Powder Technology 269 (2015) 541–547

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Breakage probability of granules during repeated loading

Salman, Alexander Russell *, Sergej Aman, Jürgen Tomas

Mechanical Process Engineering, Institute of Process Engineering, Otto von Guericke University of Magdeburg, Universitätsplatz-2, 39106 Magdeburg, Germany

ARTICLE INFO

Article history:
Received 17 May 2014
Received in revised form 18 September 2014
Accepted 20 September 2014
Available online 28 September 2014

Keywords:
Compression
Impact
Double-impact
Granules
Breakage
Preloading

ABSTRACT

In order to investigate the breakage behaviour of inhomogeneous particulate products such as fine agglomerates i.e. granules, their structural inhomogeneity has to be taken into consideration. In this article, considering the contact at each load during repeated loading, we describe from a micro-mechanical perspective, the differences in the contact area, contact stiffness and fatigue, and from an energetic perspective, the differences in the breakage probability. As model test materials, Geldart D elasto-plastic γ-Al_2O_3 granules had been selected and tested by quasi-static compression, low-velocity dynamic pendulum double-impact and high-velocity dynamic impact using a pneumatic cannon. Furthermore, we also describe the influence of preloading by double-impact on the breakage probability of granules subsequently loaded by dynamic impact.

1. Introduction

In contrast to metals and metalloids, granules consist of several primary particles, which adhere together by adhesion forces at their randomly distributed contacts. Depending on the granulation process, the internal adhesive forces are influenced by the superposition of different interactions forming material bridges i.e. liquid or solid bridges or sinter necks or even interlocking of primary particles [1–3]. Therefore, mechanical behaviour of granules depends upon these randomly distributed micro-binding mechanisms, which result in distributed mechanical properties such as stiffness and strength [4,5]. Thus, estimating product failure (by breakage) of granulated products can be done only by analysing their distributed strength [6–9].

In comparison to single granule loading until failure, repeated loading of single granules resemble much more realistic conditions that occur during industrial processing where granules are exposed to multiple loading events [10,11]. Single granule loading tests allow the isolation and prediction of single granule breakage in industrial systems, in order to develop an understanding of the micro-processes and micro-mechanisms that constitute failure [12]. The breakage behaviour of particulate products has been a topic of research for almost a century. Fig. 1 presents the historical development of understanding the breakage patterns of a spherical rigid particle as a consequence of the micro-crack propagation during elastic and plastic deformation at impact loading.

Khanal et al. [16] observed this breakage pattern i.e. the formation and propagation of micro-cracks leading to primary breakage in coarse agglomerates such as concrete during repeated loading. Antonyuk et al. [17] and Müller et al. [18] observed the same for fine agglomerates such as granules. Furthermore, Antonyuk et al. [17] described the decreasing strength and increasing stiffness with increasing sizes, while Müller et al. [18] described the decreasing strength and stiffness with increasing pore saturation with moisture. Similar findings with additional considerations such as the influences of viscosity and surface tension of moisture content in the granule have been reported in detail by Iveson and Page [19]. The authors showed how viscous effects are negligible during processing of granules at low strain rates and vice versa.

Aman et al. [20] investigated the breakage probability of irregularly shaped particles and showed that in spite of this shape-related inhibition, yet the relationship between the breakage force and breakage energy distribution is linear. Recently, Russell et al. [21] showed that the higher the compressive loading rate, the higher is the compressive load requirement to initiate breakage in granules. In spite of such a comprehensive research background on the description of instantaneous breakage of granules at loading, yet granular dynamics is not sufficiently understood when breakage results during repeated loading. Russell et al. [22] showed experimentally that granules are weakened during repeated compression and eventually break at lower loads in comparison to fresh granules. Nevertheless, the authors showed in [11], that the critical number of constant compressive loads required to initiate breakage shows a wide scatter owing to the highly distributed strength which changes after each compressive load. As a different approach, Beekman et al. [23] investigated the strength of granules in terms of

* Corresponding author. Tel.: +49 391 67 54952; fax: +49 391 67 11160.
E-mail address: alexander.russell@ovgu.de (A. Russell).

http://dx.doi.org/10.1016/j.powtec.2014.09.044
0032-5910/

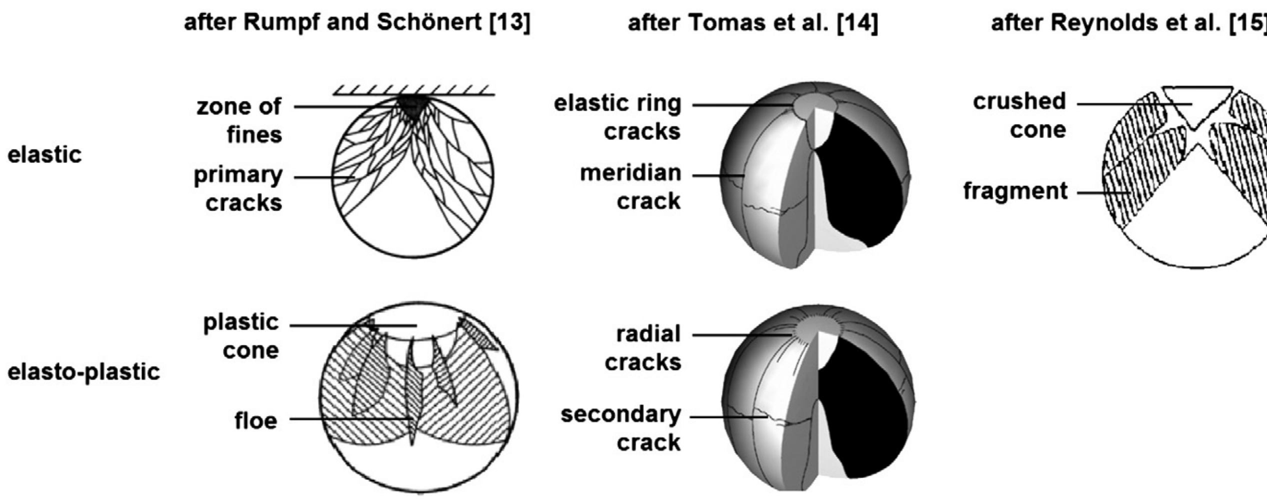

Fig. 1. Cracking patterns in a spherical particle during elastic and plastic deformations at impact loading after Rumpf and Schönert [13], Tomas et al. [14] and Reynolds et al. [15].

their attrition resistance and fatigue lifetime under impact loads. The same procedure was also performed at comparatively lower loading energies by King and Bourgeois [24] and Tavares and King [25]. Their pioneering works confirm that fatigue i.e. damage accumulation ultimately results in progressive weakening leading to breakage of the granule. In contrast to breakage resulting from progressive weakening due to damage accumulation, Petukhov and Kalman [26] reported of the increase in strength during repeated impact loading. This was confirmed by the pioneering works of Kalman and co-workers by integrating the testing methods with comminution systems (see [27,28]).

Furthermore, breakage is always history-dependent, i.e. the number, content and distribution of micro-cracks and dislocations during a loading cycle, varies based on the deformation caused by the previous loading cycles (see [17,21,23]). Therefore, an arrangement of certain loading contacts around a granule's surface generates differences in the intrinsically deforming zones and alters the distributed strength. In this article, we describe results from compression and impact tests, which are appropriate experimental endeavours to investigate the strength of single granules at low and high strain rates, respectively. While investigating the strength of a granule by repeated compressive loading, the contacts had been controlled and arranged appropriately as desired. On the other hand, during impact of a granule using a pneumatic cannon, the granules had been loaded at randomly distributed contacts. Furthermore, we also describe the influence of preloading by pendulum double-impact on the breakage probability of granules subsequently loaded by pneumatic impact.

2. Theory and models

2.1. Stress state

During compression of a comparatively soft spherical granule with a smooth stiff punch (flat surface), the deformable granule's contact area deforms as a circle with radius r_K (Fig. 2a).

The contact radius r_K and the internal pressure distribution p depend upon the stiffness and the radius of curvature of the granule $1/r$. Hertz [29] predicted the elastic pressure distribution $p(r_K)$ to be elliptically distributed within the loaded spherical solid. According to Hertz, the maximum contact pressure occurs at the centre of the contact at depth K. All three principal stresses σ_1, σ_2 and σ_3 at point K can be calculated in terms of pressure (see Antonyuk [17]), while the shear stress τ can be calculated with the well-known failure criterion according to Tresca [30]. The shear stress τ is larger than the maximum tensile stress at the circumference of the contact zone and is responsible for incipient crack generation.

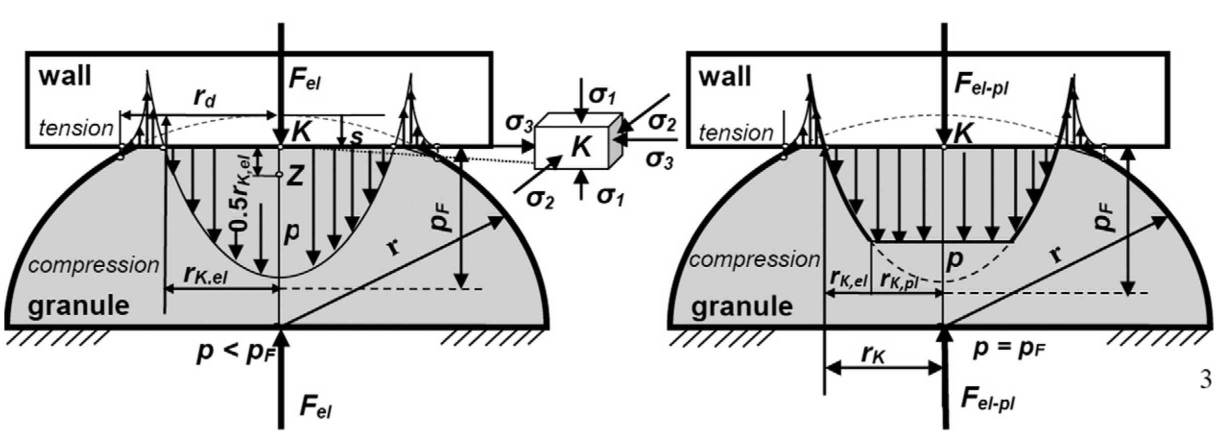

Fig. 2. Stress state during elastic and elasto-plastic deformation (after Antonyuk et al. [17]).