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Dynamic fracture of manufactured powder compacted cylindrical components

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Abstract

A theoretical model for dynamic failure of powder compacts is presented. The model is a modification of Chen's model for brittle materials to adapt with the special features of powder compacts. The model uses the damage mechanics to evaluate a linear isotropic damage parameter (D) from initial damage state of compacts (D_0) to one at the final failure. The initial damage state (D_0) depends on the degree of compaction and the variables incorporated in the compaction process of a pure material with assumed zero damage state.

Series of cylindrical powder compacts made of di-pac sugar, sodium chloride, potassium bromide, and paracetamol d.c. powders are loaded dynamically according to the traditional known diametral compression (Brazilian) test. These materials are typical of the many powders used in the pharmaceutical industry. Thus, these experiments are utilized to obtain the fracture strain rate and the material constants involved in the model. The experimental results are found to be in a very good agreement with the suggested model.

Keywords: Fracture mechanics; Damage theory; Failure analysis of powder compacts; Powder technology

1. Introduction

The demand for higher quality of the increasing varieties of products produced by compaction in a wide range of industries, such like metallurgy, ceramics, plastics and pharmaceuticals, has encouraged detailed research into both the mechanism of powder compaction and the final product mechanical properties and characteristics.

Although it is not perfect, the diametral compression test known as the "Brazilian disc test" has proved very useful in quantitatively describing the strength of the compacts, particularly in the pharmaceutical industry [1–4]. This test has been intensively used over the last few decades, but most of the works reported in the literature tend to utilize it quantitatively to calculate the fracture strength and overlooked the fracture mechanics aspect of this test and the proper analysis of the failure process involved [3,5]. However, with the increasing production rates in the modern industries the need for fundamental understanding of the dynamics of the compaction and fracture patterns is highly essential [4,6–8]. Unfortunately in powder compacted components, the Brazilian test usually carried out at low speeds of compression load application. In fact, to the author's knowledge, very few attempts were made to study the failure behavior in powder compacts under shock loading [9,10].

Generally, fracture mechanics and failure mechanisms investigations have progressed well in the last 20 years [6–8,11,12]. Nevertheless, dynamic fracture is not addressed until recently when crack behavior such as curvings and branchings are correlated with microstructural response [4,13]. It became known that, failure modes of materials are dominated by the loading characteristics and the structure of the materials [6,14,15]. However, for materials subjected to high strain rate type of loading, dynamic effects cannot be ignored [4,16]. Transient dynamic effects may cause the failure modes appeared differently, because of the high frequency of loading actions.

The dynamic failure of ductile metals was extensively studied by considering the failure process as being initiated by the nucleation of voids around inclusions and their subsequent growth and coalescence, as suggested by McClintock [17] and applied by Riceand and Tracey [18] and others [19–22]. Also, dynamic failure of brittle materials receives considerable attention by many investigators. Bless [23], working on ceramics found some correlations between the dynamic failure of such material and their bulk properties such as the bulk modulus, confined compressive

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strength, Hugoniat elastic limit (i.e. shock strength) and tensile strength.

It is important to state that, in spite of the vast amount of information available in the field of powder technology, there are little or no attempts that could be sighted in the literature describing quantitatively or analyzing theoretically the dynamic failure of powder compacts. This could be due to the fact that, it is extremely difficult to model the compaction process and consequently the final compact [8,14,15,24]. The large number of compaction parameters and the overlapping and changing mechanisms involved makes it almost impossible to find a general constitutive equation to describe the whole process [14,15]. Consequently the, strength, mechanical properties and rupture of such materials which depend strongly on many factors such as, the powder characteristics, compression method and pressure, the rate of load application, the die and punches shape used in manufacturing, etc. [6,7,24].

In this work, a theoretical model and complete analysis for the failure behavior of cylindrical powder compacts under dynamic diametral compression loading is presented. This model is a modification of Chen's [25] model for dynamic fracture of rocks. The modifications in the proposed model take into consideration the differences between the powder compacts and the rocks. In addition, the suggested model considers the compacted material as a material initially damaged by a certain quantity of damage (D_0). This initial damage depends on the manufacturing parameters for each compact. The model applies the damage mechanics to evaluate a damage variable (D) which changes from (D_0) at the initial conditions of the compact to one at the complete fracture. The model is based on the strain rate dependent brittle fracture for a material contains randomly distributed cracks [25]. The model is tested and verified by experimentally obtained results on several types of powder compacts encountered in the pharmaceutical industry.

2. Analytical model

The powder compacts could be considered as a homogeneous material permeated by an array of randomly distributed cracks. The size, number, and shape of cracks depend on the bonding mechanism and the manufacturing parameters. These microcracks grow and interact with one another, when loaded, up to final failure. In such case, therefore, continuous damage mechanics seems to be a good way to model the failure of powder compacts. Continuous damage means that the mechanical effects of progressive microcracking represented by a set of state variables, which act on the elastic and/or plastic behavior of the material at the macroscopic level [26]. Krajeinovic [27] defined the damage variable as the ratio of the net area of a material to its initial area in which voids are growing under sustained loads.

Assuming a random array of penny-shaped cracks in an isotropic elastic medium, the damage (D), degrades the material stiffness following the equations derived by Budiansky and O'Connell [28], could be written in the form:

$$D = 1 - \frac{\gamma}{\gamma_0} \tag{1}$$

where γ and γ_0 denote the bulk modulus for damaged and undamaged material, respectively. The constitutive equation with isotropic damage may take the form:

$$\sigma = (1 - D)E\varepsilon \tag{2}$$

with E as the initial elasticity tensor of the virgin material, σ and ε the stress and strain tensors.

In Chen's model, the damage is related to the damaged Poisson's ratio ν and crack density parameter, C_d, through:

$$D = 1 - \frac{16}{9}\frac{1-\nu^2}{1-2\nu_0}C_\text{d} \tag{3}$$

where ν_0 is the undamaged Poisson's ratio, and

$$C_\text{d} = \frac{45}{16}\frac{(\nu_0-\nu)(2-\nu)}{(1-\nu^2)[10\nu-\nu_0(1+3\nu)]} \tag{4}$$

In powder compacts, the initial crack density could be estimated from the relation between the density of the pure material and that of the compacted material, which is known as "the relative density" of the compacts.

Following the work of Kipp and Grady [29], and Grady [30] on oil shale, Chen [25] correlated the crack density parameter in brittle materials to the material properties, pressure level, and strain rate through the expression:

$$C_\text{d} = \frac{5}{2}\frac{k}{(3K)^m}\left(\frac{K_\text{IC}}{\rho C}\right)^2 p^m \dot{\varepsilon}_\text{max}^{-2} \tag{5}$$

where k and m are material constraints determined experimentally, K the bulk modulus, K_IC the material fracture toughness, C the uniaxial wave speed, ρ the mass density, p the pressure level, and $\dot{\varepsilon}_\text{max}$ is the maximum volumetric strain rate experienced through the fracture process.

Knowing the material constraints (k, m), Eq. (5) could be used to determine the crack density parameter C_d of the damaged material. Consequently, the damaged Poisson's ratio could be obtained from Eq. (4) and the value of damage (D) from Eq. (3).

3. Materials and experimental techniques

The dynamic diametral compression test is carried out on compacts made from di-pac sugar, potassium bromide, paracetamol d.c., and sodium chloride. The loading set-up consists of a lower hard steel plate, 10 mm thick, and an upper guided moving mass of 2 kg.

In all the cases, a high-speed camera (IMACON 760), using Polaroid films and complete with a flash unit, observes the crack initiation, propagation, and the final failure of the compacts. To carry out the high-speed photography of these samples, the compacts are placed on the top of the lower plate edge wise, then a piece of aluminium foil is placed as near as possible to sample top, which in turn is connected to the triggering switch on the high-speed flash and camera units. Then, the triggering circuit completed by connecting the upper falling mass to the same triggering switch in the flash and camera. With the camera switch on "ready" and the tub mass raised to the required height of 290 mm, the trigger switch is adjusted. The tub mass is then allowed to fall onto the specimen. As soon as it touches the aluminium foil, closes the triggering circuit and operates the high-speed flash and camera, and a 10-frame picture succession covering a time of 100 μs is obtained. In this manner, three good pictures for each material are obtained for subsequent analysis. A typical picture obtained for di-pac sugar sample is displayed in Fig. 1. For more details and analysis regarding the materials characteristics, specifications, equipments, measurements and experimental techniques, the work of Es-Saheb [9] can be consulted.