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(RESEARCH ARTICLE)

The cumulative breakage probability by repeated stressing of γ-Al_2O_3 granules

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Abstract

The cumulative breakage probability by repeated stressing of γ-Al_2O_3 granules, was described using two models. The first model, where breakage probability by single stressing of granules remains constant, was not suitable for repeated stressing. The model was inappropriate to determine the change in the particle's microstructure during stressing. Whereas in the second model, the hardening effect to be taken into account during stressing and was defined by a reduction factor of breakage probability. The deformation behavior of granules was used to indicate the change of microstructure of particles during stressing. In this case, the stiffness of the granules increased by means of plastic yielding and consolidation granules. In the compression test, the stiffness increased rapidly through fixed treatment. Meanwhile, in the case of rotated treatment the stiffness was significantly unaffected, as it was randomly distributed throughout the particle surface. Consequently, the cumulative breakage probability of rotated granules was lower compared to the fixed one.

Keywords: Breakage Probability; Granules; Stressing Model; γ-Al_2O_3.

1. Introduction

Granules shatter unintentionally in handling and conveying systems when the particles go through multiple stressful events. This cyclic straining may be the source of the harm that is called fatigue. A range of disciplines evaluated how granules behaved under cyclic stress. Numerous researchers have examined particulate matter through integrated industrial settings, such as drop tests [1-2], air-gun fatigue testing [3-4], compression testing [5-6], and other methods

Pandey et al. [7] presented a nonlinear system that applies stress to a single particle until it fractures. Srinivasan et al. [8] has presented an innovative model based on continuum fracture mechanics to explain breakage by recurrent low-energy straining. Particle breakage was shown to be the final outcome of the fractures that build from single hits and the cumulative weakening that occurs after repeated collisions. Based on their past, the repeated hits reveal details about the particles' breakage behavior. Sergej et al. [9] offered a few techniques that enable characterizing granules by their fatigue lifetime, breaking mechanism under impact loads, and attrition resistance. Tavares et al. [10] shown that the strength of the examined particles increased with the stressing number in the context of repeated stressing. Only the stronger particles in this instance survived and were fed to the next stressful event, whereas the weaker particles broke. Conversely, the buildup of microcracks brought on by repetitive straining should cause the strength of the particles that survive to decrease.

Repeated straining causes materials to deform, which results in breakage at stresses that are much lower than the fracture stress during a single stressing event [11]. By utilizing the Wöhler curve, Toribio et al. [12] determined that the number of cycles up to the fracture decreases with increasing stress amplitude. Research on agglomerates and solid particles shows that repetitive straining has a significant impact on deformation behavior. During impact, Wenhao [13] reported that the elastic-plastic stiffness of the particles increased.

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The material's resistance to loading is influenced by changes in the microstructure of the particles. With repetitive deformation, the contact stiffness increases in the normal direction [14]. Granule breakage behavior during compression is an intriguing area of study. Understanding the force-displacement characteristics of granules brought on by frequent straining is essential. However, the research detailed here take into account particle behavior without accounting for the possibility that the stress is applied to fixed or different sites on the particle surface. This fact can have a major impact on the particle strength and deformation. Repetitive straining at a particular stressing point will dominate the development of microcracks with gradual weakening [4]. Granule consolidation results in an increase in granule stiffness [15]. Granule consolidation is accompanied by the formation of microcracks, or the breaking of bridges between initial particles. It is possible to identify the weak points of particles with low strength by adjusting the point of stressing. The more stressing there is, the higher the probability of breaking.

2. Material and methods

2.1 Experiment Setup

2.1.1 Double-Impact Equipment

Double impact equipment was designed to analyze the behavior of particles subjected to repeated stress concerning the point of impact (see Fig. 1a). The particle is struck by dropping a leveling load from a specified height. It is secured onto a robust metal plate composed of tungsten carbide. γ-Al_2O_3 granules, with diameters ranging from 1.62 to 2.50 mm, were utilized as the model material to assess the likelihood of breakage under double impact conditions. During the experiments, the particle was positioned in two configurations: fixed and rotated.

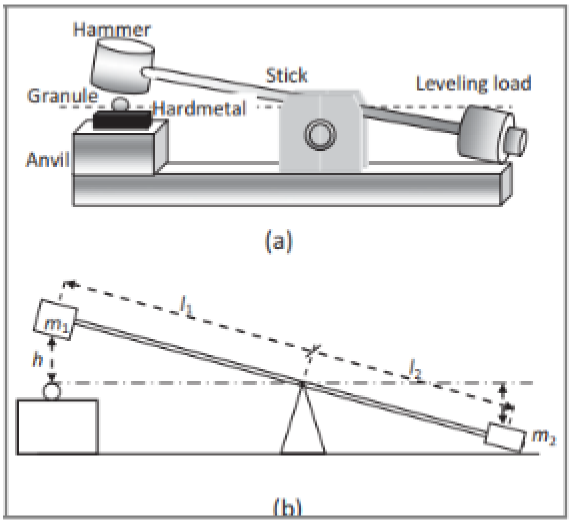

Figure 1 Equipment for conducting double impact tests along with the schematic diagram of the apparatus.

2.1.2 Breakage Probability Models

Initially, the model is described in which the breakage probability (w) for each individual particle under stress remains unchanged, meaning it is not influenced by the frequency of stressing events (i) or the characteristics of the particles. According to this model, there is an absence of plastic yielding and granule consolidation during the stressing process. The quantity of particles that break (N_b) following the initial stressing is

$$N_b = N_0 w \quad (1)$$

The N_0 represents the initial quantity of particles, while w denotes the probability of breakage occurring during any given event. The count of unbroken particles following the initial stress application is:

$$N_{nb}(1) = N_0(1 - w) \quad (2)$$

The quantity of intact particles following the second application of stress can be determined as follows:

$$N_{nb}(2) = N_0(1 - w)^2 \quad (3)$$

The quantity of particles that remain intact following n stress events is:

$$N_{nb}(n) = N_0(1 - w)^n \quad (4)$$

As a result, the quantity of fractured particles is:

$$N_{nb}(n) = N_0 - N_{nb}(1-w)^n \quad (5)$$

The overall probability of breakage after *n* stressing events is expressed as follows:

$$P(n) = N_b/N_0 = 1-(1-w)^n \quad (6)$$

Granules within comminution, handling, and conveying systems undergo multiple instances of stress. This cyclic stress can lead to material degradation, which is generally an undesirable phenomenon. Such degradation can result in challenges related to dust generation, alterations in material properties, and a decline in product quality. Consequently, the subsequent model incorporates the variations in particle characteristics. In this scenario, the probability of breakage is diminished due to the hardening that occurs following each stress event. As a result, this model is referred to as the hardening model. To quantify the extent of hardening, the parameter $q < 1$ has been introduced. After i instances of stress, the breakage probability $w(i)$ is reduced according to:

$$w(i) = qw(i-1) = q^{i-1}w_0 \quad (7)$$

The initial breakage probability is denoted as w_0. The calculation of the number of broken particles following the initial stress application was performed using the following method:

$$N_b(1) = N_0 w_0 \quad (8)$$

As a result, the quantity of intact particles following the initial stress application was:

$$N_b(1) = N_0(1-w_0) \quad (9)$$

The count of intact particles following the second and i-th stressing event was determined by:

$$N_{nb}(2) = N_0(1-w_0)(1-qw_0) \quad (10)$$

$$N_{nb}(n) = N_0(1-\prod_{i=1}^{n}(1-q^{i-1}w_0) \quad (11)$$

Consequently, the quantity of fractured particles following the initial stress application was:

$$N_b(n) = N_0 - N_{nb}(n) = N_0(1-\prod_{i=1}^{n}(1-q^{i-1}w_0)) \quad (12)$$

The results for the cumulative breakage probability were as follows:

$$P(n) = \frac{N_b}{N_0} = 1-\prod_{i=1}^{n}1-q^{i-1}w_0) \quad (13)$$

2.2 Energy of double impact

The equipment model's suitable weight and height combinations are chosen to calculate the impact energy (E_{imp}). To fine-tune the impact energy, change the distance between the hammer and the hard metal. The energy of each impact was determined by adding the difference between height (h_0) and m_1, with $m_{1,2}$ representing the mass of the load and leveling load, $h_{1,2}$ representing the height of the hammer and leveling load, and q representing the weight of unit length of stick. This calculation followed the formula in Fig. 1b.

Not all of the energy supplied by the striker is utilized to break the particle in the twofold impact test. Some residual energy can be computed using Eq. (14) [7] and is still available for the striker to restitution (rebound). The ability to quantify the percentage of energy genuinely absorbed by the particle by determining the striker's leftover energy is one benefit of the twofold impact test.

The ratio of energy absorption (e_n) to elastic strain energy is independent of the amount of the maximum load [7]. The apparatus establishes a lever principle with a weight and fulcrum. The lever weight gains potential energy (E_{imp}) upon lifting, and impact energy is presented by the moment of inertia at the fulcrum.

Through the introduction of e_n, E_{imp} becomes:

$$E_{imp} = Ee_n \quad (14)$$

With

$$E = m_1gh_1 - m_2gh_2 + \frac{\rho l_1}{2} - \rho l_2/2 \quad (15)$$

2.3 Compression Testing by Repeated Stressing

A compression test was used to examine the impact of repetitive stresses on the deformation behavior of granules. The technology utilized to measure granule strength was a contemporary one from Etewe GmbH in Karlsruhe. Granules with a size range of 0.05 to 20 mm, a maximum breakage force of 1 kN, and a stressing velocity (deformation rate) of 0.01 to 2.5 mm s–1 can all be tested for compression with this apparatus (Fig. 2).

Figure 2 Compression test.

A controlled rate of axial deformation is applied when applying the axial stress. The punch crushes the granule up to the specified force as it travels toward the top fixed plate during the repeated compression test. After that, the punch descends to release its load. A CCD camera can capture the breaking process. Measurements were made of the displacement, force, and time during the straining.

As a model material, the 1.62–2.50 mm-diameter γ-Al_2O_3 granules were also utilized to examine the breakage likelihood under compression straining. In every experiment, 200 particles were tested at varying stressing velocities (v_B) between 0.02 and 0.15-mm s–1. Five stresses were applied to each particle. The experiment was conducted utilizing two treatments, a fixed treatment and a rotating treatment, just like in the prior protocol. In the past, the particle was visibly marked with a basic-colored pencil to prevent the same point from being emphasized repeatedly.

3. Results and discussion

3.1 Probability of Breakage under Double Impact

Two models—the constant and the reduced breakage probability model—were used to characterize the breakage probability during cyclic stressing. According to a constant model of breakage probability for both repeated and fixed loading, the breakage probability based on the stressing number in Fig. 3 was fitted.

For both fixed and rotating stressing, there were differences in the measured breakage probability by first stressing (w_0). The initial breakage risk had a tiny difference (about 2%) but increased due to the repeated multiplication that occurs throughout calculating. It is evident that the repeated stressing test for both fixed and rotational grains cannot be fitted by the model of constant probability.

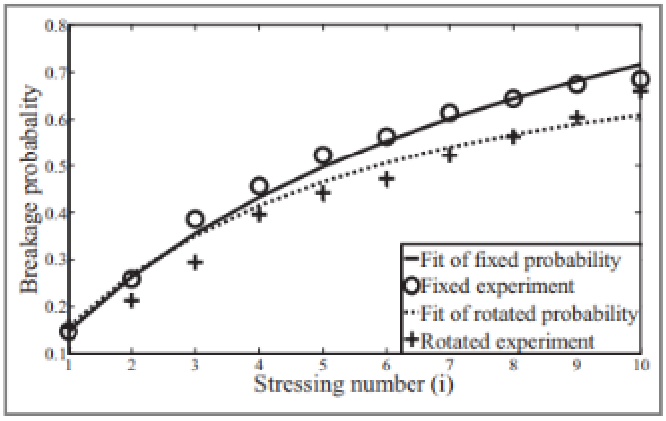

Figure 3 Data fit according to the hardening model. The chance of cumulative breakage was calculated for both rotational and stationary grains.

There was a difference between the model-calculated cumulative breakage probability and the one that was observed. Examining the hardening model in this context for a drop in breakage likelihood following stressing is intriguing. Rotated granules were found to be stronger than fixed ones, according to the results of applying the hardening model as presented in Eq. (14) to the data. As a result, it was discovered that the breakage probability of fixed granules was lower than that of rotational granules.

3.2 Result of Repeated Compression

Investigating the granules' deformation behavior allowed researchers to better understand the impact of repetitive straining. According to the hardening model, the granule's stiffness increased with each stressing cycle. It happened as a result of the material strengthening caused by plastic yielding and the creation of dislocation. A certain amount of granule structural consolidation resulted from the plastic yielding of the solid bridge link. Increasing stiffness was the defining characteristic of the elastic-plastic deformation behavior. For granulates receiving a fixed and rotating treatment, this behavior was different. Compared to the rotating treatment, the fixed treatment experienced a higher intensity of dislocation development. As a result, as shown by the force-displacement curves in Fig. 4 and 5, the stiffness of fixed granules rose even further.

The repeated stressing under compression test was set up at the force F at 0,15 that corresponds to 15 % of breakage probability by single stressing. The same magnitude of initial breakage probability was performed by double impact test.

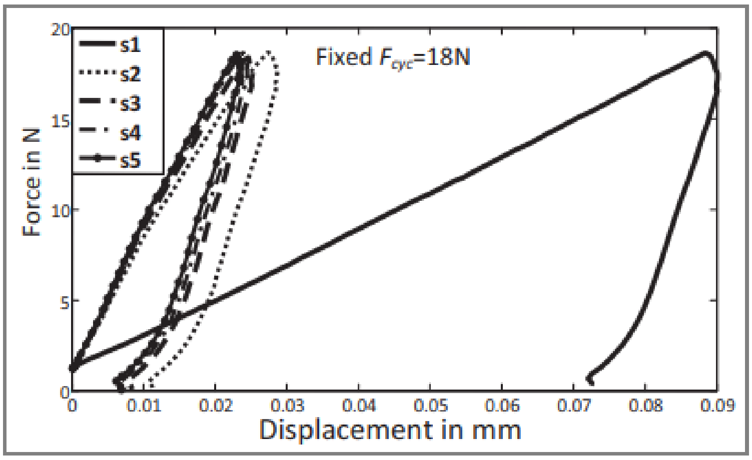

Figure 4 Curves showing force displacement obtained from repeatedly compressing stationary grains. S_n is the number that is stressed.

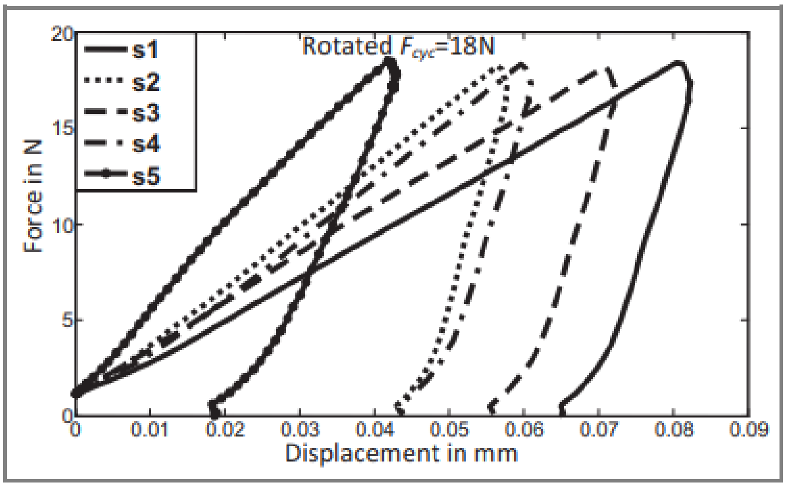

Figure 5 Force-displacement curves produced when rotating granules are repeatedly compressed.

In case of fixed granules, the large elastic-plastic deformation was performed at first stressing (s_1). The reduction of deformation showed a stiffening effect during repeated stressing which was obviously represented by the stressing sequence s_n.

The term "cyclic stiffening" or "hardening" refers to the material's structural change, which is particularly noticeable at the fixed contact sites where significant stresses are present. Structure is consolidated through the straining of fixed granules.

When granules were treated in a rotating manner, the stiffness tended to disperse erratically and may have been minimally impacted by the stressing number. The elastic-plastic deformation behavior at initial stressing s_1 during the fixed treatment was comparable to the elastic-plastic deformation behavior. In all stressful events, the deformation behavior was essentially the same. It appears that the stressing sequence s_n curves were dispersed at random. The stress sites on the granule's surface were dispersed at random during the rotating treatment, which had less of an impact on the mechanical structure. The material's structure at the contact locations is unaffected by the cyclic loading. Treatment rotation did not significantly increase the number of stressed individuals, causing dislocation and consolidation. Consequently, compared to the rotating method, the breakage chance is higher in the fixed treatment.

The number of stressing events ($s_{1\text{-}5}$) does not significantly alter the elastic-plastic deformation behavior, which is dependent on the stressing point. Depending on the straining point, the stiffness spread at random.

The results indicate that the stressing energy produced by the fixed and rotating treatments was 0.81 and 0.82 mJ, respectively, and hence they are regarded as equal. It also amply shown how much less stressful energy there was in a compression test than there was in a double-impact test.

4. Conclusion

Two models were used to characterize the cumulative breakage, or probability, caused by repeatedly straining γ-Al_2O_3 granules. The first model was unsuitable for repeated stressing because it assumed a constant breakage probability due to a single stressing of granules. The model was unsuitable for determining how the microstructure of the particle changed under stress.

In contrast, the second model described the hardening impact to be considered during stressing by a breakage probability reduction factor. Granule deformation behavior was utilized to show how the microstructure of the particles changed under stress. In this instance, the use of plastic yielding and consolidation grains enhanced the granules' rigidity.

With fixed treatment, the stiffness rose quickly in the compression test. On the other hand, since the stiffness in the rotational treatment was dispersed randomly across the particle surface, it remained mostly unchanged. As a result, the rotating granules' cumulative breakage probability was smaller than the fixed one.

Compliance with ethical standard

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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