between spheres give place to compressive residual stresses. Similarly to the distribution of the equivalent stress the residual stresses do not change appreciably with increasing external loading.
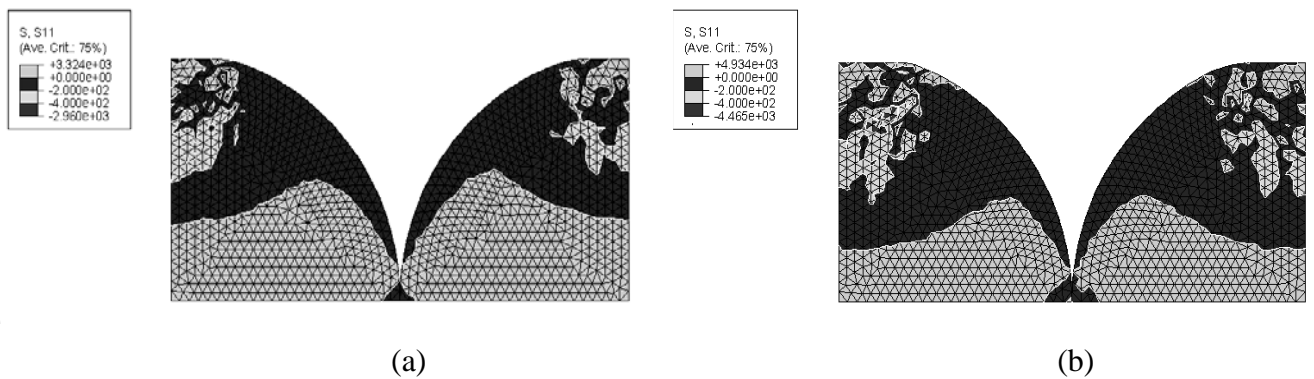

Fig.5. Distribution of the residual σ_x stress after two loading cycles: a) 44 MPa, b) 82 MPa. Grey tensile and black compressive residual stresses.

The distributions of the residual σ_x stresses are shown in Fig.5. The patterns of the residual stresses in both directions are very similar.
It is obvious that this complex state of local residual stresses cannot be ignored when trying to model the elastoplastic behaviour during compaction of metal powders. Continuous plasticity models based on geological materials cannot content the complexity derived from the ductility of metal grains.

Conclusions

The following conclusions can be derived from the results obtained in this work:

1. The elastic behaviour, under ideal conditions of non plastification of the contacts, follows a potential law with exponent of 1.5. Consequently the Young modulus changes with the external applied stress.
2. Plastification of the area surrounding the contacts between particles occurs immediately with applied load, but its extension growths moderately during posterior deformation. A complex state of local tensile and compressive residual stresses develops around the contacts areas that are bound to affect macroscopic material mechanical parameters. Loads transmit mainly vertically.

Acknowledgments

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