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Cracking cone fracture after cold compaction of argillaceous particles

SAÏD ABID[1,2], MOHAMED BOUAZIZ[2] and HATEM KSIBI[1,]*
[1]Sfax University, IPEIS, P. Box 1172, Sfax 3018, Tunisia
[2]ENIS, P. Box <W>, Sfax 3038, Tunisia

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Abstract. **Cold uniaxial pressing of powder into a green body is a common forming process used in ceramic and pharmaceutical industries. Argillaceous particles are used as a model system to investigate granule failure during compaction. Indeed, the volume enclosed between the die and punches is reduced and the powder consolidates until a final height is obtained or a prescribed compacting pressure is reached. Desired properties of the green body are high strength, uniform density, no defects and fracture. In this work an experimental investigation has been focused on the 'cracking cone' fracture in powder compacts. This includes studies of crack propagation and determination of operating conditions to avoid the green body fracture. The numerical modelling is implemented using a finite element method based on the Von Mises criterion. A case of simulation is presented to demonstrate the ability of the model to compute the distribution of the relative stresses.**

Keywords. **Cold compaction; fracture; powder technology; mechanical properties; cracking cone.**

1. Introduction

Powder compaction is a production method commonly used in the manufacturing industry such as those in the ceramic forming, pharmaceutical and detergent industries (Meyers *et al* 2006; Lee and Kim 2007). The granulated material is consolidated by application of pressure. Artifacts of the granule structure often persist as pores and laminations after compaction, and may persist as defects in the sintered microstructure. Such defects can be detrimental to the properties of the final part called 'green body'. Thus, it is desirable to eliminate the granule structure as completely as possible during the compaction.

In cold uniaxial powder compaction, the powder is formed into a desired shape with rigid tools and a die. A critical property in the powder pressing process is the mechanical properties of the formed piece. Beyond a defect-free green body, the desired properties are high strength and a uniform density. The compression induces a tensile stress perpendicular to the compressed diameter.

The current paper investigates the compaction of argillaceous powders experimentally. As the goal is to identify the break of a compacted cylindrical piece and the formation of the 'cracking cone' fracture, a series of experiments has been performed by varying the compaction pressure. Firstly, a description of the experimental setup is given and work conditions are defined and summarized in table 1. Successive photographs of several samples are taken after compaction. By using optical microscope, we have studied the compaction pressure effect on the granule size of powders.

In the second section, we discuss experimental results and shows reliability of the fracture propagation to the pressure via a simple model using a continuum medium. Indeed, the validation is performed by the numerical modelling of the stress field using the software Cosmos-Works®.

2. Description of setup

Pressing in a practical situation is commonly done uniaxially (figure 1). The powder is poured into the form by a powder-shoe and a top punch moves downwards applying a uniaxial pressure on the argillaceous particles. The mould is a cylinder with a steel disk-front and a back plate pressed into place in order to confine the powder in between. The dimensions of the mould are 30×10^{-3} m inner diameter and 60×10^{-3} m length. The pressing system has been designed with a run of instruments enabling to control the compaction process. In fact, the press setup includes three main operations: the feeding with powder, the continuous compaction by displacing the top punch, and the ejection operation.

The necessary force to move the punch to the desired distance is a function of the deformation mechanism of the material being compressed. Materials held under constant stress conditions may yield creep, hence additional punch movement, and therefore, additional compaction work.

*Author for correspondence (hatem.ksibi@ipeis.rnu.in)

3. Operating conditions

Firstly, the initial powder of clay was granulated, dried and sieved manually before pressing to obtain a calibrated powder size as shown in figure 2(a). The average particle size of the formed aggregates is around 20×10^{-6} m. The pressure is varied by activating a hydraulic jack from 40–180 bars as given in table 1.

The compaction operation is stopped when the top punch comes to the butt detector fixed conveniently to the desired length of the argillaceous compacted die. After pressing, the detail is ejected and is now called a 'green body'. The mechanical strength of the green body is enough to handle it after pressing but not enough to use it in practical situations with increasing loads. To enhance the mechanical behaviour in some cases, the powder particles need to be welded together using for example heat treatment as is known in ceramics (Miyashita *et al* 1992).

Table 1. Experimental conditions of the cold compaction of argillaceous powders.

	P (±2 bar)	R (10^{-3} m)	A (10^{-3} m)	E (10^{-3} m)
Run 1	50	11·96	9·22	6·76
Run 2	70	10·71	10·44	6·51
Run 3	90	9·92	9·38	7·02
Run 4	140	9·57	10·65	6·76
Run 5	180	7·78	13·3	4·23
Run 6	200	6·24	11·38	11·24

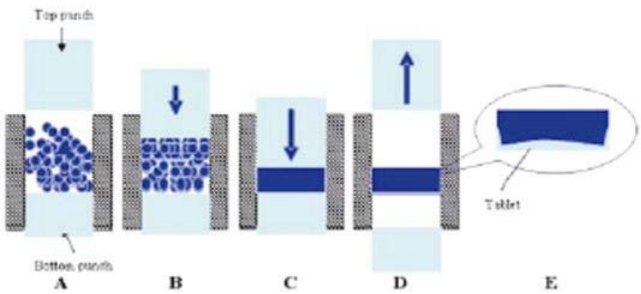

Figure 1. Description of the setup.

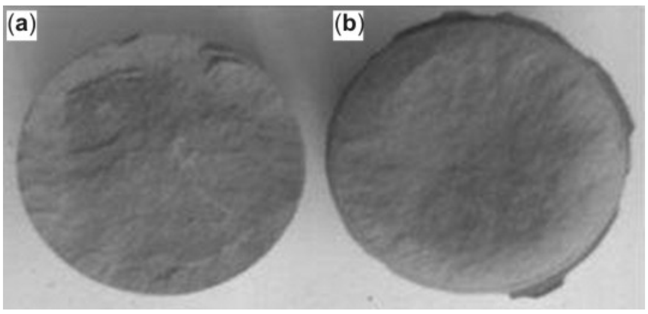

Figure 2. Fracture of the compacted powder after ejection.

Although the ejection operation is carefully conducted, the formed green body is broken in every case. The fracture is always localized at the bottom of the formed piece. It is divided into two parts (a) and (b) as shown in figure 2. The part (b) is called as the 'cracking cone' by a few workers (Latella *et al* 1997; Salman *et al* 2004). Table 1 summarizes the effect of the compaction pressure on the 'cracking cone' dimensions at each run where R is its radius; E the cone height, and A the distance between axis.

4. Experimental

4.1 *Reduction in particle size*

During the compaction step, increase of the material density is mainly due to rearrangement of powder particles. In this stage, the particles are locked up and the mechanism that controls the increasing density is mostly plastic deformation. In material at full density, voids exist between the particles and the assembly of powder has no strength or a very low one (Liu and Davies 1997). The number of touching neighbour particles, also called the coordination number, is low. As pressure is applied, the first response is particle rearrangement, filling the large pores. Increasing pressure provides a higher coordination number as new particle contacts are formed. The particle contacts undergo elastic deformation and at high pressure plastic deformation enlarges the contact area. At this level of pressure, the fragmentation of powder particles and aggregates occurs.

Since particle aggregates are brittle, failure results in fragmentation as shown in figure 3. We find that the number of small particles increases compared to that before compaction. The histogram depicted in figure 4 carries out the fragmentation behaviour and shows the tendency of a new particle size distribution (PSD).

Particle size analysis of the resulting fragments demonstrates the statistical nature of granule failure during compaction; with some granules failing at very low applied pressures while a large fraction persists at even the highest applied loads.

4.2 *Effect of pressure upon ejection operation*

The experimental results show that dimensions of the cracking cone (radius, height, angle…) depend on the compaction pressure level and also on the restructure of powders at each level of pressure. Indeed, optical measurements show that dimensions vary enormously with the pressure level as it is the case for the radius (R) given in table 1.

We notice that the crack should be in the direction of the maximum shear stress intensity factor that is in the original crack plane or at a small angle from the original

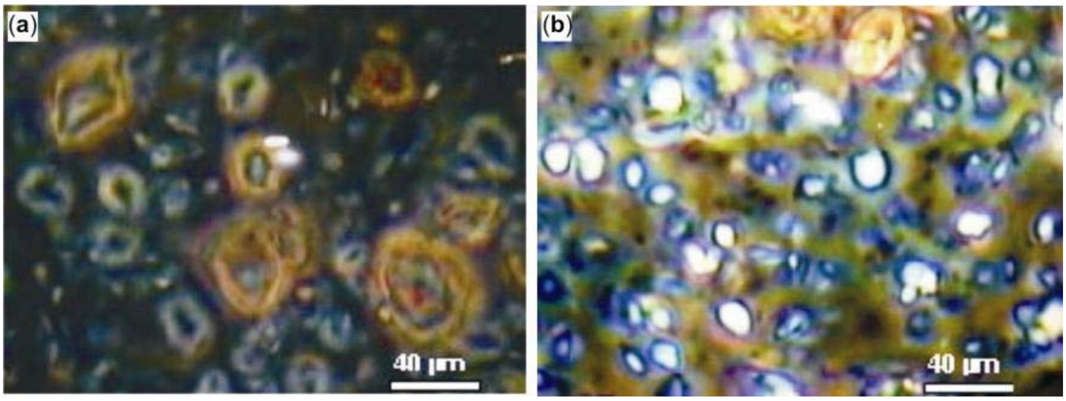

Figure 3. Photomicrographs of argillaceous particles (**a**) before and (**b**) after compaction (b: particles are carefully taken from the cracking cone surface).

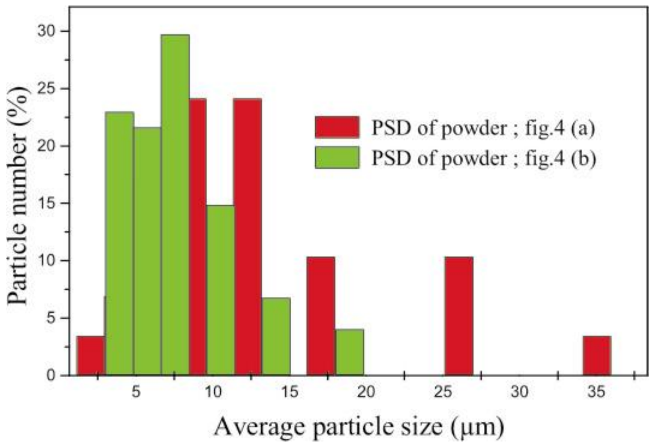

Figure 4. Histograms of powders before and after compaction.

crack plane. In other words, the analysis proved that a more robust fracture criterion is needed to predict the occurrence of the crack. In literature, experimental and numerical simulation results on crack growth in compacted materials under compression indicate the same trend of crack propagation (Mori 2006).

In fact, a crack can generally grow in different manners as the pressure varies. At a low pressure, it grows via incipient kink at an angle from the original crack plane. But under increasing pressure, it grows as a combination of open and shear crack. Finally, under substantially high pressure, the crack grows as a shear crack, straight ahead or at a small angle from the original crack plane.

4.3 *Numerical validation*

The separation or fragmentation of a solid body into two or more parts, under the action of stress, is a common definition of fracture, which is a result of crack initiation and propagation. The manufacturing of a green compact can vary from part to part depending on shape etc although most compacts are pro-produced in several process stages.

When powder is compacted, the inter-particle bonds can break as the trapped air tries to escape under pressure. Insufficient vertical powder transfer in a levelled tool is another source of cracks as regions of partly compacted powder have to move relatively towards each other, causing shearing zones.

In this approach, powders are modelled as a continuum medium and the compaction behaviour is analysed by solving boundary value problems, i.e. partial differential equations representing balance laws of mass, energy and momentum and constitutive laws, such as stress–strain relations. Powders are generally assumed to be elastic–plastic materials with appropriate yield surfaces to represent the yield behaviour of the materials. Whereas, as a first approximation, the compacted powder behaviour is considered elastic with the hypothesis of small displacements and rotations. We apply the standard finite element Galerkin discretization process to the standard displacement formulation with independent approximation of displacement (the isoparametric concept). This simple model is developed with respect to the Hooke law. The discritization via finite element method of the virtual work displacement includes inertial, soliciting, and cushioning forces.

One of the most important material parameters that affect powder yielding under hydrostatic and shear stresses is the Young's modulus. This can be simply determined by means of powder compaction experiments and establishing the stress–strain curves at different levels of density. In this simulation, the Young's modulus is set at a low value as we consider the compacted powder as a soft material medium.

To compare the simulation results with experimental measurements, a verification of the crack cone shape has been performed. The Von Mises constraint field is determined by computer simulation using CosmosWorks soft-

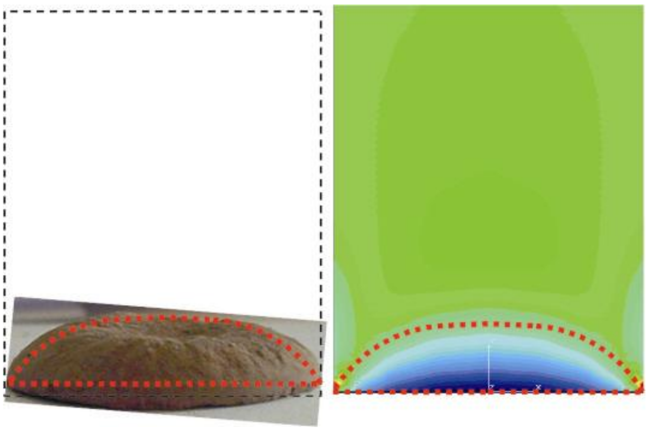

Figure 5. Comparison between the cracking cone profile (in red dots) and the stress isovalues after compaction.

ware. Figure 5 shows the obtained isovalues of a horizontal section through the pressed green body in run 1 seal together with the crack cone obtained experimentally. The dashed contour lines (in red) are very similar in the two pictures.

There are several potential explanations for the slight differences in the absolute values on these plots. We underline that experimental measurements could lead to systematic deviations. Also, numerical calculations are done using hypothesis, mainly the continuum material medium. Therefore, experiments with different calculations are in good agreement.

5. Conclusions

This work has been performed to investigate residual stress development, tensile fracture and mechanical properties of powder compacts. We fabricated argillaceous green bodies using a compaction process and simulated their stress fields in the same conditions.

Compacting pressure, upper punch hold down and die taper geometry have a significant influence on the residual stress state while die wall friction has a small influence. It is concluded that the ejection part of the pressing cycle or more precisely the process of the powder compact release from the die is the main reason for high residual stresses.

The application using the finite element simulation method is a possible optimization of the compressing process. Although at the moment, the model assumes a simple linear constitutive law for the filled cells and linear interpolation functions for the displacement field, the obtained results are very promising.

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