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Computational investigation of impact attrition of particles

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ABSTRACT

The attrition of particles plays an important role in process engineering due to the large effects on the technical processes. In the present work, the possibility of using the Finite Element Method (FEM) for analyzing the attrition of single particles was investigated. Besides the energy based and system specific models, an experimentally verified theoretical model for calculating the attrition of semi-brittle particles was selected, which served as the reference work. Particle-plate models with a regular hexahedral particle geometry and particle edge lengths of 2, 3, 4 and 5 mm were created. The target plate was assumed to be rigid, while the particle is defined within a Lagrange reference frame. After the geometries were created, a fine mesh was generated and the grid study has been carried out for each model to get the optimum computational grid. First, the particle attrition of magnesium oxide and sodium chloride was simulated by application of the geometric strain factor and the corresponding deletion of highly distorted elements from the impact region. Finding and verification of the optimum geometric strain factors were based on the experimental results of the reference work. Afterwards, both the effects of the impact velocity and particle size on the particle attrition were examined. In the theoretical model, the fractional mass loss is given as a linear function of the particle size. However, the experimental and simulation results have an almost asymptotic behavior with a trend towards a constant value. This means that the proportionality factor of the theoretical model for the particle size parameter should be further investigated and modified. Furthermore, the attrition of aluminum nitride was modeled by using the empirical material failure model of Johnson–Holmquist 2. Since this material has not been experimentally investigated, the comparison was followed by using the theoretical model results. The results of aluminum nitride attrition as a function of the impact velocity and particle size exhibited the same trend as the experimentally investigated magnesium oxide particle.

1. Introduction

By carrying out the literature survey, it is found that almost all the recent research works relating to the particle attrition and breakage are empirical works. Moreover, these are usually only valid for specific systems in combination with a defined apparatus and/or process. Examples of the energy-based models can be mentioned such as Rittinger model [1] for particle breakage and the model of Kelsall et al. [2] for a continuous grinding process. Furthermore, a series of practical works were carried out on the breakage of particles in fluidized beds. Forsythe and Hertwig [3] studied the breakage of catalytic particles by means of a high-speed air jet. Ray and Jiang [4] investigated the breakage behavior of limestone in fluidized beds with bubbles. Salman et al. [5] studied experimentally the fragmentation of particles specifically as a function of the impact velocity and impact angle but did not study the particle attrition. The attrition of a single semi-brittle particle due to the impact with a target surface was investigated by Ghadiri and Zhang [6,7]. They have also developed a mechanistical model based on the theory of fracture mechanics with which the particle attrition of different semi-brittle materials can be predicted. They [7] have validated their theoretical model by experimental results. The mass loss of a single particle which impinges to a hard ductile surface was measured precisely by particle weight measurement before and after the impact. High-speed camera was also used to capture the particle behavior before, during and after the impact in order to observe the particle rebound characteristics. The experimental results and the developed theoretical model of Ghadiri and Zhang [6,7] represent the optimal reference work for the current study of particle attrition using FEM modeling. The experimental setup, implementation and boundary conditions of the experimental measurements of particle attrition are described shortly in this work. Experimental tests are modeled by generating the geometry of the particle and target plate and finding an optimum computational grid. The material models and the applied element erosion model are presented. Finally, the simulation results are compared and validated by both the experimental data and the results gained from the theoretical model of Ghadiri and Zhang [6,7].

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2. Description of the experiments

In experimental study of particle attrition by Zhang and Ghadiri [6], three materials namely as magnesium oxide (MgO), sodium chloride (NaCl) and potassium chloride (KCl) were investigated. The regular hexahedron (cubic) particles with edge length sizes of 2, 3, 4 and 5 mm were used in the experiments. Use of such materials was based on their extensive available knowledge and also their great practical relevance. In addition, a variety of other materials show the same attrition behavior. The particle size was determined using a caliper with a measuring tolerance of 0.02 mm. Furthermore, each particle was analyzed before the test with a light microscope for possible available processing damages such as cracks. The material loss due to particle attrition was determined gravimetrically using a high precision balance with a precision of 10^{-6} g. In this case, the mass loss per particle after 5, 10, 15 and 20 impacts was measured. Due to the precise weight measurement and the subsequent calculation of the fractional loss based on the original mass, the error in experimental results was found to be very small. The fractional loss is calculated with the following equation:

$$\xi_{0,N} = \frac{1}{N}\frac{M(0)-M(N)}{M(0)} \tag{1}$$

where M(0) is the initial mass of the particle and M(N) is the mass of the particle after the N^{th} impact. The experimentally investigated impact velocities associated with the respective materials are listed in Table 1.

For magnesium oxide with edge size of 2 mm, the minimum tested impact velocity was 4.5 m/s, which corresponds to the particle velocity in free fall from particle holder to the target surface. The minimum impact velocity of sodium chloride and potassium chloride was 4.3 m/s. The investigated impact velocities of 5.5 m/s and 8.4 m/s were the same for all three materials.

3. Theoretical model

As mentioned earlier, there are some empirical, mostly process-dependent models for description of the particle attrition. Ghadiri and Zhang [7] noted that none of the models describe the influence of material properties and forces on the attrition rate. Therefore, none of the models provide an insight into the attrition process. In their model, the mechanical failure of a single particle due to the impact on a rigid target plate in a range of velocities was examined. This range coincides with the usual impact velocities in industrial processes. This was done by application of fracture mechanics. The single particle analysis reduced the analysis complexity and enabled more precise measurements. It is known that the brittle particles break due to the generated cracks under exposure to stresses and strains. Based on the fracture mechanics, the conditions for a breakage of a solid particle can be determined. This is done by the energy which is needed to increase the surface area due to the breakage. This energy is described by the elastic energy stored in the particles [8].

In general, particle attrition occurs due to the surface damage. Surface damage is caused by the formation of near-surface lateral cracks [9]. This process can be referred as chipping. Studies [10] have shown that brittle materials follow the chipping mechanism when they are impacting on a target surface. The impact ensures the plastic deformation of the impacted area and the near-surface cracks development. These cracks are known to be mainly responsible for material removal and thus the particle attrition. In addition, radial tiny cracks generated at the low impact velocities do not affect the wear. In fact they do not penetrate far enough into the particle. However, at high impact velocities, radial cracks cause the particle to be fragmented. This process is related to the grinding and breakage processes and therefore, is not considered in this work. A series of works were carried out to study the damage due to the impact of a projectile on a target plate. The analysis of such damage is usually done by quasi-static impact of a projectile [11,12]. The theoretical model is essentially based on the impact analysis, coupled with dynamic impact properties. Earlier works [10] showed that the crack shape of the impacted corner of a particle is identical to that of a flat surface impacted by an indenter. By impact fracture, there is a critical parameter of the indentation above which the fracture is induced. This parameter is defined with the following equation [13–15]:

$$r_c \cong \alpha' \frac{E\Gamma}{Y^2} \tag{2}$$

where α' is a constant, E is the elasticity modulus, Γ is the surface fracture energy and Y is the yield point stress. For development of lateral cracks, the functional relationship between the critical parameter of the indentation (r_c) and material properties is of a great importance. Eq. (3) developed by Ghadiri and Zhang [7] describes the fractional loss caused by the impact, depending on the material properties and impact conditions. It should be noted that based on this model, the fractional loss (ξ) is proportional to the incident kinetic energy (v: impact velocity) and varies linearly with the particle size (l: characteristic particle size). The parameter group H/K_c^2 describes the ratio of material resistance to deformation and fracture as follows:

$$\xi \propto \frac{\rho v^2 l H}{{K_c}^2} \tag{3}$$

where ρ is the particle density, H is the hardness and K_c is the fracture toughness. It turns out that high values of hardness leads to chipping mechanism, where the materials with low hardness have greater tendency to deform plastically without losing much material [7]. When using Eq. (3), it is possible to introduce a proportionality factor to fit the theoretical results to the experimental data. One way to find out the proportionality factor is the use of a theoretical approach. The second method is the experimental determination of the constant. It was proved that a single proportionality factor for various materials that have a similar failure behavior is valid. The factor has to reflect only the chipping mechanism of the geometry. With this assumption, a dimensionless attrition tendency parameter (η) can be defined as Eq. (4) [7].

$$\eta = \alpha \frac{\rho v^2 l H}{{K_c}^2} \tag{4}$$

where α is the proportionality factor. Since the fractional loss per impact (ξ) is proportional to attrition tendency parameter (η), the following equation can be derived:

$$\xi = \alpha\eta. \tag{5}$$

4. Modeling

The settings of simulations were defined in the “Explicit Dynamics” program. This allows to fully describe the model and to define the

Table 1
Experimentally investigated impact velocities for various materials.

Impact velocity v_i (m/s)	Magnesium oxide (MgO)	Sodium chloride (NaCl)	Potassium chloride (KCl)
4.3	–	x	x
4.5	x	–	–
5.5	x	x	x
8.4	x	x	x