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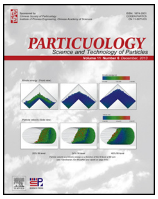

Correlation of powder flow properties to interparticle interactions at ambient and high temperatures

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ABSTRACT

A combination of a continuum approach and a particle–particle approach to describe the multi-scale nature of the mechanical properties of bulk solids may be beneficial to scientific and engineering applications. In this paper, a procedure is proposed to estimate the interparticle forces beginning with the bulk flow properties as measured with standardized techniques. In particular, the relationship between interparticle forces and bulk solid tensile strength is adopted based on the microscale approaches of Rumpf (1970) and Molerus (1975). The flow properties of fluid cracking catalyst (FCC), corundum and glass bead powders were all characterized with a modified Schulze ring shear cell capable of operating at temperatures up to 500 °C. The powder test conditions were selected such that the van der Waals forces were the most significant particle–particle interactions. The model equations describe two cases, in which either elastic or plastic deformation of the contact points is assumed. The results indicate that the model provides the correct order of magnitude for the values of the tensile strength when proper values for the mean curvature radius at the contact points are taken into account. A sensitivity analysis for the main parameters in the model was performed. This analysis indicated that the assumption of plastic deformation at contact surfaces coupled with a decrease in porosity justified an increase of the tensile strength with consolidation stress. Furthermore, the effect of temperature on the measured flow behavior can be explained as a change in the strength of the material.

1. Introduction

The flow behavior of granular materials is generally described using a continuum mechanics approach. This approach is also used in engineering to design equipment for the handling and storage of granular materials. In particular, the stress distribution inside a bulk solid is modeled with the Mohr–Coulomb analysis, and the granular material is assumed to be a solid for which failure occurs when the normal and shear stresses exceed the yield limits (Neddermann, 1992; Schulze, 2008). With these theoretical assumptions, the stress distribution in powder beds (Janssen, 1895; Walker, 1966; Walters, 1973) can be estimated to enable the design of handling and storage equipment (Chen, Yuan, Shen, & Zhang, 2012; Fitzpatrick, Barringer, & Iqbal, 2004). For design purposes, different techniques are employed for the measurement of powder flow properties. The most used characterization devices are translational and rotational shear cells (Jenike, 1964; Schulze, 1994, 2008; Schwedes, 2003). Furthermore, flow behavior is often analyzed under different conditions to estimate and correlate the flow properties to realistic process conditions. Such conditions can include high temperature (Kanaoka, Hata, & Makino, 2001; Pilpel & Britten, 1979; Pilz & Löffler, 1995; Tomasetta, Barletta, & Poletto, 2011), high humidity and moisture content (Gröger, Tüzün, & Heyes, 2003; Landi, Barletta, & Poletto, 2011; Landi, Barletta, Lettieri, & Poletto, 2012; Liang et al., 2012; Pierrat & Caram, 1997; Pierrat, Agrawal, & Caram, 1998) and loose compaction conditions such as in fluidized (Barletta & Poletto, 2012; Bruni, Lettieri, Newton, & Barletta, 2007; Kono, Aksoy, & Itani, 1994) or aerated powder beds (Bruni, Barletta, Poletto, & Lettieri, 2007; Chen, Yuan, Chyang, & Zhuan, 2011; Johanson & Barletta, 2004; Tomasetta, Barletta, Lettieri, & Poletto, 2012).

Particle properties, such as size and shape (Fu et al., 2012; Liang et al., 2012), and mechanical properties (Medhe, Pitchumani, & Tomas, 2005; Molerus, 1975; Pilpel & Britten, 1979; Tomas, 2001a, 2001b) affect the flowability of powders. In fact, powder flowability is related to the type and magnitude of the interactions between particles that act at a microscopic scale. Many studies have highlighted the significant role of interparticle interactions by directly measuring the forces between particles (Forsyth, Hutton, & Rhodes, 2002; Pagliai, Simons, & Rhodes, 2007; Tanaka, Komogata, Tsukada,

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Nomenclature

a	parameter in Eq. (A.4), N
A	Hamaker constant, N m
b	parameter in Eq. (A.4), N^{-1}
c	parameter in Eq. (A.4)
C	powder cohesion, Pa
d	particle diameter, m
d_{10}	10th percentile particle diameter, m
d_{50}	volume median particle diameter, m
d_{90}	90th percentile particle diameter, m
d_{sv}	particle Sauter mean diameter, m
k	coordination number
f_c	unconfined yield strength, Pa
F_c	mean isotropic contact force, N
F_N	mean isotropic consolidation force at the particle contact, N
F'_N	non-uniform consolidation force at the particle contact, N
F_{vdW}	mean isotropic van der Waals force at the particle contact, N
F'_{vdW}	non-uniform van der Waals force at the particle contact, N
$p(F')$	contact force distribution function
p_f	particle material compressive strength, Pa
r	mean curvature radius at contact points, m
r^*_{el}	mean curvature radius at contact points estimated with an elastic contact hypothesis, m
r^*_{pl}	mean curvature radius at contact points estimated with a plastic contact hypothesis, m
T	temperature, °C
z_0	interparticle separation distance, m

Greek symbols

ε	porosity of the bulk solid
ε^*	reference porosity in the sensitivity analysis
ϕ	angle of internal friction, deg
ρ_b	bulk density, kg/m^3
ρ_p	particle density, kg/m^3
σ	normal stress, Pa
σ_1	major principal stress, Pa
σ_2	minor principal stress, Pa
σ_c	normal stress at consolidation, Pa
σ_f	compressive yield strength, Pa
σ_{pr}	normal stress of pre-shear in shear test, Pa
σ_t	tensile strength of the bulk solid, Pa
τ	shear stress, Pa
τ_{pr}	shear stress of pre-shear in shear test, Pa

& Kamiya, 2008). Other works have assessed the effect of environmental conditions, i.e., humidity (Forsyth et al., 2002; Gröger et al., 2003; Landi et al., 2011, 2012) and temperature (Cui & Chaouki, 2004; Pagliai et al., 2007; Pilpel & Britten, 1979; Xu & Zhu, 2006), on interparticle interactions. The role of interparticle forces becomes more significant at the low consolidation levels found, for example, in aerated or fluidized beds, where body forces due to gravity are counterbalanced by the drag force exerted by the upper fluidizing flow. In this situation, the powder behavior is determined by the relative weighting of the interparticle forces compared to the mass and hydrodynamic forces (Bruni, Lettieri, et al., 2007; Hou, Zhou, & Yu, 2012; Molerus, 1982; Mutsers & Rietema, 1977; Rietema & Piepers, 1990). In contrast, high consolidation levels can cause more compacted packing structures and can increase the compressive forces at the contact points of the particles. More compacted packing increases the number of contacts between particles (Kojima & Elliott, 2012) while the increase in the compressive forces can generate deformation and flattening at the contact points (Medhe et al., 2005; Molerus, 1975; Tomas, 2001a, 2001b). These effects enhance the cohesive behavior of the powder under increased consolidation stress.

For scientific and engineering purposes, a combination of the continuum approach and a particle–particle approach may be useful to describe the multi-scale nature of the mechanical properties of bulk solids. In particular, a microscopic model that is able to quantitatively estimate the interparticle interactions from the bulk flow properties might make it possible to characterize powders by means of easy-to-use shear testers and to predict powder behavior under consolidation conditions other than those used in the shear testing. Stress transmission inside granular materials has been analyzed using several mathematical models (Castellanos, 2005; Edwards & Grinev, 1999; Medhe et al., 2005; Molerus, 1975; Quintanilla, Castellanos, & Valverde, 2001; Tomas, 2001a, 2001b). Moreover, discrete element method (DEM) simulations have been performed to predict the flow behavior of powders for different applications (Hou et al., 2012; Luding, 2005; Tykhoniuk et al., 2007; Zhu, Wu, & Yu, 2005).

In this paper, we propose a procedure to correlate interparticle forces with bulk flow properties that have been measured with standardized techniques. This approach is a first step toward the effective use of measured bulk flow properties to predict the flow behavior beyond the tested consolidation conditions. We considered the flow properties of fluid cracking catalyst (FCC), corundum and glass bead powders, which were measured with a modified Schulze ring shear cell capable of operating at temperatures up to 500 °C. This paper is limited to testing powder conditions for which van der Waals forces are the most significant particle–particle interactions. Our procedure to relate interparticle forces with bulk flow properties is based on the microscale approaches of Rumpf (1970) and Molerus (1975), which are discussed on the basis of a sensitivity analysis.

2. Theory

To relate binary interparticle interactions to bulk flow properties, a combination of the Rumpf (1970) and Molerus (1975) approaches was followed. Accordingly, the following simplifying assumptions were made:

1. Particles are organized in a randomly packed assembly.
2. Particles are spherical and monodisperse.
3. The contact areas between particles are small enough in comparison with the particle surface that contact areas can be assumed to be contact points.
4. The contact points are distributed over each particle's spherical surface with equal probability.
5. The packing structure is isotropic.
6. The transmission of an isostatic state of compressive stress with three equal principal stresses is assumed.

Starting from these hypotheses, Rumpf (1970) and Molerus (1975) derived the following equation relating the isostatic stress, σ, with a mean isotropic contact force, F_c:

$$\sigma = \frac{F_c}{d^2}\frac{k(1-\varepsilon)}{\pi}, \qquad (1)$$

where k is the coordination number (i.e., the mean number of contact points between a particle and its adjacent neighbors), d is the particle diameter and ε is the assembly porosity. To apply Eq. (1), additional hypotheses were considered: