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Experimental investigation and discrete simulation of fragmentation in expanded breakfast cereals

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ABSTRACT

The fragmentation behaviour of brittle airy cereal product is studied both numerically and experimentally. A cereal food item is subjected to severe compression up to the densification stage. Experimental evidence of typical airy food behaviour is pointed out including elasticity, cell collapse and densification regimes. In order to better explain the observed behaviour, especially the resulting fragmentation, a numerical approach is proposed based on the discrete element method. Predicted results show good agreement with experimental mechanical responses. In particular, the maximum force values for fragmentation and the size of resulting fragments are in good accordance with experiments. Our numerical results show that the observed fragment size distribution is the consequence of a small number of rupture events of cell walls. This result highlights the role of the airy structure associated with a particular tendency to form a bimodal size distribution of fragments.

1. Introduction

Fragmentation of brittle airy solids is a fundamental problem in applied mechanics, and is of considerable scientific and industrial interests (Chau, Wei, Wong, & Yu, 2000; Harireche & McDowell, 2003; Sun & Xu, 2008). A great number of experimental (Peleg, 1997; Peroni, Avalle, & Martella, 2006), numerical (Caty, Maire, Youssef, & Bouchet, 2008; Guo & Gibson, 1999) and analytical (Ford & Gibson, 1998; Kitazono, Sato, & Kuribayashi, 2002) studies on the behaviour of airy materials under quasi-static loading are reported in past decades (D'Addetta et al., 2001). The most important feature may be the following: the behaviour of an airy material can be derived from the properties of the base material (cell wall material) and its relative density with a reasonable accuracy (Ashby & Gibson, 1988). For an airy solid in compression, the stress–strain curve is characterized by three regimes: (1) a linear elastic regime driven by cell edge bending or face stretching, (2) a stress plateau corresponding to progressive cell collapse by elastic buckling, plastic yielding or brittle crushing, depending on the nature of the solid from which the material is made, and (3) densification, corresponding to collapse of the cells throughout the material and subsequent loading of the cell edges and faces against one another.

In food science, resistance to compressive stresses is an important physical signature of the transformed food item as it represents an intrinsic component of its texture (Chen & Opara, 2013; McDowell & Humphreys, 2002). It may represent, moreover, the prevailing mechanism that explains the mastication behaviour of many brittle food products like breakfast cereals (Yven, Guessasma, Chaunier, Della Valle, & Salles, 2010). Mechanical properties of bread also include sponginess because bread has compressive behaviour similar to that of many solid foams (Peleg, Roy, Campanella, & Normand, 1989; Scanlon, Sapirstein, & Fahloul, 2000). In that respect, it is important to distinguish between spongy ductile materials and brittle materials. The compression behaviour of both spongy and brittle food leads to fragmentation but the size characteristics of fragments are affected differently with regard to food texture (Le Bleis, Chaunier, Della Valle, Panouillé, & Réguerre, 2013; Mamlouk & Guessasma, 2013). This study focuses on the brittle behaviour of breakfast cereals.

One of the most determinant factors that affect the compression behaviour is the void arrangement within the airy structure. Determination of key relationships between mechanical parameters and structural attributes attracts much research (Guessasma, Babin, Della Valle, & Dendievel, 2008). In the case of airy starchy products, it is necessary to obtain precise information about the complex 3D structure. (Babin, Della Valle, Dendievel, Lourdin, & Salvo, 2007; Lim & Barigou, 2004). Three-dimensional characterisation and visualisation of porous materials by X-ray tomography become nowadays an important and powerful tool in that respect. The general principle of the tomography technique is described in (Landis & Keane, 2010; Olmos, Martin, Bouvard, Bellet, & Di Michiel, 2009). The technique reveals several key structural features and their evolution for unloaded and loaded samples (Lhuissier, Fallet, Salvo, & Brechet, 2009; Vasic, Grobéty, Kuebler, Graule, & Baumgartner, 2010). Although determined using the most recent imaging advances, this information is incomplete since analytical mechanical models are not capable of handling such complexity. Numerical modelling is then considered as an alternative to relate the structural

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information to some mechanical parameters through adequate simulation (Guessasma, Chaunier, Della Valle, & Lourdin, 2011). Amongst the known techniques, finite element computation is able to predict the mechanical behaviour of various porous medias (Babin, Della Valle, Dendievel, Lassoued, & Salvo, 2005; Guessasma et al., 2008). Finite element approach is known for long in food science as a predictive technique for solving heat and mass transfer problems (Irudayaraj, Haghighi, & Stroshine, 1992; Lomauro & Bakshi, 1985). Few results are available in structural mechanics having a clear focus on mechanical properties of cereals or even of food items. The method is usually accurate when it is used to virtually test porous materials under small strain conditions. However, for large strains, the method is limited by problems related to opposing cell wall contact and distortion of elements. The discrete element method (DEM) is an alternative that avoids the above mentioned drawbacks since it is a mesh free method (Hedjazi, Martin, Guessasma, Della Valle, & Dendievel, 2012; Jauffrès, Liu, & Martin, 2013). It is originally developed to study the dynamics of granular media (Liu, Martin, Delette, & Bouvard, 2010) but it shows its value for the prediction of the mechanical behaviour of polymer and metallic foams (Gibson & Ashby, 1997; Mills & Gilchrist, 2007; Viot, Bouix, Iordanoff, & Lataillade, 2010), where the material is typically represented using a large number of discrete units. It is proposed recently to tackle several challenges related to food fragmentation including texture analysis and human mastication behaviour (Sun & Xu, 2008).

In this paper, we are concerned about the implementation of the discrete element method to study the fragmentation of breakfast cereals. This type of product is a well suitable model for our study since it refers to real food. It has a brittle mechanical behaviour, like other starchy extrudates. This study combines DEM analysis with experimental characterisation of 3D airy structure of a food item, here a breakfast cereal. It relates also the predicted response to the observed mechanical behaviour.

The aim of performing a realistic mechanical modelling of food degradation is to better understand the effect of food structure on degradation mechanisms. The numerical development considered in this work is based on a deterministic approach which contrasts with statistical techniques. Since we solve the set of equations representing the problem of interest, the achieved solution is unique and deterministic. A successful deterministic simulation has the benefit of providing a rational explanation of the observed based on proposed mechanisms.

Such understanding copes with a possible control of food mastication by designing food using degradation criteria. Such criteria should be available through a deterministic model that relates the structure to food fragmentation. We have recently related experimentally oral conditions to degradation of varieties of cereal products (Hedjazi, Guessasma, Yven, Della Valle, & Salles, 2013). In that work, correlations are determined between oral conditions, jaw kinematics and product texture. We concluded that a mechanical background is needed to understand the involved mechanisms. Such understanding can be achieved using a realistic chewing simulation. We believe that this introductory work is a key step to further investigate the mastication process. Our deterministic approach is of particular significance with regard to classical mastication studies (Jalabert-Malbos, Mishellany-Dutour, Woda, & Peyron, 2007; Lenfant, Loret, Pineau, Hartmann, & Martin, 2009). On top of proposing a mechanical scenario for cereal fragmentation, we deal with human chewing as a deterministic process by suggesting quantified and objectively determined parameters that explain the produced fragment size population.

We expect a large impact of the methodology suggested in this work for the design of cereal products. It should be possible to achieve transformed cereals that can adhere to suitable degradation criteria. Our predictive analysis can be used to achieve particular airy structures that can be designed by adjusting processing conditions. This would help food industry towards the delivery of healthy cereals having optimal degradation capabilities.

2. Experimental layout

2.1. Food material

A specific breakfast cereal under the commercial name “Miel Pops”, is selected as model product for this study and purchased at a local supermarket (Fig. 1a). It is called here “the food item”. Its textural properties are determined in a previous paper (Sandoval, Chaunier, Courcoux, & Della Valle, 2008). The chemical composition is as follows: lipids 1%, proteins 5%, starch 55%, sugars 33% and moisture content 3.6% on a total basis. Starch is the major component, which justifies that the overall behaviour of the product is assumed to be similar to the one of starch extrudates. Typical dimensions of the samples are $9.1 \times 11.8 \times 13.3\,\text{mm}^3$.

2.2. Mechanical testing

Mechanical testing is performed to study crushing properties of the product assuming that such test represents the first step of a simplified human mastication process. Crushing properties are considered, in this study, as important to determine the capability of the food item to

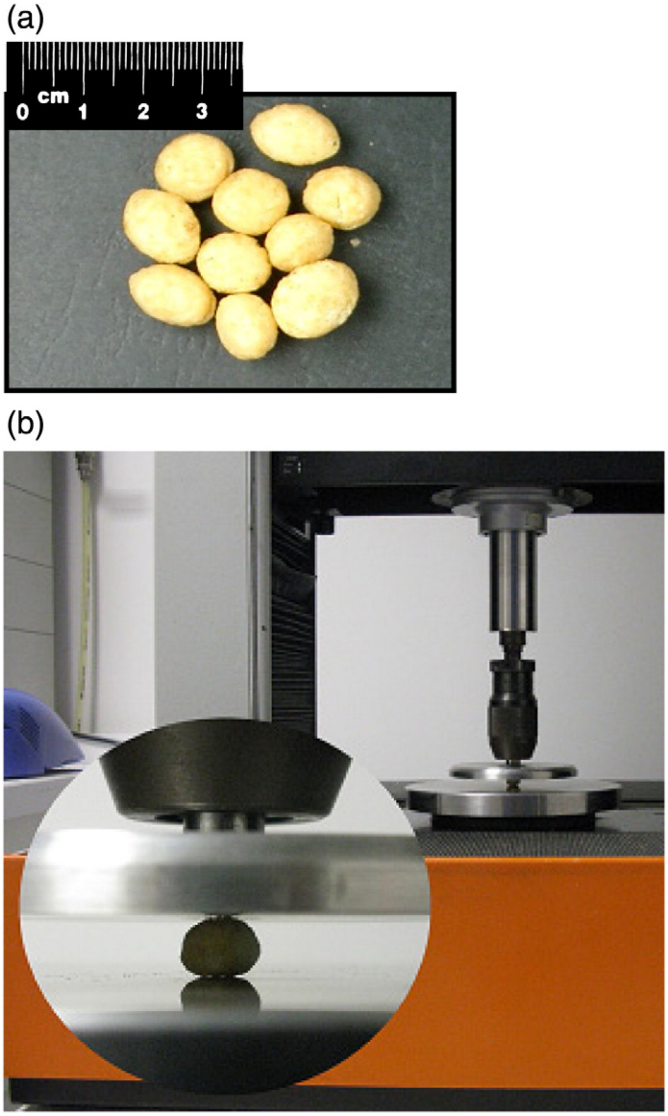

Fig. 1. (a) Breakfast cereal considered in this study. (b) Experimental setup showing uniaxial loading of the food item.