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Apparatus for measuring friction inside granular materials — Granular friction analyzer

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ABSTRACT

Flow of granular materials is a complex process but it is important to measure, because the flow of granular material during processing, handling and transportation strongly influences the quality of the final product and its cost. Flowability of granular materials depends on the characteristics of the material and on the conditions at which flow is occurring. Existing methods of measuring flowability of powders are described in this paper, and a new methodology is introduced to measure friction between granular materials under pressure induced with uniaxial compression. Apparatus also allows analysis of conditions at which granular material starts to flow when exposed to uniaxial compressive load, i.e., zero-rate flowability. We call the apparatus the Granular Friction Analyzer (GFA).

The concept of the GFA was tested by measuring four different materials with different average particle sizes. It was observed that as the particle size decreases so does its zero-rate flowability. This is in agreement with powder literature. Therefore, it can be concluded that in general the GFA method can be a very useful tool to study friction between granular materials and conditions at which the granular material flow initiates, i.e. zero-rate flowability of powders under pressure. However, further improvements are required to increase its sensitivity and accuracy.

1. Introduction

Granular materials are present in our everyday life whether as raw materials, intermediate or final products. For instance, one finds them in the food industry from cereal grains to dehydrated milk; in the pharmaceutical industry different powders are blended and compressed to produce tablets; metal, polymeric or ceramic parts can be produced through different powder sintering techniques; moreover, granular materials are present in nature as sand and rocks. In all these examples, the flow of powder during processing, handling and transportation strongly influences the quality of the product and its cost.

A granular material is defined as a collection of discrete solid particles that are filled with an interstitial fluid, usually air. From this definition, one can notice that they cannot be classified either as solids or liquids, leading to a complex behavior difficult to understand and predict [1]. In the literature, several terms are used interchangeably to describe granular materials, such as bulk solids, particulate solids and powder.

Within the world of granular materials, metal powders constitute an important part of the industry. In this context, one important topic of research nowadays is to study the flowability of powders in powder metallurgy because an increase in flowability represents an increase in the productivity of the overall process and a reduction in the cost of transportation of powders. During powder metallurgy granular materials are transported and molded under pressure.

Another example of utilizing granulated materials is in new emerging dissipative granular technology [2,3]. In this technology damping elements are made of granulated polymeric materials and encapsulated in a flexible container. Good performance of such damping elements can be achieved by pressurizing granular material to a pressure level, at which the damping element's frequency for absorbing a maximum energy substantially matches the frequency of mechanical excitation. This is possible because damping properties of polymeric (elastomeric) materials are frequency (time), temperature and pressure dependent [4,5]. In this instance also flowability of polymeric particles is important, since increased flowability ensures the equal distribution of pressure inside damping elements.

Flowability is defined as the ability of a powder to flow and results from the combination of material physical properties, which along with the equipment used for handling or processing governs how easy a granular material can flow. There are several techniques used for measuring flowability some of them require simple apparatuses while others use sophisticated setups. Simple traditional apparatuses such as Hall-flowmeters and angle of repose devices provide a comparative analysis of which particular powder flows better with respect to

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another under certain conditions of measurement [6,7]. On the other hand, more sophisticated setups as shear cells and powder rheometers can provide more quantitative information as cohesion and angle of friction that influence the flowability of powders [8,9]. Nevertheless since flowability changes according to the conditions at which flow is occurring, measuring devices more or less should resemble the handling or processing equipment in which the powder will be used [10]. An overview of the flow properties of the granular systems including voids, granular porosity and random packing characteristics is summarized in the paper of Traina et al. [11]. Since most of the measuring techniques available in the market work under gravitational and shear flows, the present paper aims to introduce a new method of characterization where the driving force for granular flow is high pressure [12,13]. Hence, apparatus allows investigation of the so-called zero-rate flowability induced by pressure. More precisely the apparatus allows investigation of friction within granular materials exposed to pressure generated by uniaxial compression. As a special case apparatus allows determination of conditions at which granular material will start to move.

2. Existing flowability measuring techniques

As previously mentioned, flowability is defined as the ability of a powder to flow. It results from the combination of material physical properties and the physical characteristics of the equipment used for handling and processing. In this context, flowability is not an inherent material property because it depends on the conditions under which the flow takes place [14]. It is important to distinguish between flow property data and flowability. The former refers to the characteristics of the powder alone which affect its flowability (e.g. cohesion strength, particle shape, surface roughness, angle of friction, etc.), whereas the latter is a description of the ability of material with certain flow properties to flow under certain conditions.

There are different approaches to estimate flowability of powders under different conditions. A general classification of flowability characterization methods is (i) traditional instrumentation, which have gravity as the driving force for flow and then either time, mass or angle of repose of the material is measured [6,7]; and (ii) modern instrumentation where more complex setups composed by many accessories are moved simultaneously to produce and control force or torque that leads to flow of the powder [8,9]. Within the traditional methods one founds the “Hall-flowmeter” and the angle of repose measurement; on the other hand, shear cells, powder rheometers and optical methods constitute the main modern instrumentation available today to measure flowability [15,16]. In the following sections a short overview of such characterization techniques is given, mainly to clearly distinguish the proposed new measuring technique from the currently available ones. The comprehensive overview is given in the book of Schulze [17].

Hall-flowmeter is a widely used standard method of powder characterization where the driving force is simply gravity. It measures the time required to discharge several grams of powder through an orifice of a standard funnel (DIN ISO 4490, ASTM B 213, MPIF No.3). As other flowability characterization methods, this test offers only a means of comparison and evaluation because in many of the cases the powder does not flow through the small orifice of the funnel. This characterization method is suitable for evaluating flow of particles in hoppers, silos and similar containers.

Another type of characterization typically used in industry because of its basic use and high reproducibility is the angle of repose (AOR) measurement [7]. In this method powder is spilled into a funnel that is held at a fixed height above a flat base, or the funnel moves up gradually to allow the sample to flow out. One requirement of these funnel-based methods is that the powder must be able to flow through an orifice, which sometimes may not happen. In this case dynamic methods can be used to measure the dynamic angle where either a cylinder or a tilting table turns until slipping of the powder occurs and then this angle is measured [7].

There are several relations in literature of how to relate AOR with flowability of a powder, Raymus [18] suggests that angles of repose below 30° indicate good flowability, 30°- 45° some cohesiveness, 45°–55° true cohesiveness, and > 55° very high cohesiveness, i.e. very limited flowability. Even though there are some standards (ISO 4324, ISO 8398, ASTM C1444, BS 4140-9, IS-6663), due to the lack of agreement in the best design or size of equipment and the way that a test should be done, one can conclude that the angle of repose measurement is a practical method (quality control method) to verify if the powder being produced today has better or worse flow properties than the one produced yesterday, more than a characterization method [7]. More recent paper by Lumay et al. [19] comprehensively reviews different standard as well as newer methods for measuring flow properties of powders and grains.

Shear cells are powerful characterization tests that allow the calculation of the angle of internal friction and the cohesion strength of a material according to the Mohr Coulomb criterion [8].

Shear cells measure the relationship between the shear stress (which leads to flow of the material) and the normal stress. The cohesion of the material is obtained by extrapolating to zero several measurements of the relationship between shear stress and normal stress in the shear cell. The cohesion of a granular material corresponds to the value of shear stress required for flow in the absence of other normal force [7]. Once cohesion is known, the friction angle can be obtained for different shear stress values. Several modifications of shear cell have been implemented to improve the sensibility of the equipment as in [9,20,21] but all of them work under the same principle described above. Comprehensive comparison of ring shear testers is presented in the paper by Schulze [22] which summarizes the results of the 2008 round robin project on ring shear testers. The round robin showed that despite different ambient conditions the range of obtained results was quite narrow.

Another type of equipment used is the powder rheometer FT4 developed by Freeman technology Ltd., Gloucestershire, UK [9]. The principle of this rheometer is based on recording the forces required to induce deformation and flow of powder inside a vessel container. The force is transmitted through a sophisticated twisted blade that is moved along a predetermined helical path [9].

Flowability of powders is related in the FT4 by two main parameters the “basic flow energy” (BFE) and the “specific energy”(SE). Both BFE and SE are measures of the work done by the system to induce flow of the powder and depend on the mode of the helical blade. Both parameters BFE and SE can provide a good relative mean of comparison of flowability of powders with different characteristics as size distribution or different external conditions as moisture [9].

Moreover the FT4 rheometer can be adapted with a shear cell that allows us to calculate the friction angle and cohesion of the powder under the principle of a standard shear cell, i.e. to measure the relationship between the shear stress (related in this case with the torque of the shear cell adaptor) and the normal stress (function of the vertical load induced by the cell adaptor) [9].

An alternative way to measure flowability is by optical means through the so-called “Particle Image velocimetry” (PIV) and “Particle tracking velocimetry” (PTV) [15,16]. In PIV the whole flow field is visualized at different points by tracer particles that are illuminated with a sheet of laser light that is pulsed to obtain images of the particles on photographic film or a video [15].

In turn, PVT is based in flow-visualization techniques such as streak photography and stroboscopic photography where the path of the particles is traced by means of multiple exposures or a photograph film with fluorescent markers. In this method you can track the particle displacements that are short compared to the mean spacing between individual particles paths, moreover, it is possible to track individual particles because the number of particle displacements per area of the image is relative small [15].