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Approach to the breakage behavior of comminuted poplar and corn stover under single impact

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ABSTRACT

Breakage behavior under impact of two different types of biomass resources (poplar and corn stover) is characterized, taking into account the influences of the impact energy, of the number of impacts, of the input particle size and of the material properties itself. Within corn stover, two fractions showed different breakage behavior and they were analyzed separately: corn cob and corn stalk and leaves. Biomass resources present several inherent complexities such as its fibrous non-brittle behavior and the non-spherical shape of their particles. Mastercurve formulation for breakage probability (S) based on the resistance of the particles against fracture (f_{mat}) and on the mass specific energy which a particle can absorb without fracture ($W_{m,\,min}$) was obtained. Moreover, a new formulation of the new particle population generated after the impact (breakage function, B) was developed incorporating two new material parameters (γ and α) to a power law function. Corn cob showed much higher threshold energy for fracture ($W_{m,\,min}$) than corn stalk/leaves and poplar. Furthermore, corn cob presented the highest values of γ and α that represent coarser new particle generation. Corn stalk/leaves and poplar showed more similar material parameters in comparison to corn cob.

1. Introduction

Comminution is one of the most used energy intensive processes in the industrial field, traditionally employed for mineral materials. Regarding the energy sector, intensive comminution is mainly performed for coal in large power plants. However, due to the issue of global warming, a gradual substitution of fossil fuels by renewable energies is necessary. Pulverized biomass may achieve a relevant contribution to this substitution [1–3] in the form of solid biofuel in co-firing power plants [4,5] and domestic or industrial boilers (as pellets or briquettes) [6] as well as liquid biofuel by means of bioethanol production [7].

Previous studies on biomass milling [8–14] have been focused on experimental test campaigns in order to characterize the effects and influences of machine parameters and biomass conditions on the specific energy requirements of the process and on the final quality product (their physical characteristics). Most of the researches dealt the hammer-milling with herbaceous resources such as switchgrass, corn stover, barley straw [8], wheat straw [9] or cardoon [10] as well as forestry resources [11]. Other authors decided to focus on the effects of design or operational mill variables like the hammer width [12], the hammer edge-shape and the hammer tip speed [9,13,14]. These authors also analyzed the effects of these variables on the final particle size.

Additionally, the physical underlying mechanisms involved inside the chamber mill are complex, unknown and random. Multiple factors related to the mechanics of contact and fracture, surface physics and the fracture mechanism are mixed in an intricate and chaotic manner. Comminution processes can be understood as the events related to the material properties and to the mill design itself as well as to the multiple interactions between them. Consequently, the type of loading mechanism against the particle must be in accordance with the breakage behavior of the particle (e.g. compression forces are applied to characterize the granule strength against fracture [15,16]). Inside the chamber mill, the single particle breakage is the expression of the most simple and elemental fracture mechanism. General laws for particle properties relevant to grinding cannot be determined from the first principles, and therefore mean particle properties or methods of probabilistic breakage mechanics have to be employed. Single particle breakage is described by mass statistical distributions as a result of the breakage probability. It can vary noticeably for the same material and at same impact conditions due to the variability in the internal particle defects. Internal flaws facilitate the particle collapse as well as affect the number and the size of the new progeny of particles [17–21]. Breakage behavior under impact can be described by the probability of fracture (breakage probability, S) and the mass size distribution of the new particle progeny from the mother one (breakage function, B), not taking into account the undestroyed particles.

The probability of fracture (S) is higher for larger particle size and under higher impact energy [17,22–26]. Higher impact energy

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($W_{m,\,kin}$) implies higher strain energy in the compressed particle potentially leading to fracture. Higher particle size (x) increases the probability of internal flaws or defects where the cracks begin. Despite of the deep qualitative knowledge of S, its mathematical form is not univocal: Weichert [27] proposed the use of Weibull distribution, Tavares and King [28] used multiple Weibull distributions, the log-normal and upper-truncated log-normal distributions, obtaining good results in many other cases [23,26,28–30]. Vogel and Peukert [31–33] found a novel formulation of S, called "mastercurve", which takes into account all the influencing variables. They defined two new material parameters (f_{mat} and $W_{m,\,min}$) to characterize the particle resistance against fracture by impact and the minimum specific energy threshold, respectively.

Regarding the breakage function (B), it was found also dependent on x and $W_{m,\,kin}$ [22,26,34]. As well as the breakage probability, the mathematical formulation of this function was fitted by different kinds of distributions: Gates–Gaudin–Schuhman, Rosin–Rammler, multi parametric log-normal, power law and others [26,35]. Moreover this distribution was closely related to the experimental phase which one best fits the experimental results.

Fracture response of the material under impact is an intrinsic part of milling models based on population balance model (PBM) or discrete element models (DEMs). The former has been widely developed for mineral applications [17,36,37] from 1970s and the latter are the future on comminution modeling [38–41] through the advances on computational power and techniques. Traditional materials under study were ores which present generally a spherical shape and brittle fracture behavior, and no data or experiences are available in the literature concerning to breakage characterization of biomass resources. Biomass presents also two important drawbacks in comparison to mineral materials that increase the complexity of the process: non-brittle fibrous behavior [42,43] and non-spherical particle shape [44–46].

In the next sections, breakage particle characterization of two different kinds of biomass (poplar and corn stover) is carried out through the single impact test in a commercial lab-scale mill. Section 2 describes the theoretical basis and experimental procedures, Section 3 shows the suitability of the Vogel and Peukert's methodology for the breakage probability (S) characterization for biomass resources, as well as a new formulation of the breakage function of the new progeny of particles. Finally, Section 4 resumes the main results and conclusions.

2. Methodology

2.1. From theoretical approach to experimental application

In order to obtain a widespread method for fracture characterization, Vogel and Peukert [31] found a new formulation for the breakage probability (S) based on two material parameters that define the particle breakage: f_{mat} as the resistance of the particulate material against fracture in impact comminution (kg J^{-1} m^{-1}) and $W_{m,\,min}$ as the expression of the mass specific threshold energy to cause fracture (J kg^{-1}):

$$S = 1 - \exp\left\{-f_{mat} x k \left(W_{m,kin} - W_{m,min}\right)\right\}. \quad (1)$$

This mastercurve allows for the characterization of the fracture probability of a particle under different conditions of impact energy, particle size and number of impacts. Vogel and Peukert [31] validated their theoretical approach with historical data of mono-impacted glass spheres ($0.0095 \le d_p \le 8$ mm) and own single impact tests with several polymers ($2 \le d_p \le 2.5$ mm) in an "ideal" impact device. However, Vogel and Peukert [32] were looking for a practicable procedure, fast and widespread useful test for breakage material characterization. Therefore, they found also very good agreement with a commercial lab-scale mill *Pulverisette-14* (Fritsch GmbH, Fig. 1) and validated the construction of the mastercurve, within an experimental tolerance of ± 15%, for the same materials.

Fig. 1. Lab-scale impact mill (Fritsch GmbH, *Pulverisette 14*).

This theory is one of the more extensively recognized on the description of the breakage probability for brittle and semi-brittle materials [37] and it has been used to model S both in academic [35,37,41,47,48] and in commercial comminution models and softwares [49]. In other studies, it was also found reliable for glass spheres [32,48], polymers, limestone [33,48], pharmaceutical powders [50,35], sand, $Al(OH)_3$ and NaCl [48]. Moreover, the formulation was also incorporated to the widespread JKMR prior art breakage model [51,52] in order to find a new breakage function formulation in which the particle size effect was incorporated [47]. A relationship between the hardness parameters $A \cdot b$ and Vogel and Peukert's parameter was found by Napier-Munn et al. [53].

Nevertheless, it is still unknown if the Vogel and Peukert's methodology also works for fibrous material like biomass. Biomass presents specific characteristics that increase the analysis complexity: 1) non-spherical particle shape and 2) fibrous non-brittle material behavior. Biomass breakage behavior can be mainly classified between elastic–plastic and elastic–viscous at a low temperature and high stressing velocity [43,42]. The aim of this work is to demonstrate if this practicable method with the commercial *Pulverisette-14* is also applicable for the breakage characterization of this kind of materials.

2.2. Biomass

Two biomass, SRF poplar and corn stover, classified like woody and herbaceous biomass (EN 14961-1:2010 EN1 [54]), have been tested in order to analyze the differences on breakage behavior between these groups of biomass resources.

SCF Poplar (*Populus* spp.) was cultivated in Fuente Vaqueros (UTM coordinates: 30N 431306 4118679), province of Granada, south of Spain. Novel fast-growing techniques based on short rotation cycles from 2 to 8 years were applied in order to obtain higher biomass production rates. This specie was selected due to previous satisfactory experiences of implementation in Southern Europe. Corn stover (*Zea Mays* L.) is a residue of corn grain, a traditionally agricultural crop with one of the highest yields of human consumption. Corn stover represents an ideally cheap, renewable and widely available feedstock. It was cultivated in Sariñena (UTM coordinates: 30N, 738030 4629314), province of Zaragoza, northeast of Spain.

After harvesting, both biomass were chipped and subsequently hammer-milled in an experimental pilot plant (facility details in [10,55]). Final comminuted particles presented a moisture content around $w_{H_2O} = 9\%$, a maximum size of 5 mm and a geometric mean diameter around 0.7 mm.

2.3. Test procedure

Materials from milling process were collected and prepared under CEN/TS 14778-1:2005 EX [56] and EN 14780:2011 [57] standard specifications, respectively. Subsequently, the samples were analyzed to obtain the moisture content (standard EN 14774-1:2009 [58]) and they