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Modelling the stress behaviour in particle bed comminution

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ABSTRACT

The stress behaviour of particle beds describes the relationship between the forces acting on the particle bed and the total energy input supplied. The stress behaviour is closely related to the compaction of the particle bed, which has to be distinguished into a purely elastic and purely plastic deformation. The elastic deformation can be characterized by the elasticity E of the particle bed as a material-specific parameter which is different to the *E*-modulus of solids. The description of the purely plastic deformation of a particle bed allows to deduce a model of the stress behaviour.

1. Introduction

Compaction is the first visible change when an external load is applied to a confined particle bed. The particles rearrange themselves into a denser packing and the original volume of the bed decreases due to a falling void volume. If the load on the individual particles exceeds a critical value they start to break, producing a large number of smaller fragments with a corresponding size distribution. This is the objective of particle bed comminution of the type that is applied in, for example, vertical roller mills and high-pressure roller presses (Hanisch and Schubert, 1984; Hanisch and Schubert, 1986; Schönert, 1996) as well as cone crushers above the choke level (Lee and Evertsson, 2012; Evertsson, 2000).

The relationship between the forces acting on the particle bed (bed pressure p) and the total energy input supplied (energy absorption E_m) is described by the stress behaviour of the particle bed. The bed pressure is the main influencing variable during compaction, the energy absorption the main influencing one during comminution. The modelling of the stress behaviour based on previously published compaction models led to very complex solutions in spite of a number of simplifications (Müller, 1989; Schönert et al., 1990). Therefore it remains to be clarified to which extent it is justified ignoring the elastic recovery and to which extent the description of the compaction and stressing behaviour have to be expanded to include this aspect.

In addition to the external load, which acts integrally on a particle bed, there are stresses and resultant compaction gradients within the particle bed. Depending on the pressure level the literature essentially distinguishes between two sub-processes during compaction, each with two possible sub-categories (Mani et al., 2003; Cooper and Eaton, 1962; German, 1994; van der Zwan and Siskens, 1982). Because of the stress gradients in the particle bed these sub-processes take place in parallel to one another.

1.1. Rearrangement

At low pressure levels (about <10 MPa) the particles rearrange themselves into a closed mass by rotating and sliding over each other (Fig. 1a). The original particle contacts are eliminated and the interstitial spaces are filled which are of the same order of magnitude as the particles themselves. In spite of the friction between the particles the individual particles retain most of their properties as well as their external shape and internal structure (Mani et al., 2004). Locally restricted individual particles undergo short-term elastic deformation.

1.2. Comminution and/or plastic deformation

At higher pressure levels cracks are formed within the particles which ultimately lead to fracture if the stress intensity is sufficiently strong (Fig. 1b) (Rumpf, 1974). The particles are also brought closer together by the high load so that they not only undergo local elastic deformation but also increasingly plastic deformation throughout the particle bed (Fig. 1c). Both micro-processes take place material dependent one after the other or in parallel to each other. Unlike pure rearrangement, this sub-process can also fill those spaces between the particles that are much smaller than the original particle size.

With plastic deformation the contacts between the particles change from point contacts to planar contacts. This greatly increases the adhesive forces between the particles and the resistance of the particle bed to further compaction (Rumpf et al., 1978). Therefore the volume of the

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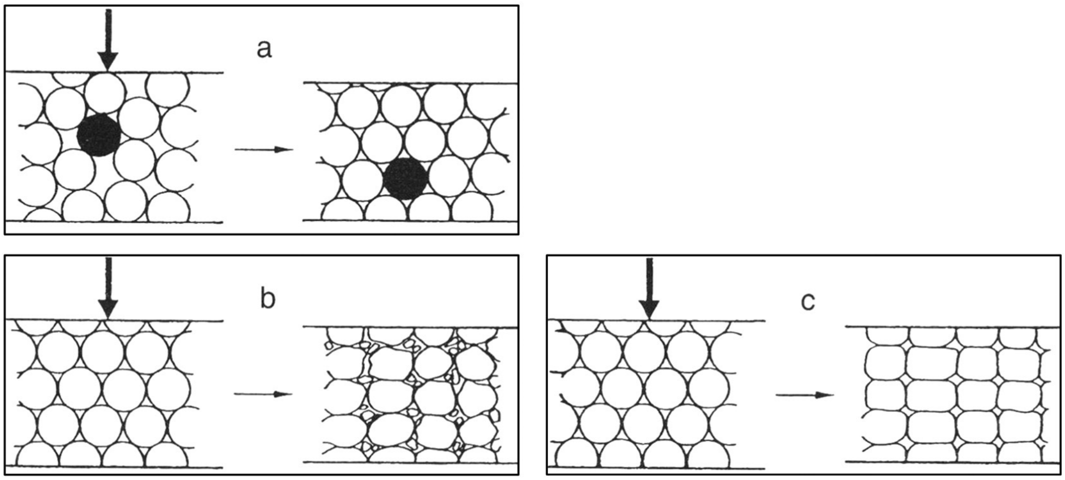

Fig. 1. Sub-processes occurring during compaction through (a) rearrangement, (b) comminution and (c) plastic deformation (from (Schubert, 2003) according to (Cooper and Eaton, 1962)).

particle bed only changes very slightly above 100 MPa bed pressure. Even if there is a subsequent drop in the external load the particles remain adhering to one another because of the high adhesive forces.

1.3. De-aeration and irreversible rearrangement

In addition to the two sub-processes described above, which mainly affect the solid particles, two additional sub-processes which are seldom mentioned in literature have to be considered in order to comprehensively understand the effects in particle bed comminution. On one side the fluid in the voids of the particle bed is displaced provided that it has the time and opportunity to escape (Mütze and Husemann, 2008). Especially in the cases of high stress velocities and fine-grained feed materials a part of the fluid becomes trapped in the voids and is compressed with the particle bed. On the other side the part of the energy that is stored in the elastic stress field of the particle bed leads to an expansion when the external load is reduced.

This expansion is greater the higher the previous external load but shows always a similar behaviour pattern (Müller, 1989; Heckel, 1961). Also irreversible rearrangement phenomena may occur alongside these reversible (elastic) deformation during the recovery. The irreversible rearrangement has two causes. On the one hand and in contrast to the axial stress field, the stress field in the radial direction is maintained during the recovery. On the other hand, the fluid expands which was trapped during compaction. The radial stress field and the expanding fluid cause inhomogeneous stress gradients in the particle bed. This can reach orders of magnitude that exceed the strength of the compacted particle bed and lead to bursting. However, bursting is of minor importance since the focus in particle bed comminution is on breaking the material rather than on the compact body of the product.

2. Modelling

2.1. Compaction behaviour

The compaction behaviour is affected not only by the applied pressure but essentially also by the particle size of the feed material, the stress velocity, and the material moisture. In the field of particle bed comminution this behaviour has been investigated comprehensively for quartz and limestone in the size range from 1 to 2500 μm for applied pressures of up to 1000 MPa, moisture contents of up to 20 % and stressing rates of up to 60 cm/s (Müller, 1989; Schönert et al., 1990; Mütze, 2011; Oettel, 2002). The compaction behaviour is modelled mathematically by interpolation formulae that in most cases use two or three, or more rarely four or more, adjustment parameters. Depending on the author, the compaction is described by terms such as “porosity”, “relative volume”, “relative density”, “relative void volume” or “normalized compaction”, which makes it difficult to compare the work.

The inner structure of a particle bed is a result of its initial condition, the stressing mechanism and intensity, as well as the compaction behaviour of the bulk material. The structure is often described integral by the bulk density of the particle bed ρ_b which is mostly related to the condition of the particle bed prior to stressing (e.g. the loose bulk density $\rho_{b,0}=\rho_b(p\cong 0)$) (Sonnergaard, 1999). However, especially for fine-grained materials arises a problem here since the interactions between the particles and thus the inner structure of a particle bed depend strongly on the previous load or load cycles. Therefore the state of a “loose particle bed” depends strongly on the measurement method which is used to characterize this state (e. g. DIN EN ISO 60). Regardless of those considerations, the normalized compression (Eq. (1)) has been selected in particle bed comminution as a model parameter (Müller, 1989; Schönert et al., 1990). It relates changes of the bulk density $(\rho_b-\rho_{b,0})$ to a maximum possible change $(\rho_s-\rho_{b,0})$, which is indicated by the solid density ρ_s. Therefore the normalized compression allows to compare materials with each other, which differ in the type of material and/or the initial structure of the particle bed.

$$\Theta(p)=\frac{\rho_b(p)-\rho_{b,0}}{\rho_s-\rho_{b,0}} \tag{1}$$

Four fundamental models that are often quoted were developed by Walker (1923), Heckel (1961); Cooper and Eaton (1962), and Kawakita and Lüdde (1971) (Sonnergaard, 1999; Denny, 2002). They are used mainly for pharmaceutical, metallic, and ceramic powders. Models have also been formulated in the field of particle bed comminution by Schönert (Schönert et al., 1990), Evertsson (Evertsson, 2000), and Oettel (Oettel, 2002) and for bulk materials mechanics by Tomas (Grossmann et al., 2004). This last model was to first attempt to replace to the empirical description of the compaction behaviour with universal validity based on measurable, material-specific parameters (Müller et al., 2006). It has been agreed that the ideal particle bed should form the basis for investigations (Schönert, 1996; Mütze et al., 2011) since an ideal particle bed allows to ignore the influence of stress gradients inside the particle bed as mentioned at the outset.

The compaction models are often used to indicate connections between the parameters in the model equations and selected powder properties such as density and the volumetric fraction of the solid material. There is hardly any discussion of the factors affecting the variables that are relevant for process engineers or in particle bed comminution,

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