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Volume digital image correlation to assess displacement field in compression loaded bread crumb under X-ray microtomography

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A R T I C L E I N F O

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A B S T R A C T

In this study, we present an original approach to assess structural changes during bread crumb compression using a mechanical testing bench coupled to 3D X-ray microtomography. X-ray images taken at different levels of compression of the bread crumb are processed using image analysis. A subset-based digital volume correlation method is used to achieve the 3D displacement field. Within the limit of the approach, deterministic search strategy is implemented for solving subset displacement in each deformed image with regards to the undeformed one. The predicted displacement field in the transverse directions shows differences that depend on local cell arrangement as confirmed by finite element analysis. The displacement component in the loading direction is affected by the magnitude of imposed displacement and shows more regular change. Large displacement levels in the compression direction are in good agreement with the imposed experimental displacement. The results presented here are promising in a sense of possible identification of local foam properties. New insights are expected to achieve better understanding of structural heterogeneities in the overall perception of the product.

Industrial relevance: Texture evaluation of cereal product is an important aspect for testing consumer acceptability of new designed products. Mechanical evaluation of backed products is a systemic route for determining texture of cereal based product. From the industrial viewpoint, mechanical evaluation allows saving both time and cost compared to panel evaluation. We demonstrate that better understanding of structural changes during texture evaluation can be achieved in addition to texture evaluation. Sensing structural changes during bread crumb compression is achievable by combining novel imaging technique and processing based on image analysis. We present thus an efficient way to predict displacements during compression of freshly baked product. This method can be used in different practical situations such as in plants or labs at the cost of having access to 3D imaging facilities.

1. Introduction

Bread quality is naturally reflected by texture properties for which the porous architecture deserves credit (Gondek et al., 2013; Kilcast & McKenna, 2004; Scanlon & Zghal, 2001). As the main evaluation of bread occurs in the mouth (Szczesniak, 2002), sensory perception of bread "hardness" turns to be related to its relative density (Zghal, Scanlon, & Sapirstein, 2002). This is, in turn, a major descriptor of the cellular structure of bread. Texture determination using mechanical testing presents a systematic tool that may come to compete with panel evaluation of quality (Zghal et al., 2002). For varieties of backed products, mechanical evaluation becomes now a standard of texture evaluation (Clubbs, Vittadini, Shellhammer, & Vodovotz, 2005; Ruttarattanamongkol, Wagner, & Rizvi, 2011). As far as the porous structure is concerned, 3D assessment of the underlying deformation mechanisms is needed to assess the role of microstructure in bread crumb deformation during compression.

X-ray microtomography is a powerful imaging technique that allows 3D description of structural features (Herremans et al., 2013). It is used in situations where 2D classical imaging techniques are insufficient to fully capture microstructural details especially for heterogeneous materials like airy solids (Mamlouk & Guessasma, 2013). In most analysis, 3D static views are acquired allowing the determination of structural quantifiers (Guessasma, Babin, Della Valle, & Dendievel, 2008; Herremans et al., 2013). 3D granulometry techniques, as part of static image analysis, allow the determination of size distributions of features of interest such as voids or struts. Time evolution of these distributions can be also achieved but the technique uses only one image per condition to issue overall characteristics.

The use of granulometry technique to follow the kinetics of foam transformation is, however, inconclusive. For instance, the study of bread mastication relies on the ability to determine deformation within the bread structure. Such deformation is accessible from the first

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derivative of displacement maps. These maps are only achieved by comparing two successive snapshots of the phenomenon.

In the present study, we explore microstructural changes using microtomography when the bread crumb experiences deformation. The load response of a bread crumb compression is typical of an open cellular material. Cells themselves do not deform through compression but the whole load transfer goes to the cell walls. Even if cells are close shapes, which is not the case here, normal stresses on cell walls do take place as a consequence of increasing air pressure inside the cells.

When the imposed displacement is small enough, cell walls elastically bend and deform uniaxially. Further increase of the load leads to a stress plateau, due to cell wall yielding. Cell collapse occurs after few percent of imposed displacement (Guessasma, Chaunier, Della Valle, & Lourdin, 2011) since cell walls yield at relatively low stress. An exponential stress increase is achieved at the densification stage where contact between opposing cell walls becomes predominant.

In this paper, we focus our attention on the technical aspects related to the postprocessing of 3D images. For such purpose, we need to come up with adequate techniques to retrieve time-dependent quantifiers. Several studies combined finite element approaches with X-ray tomography images to obtain numerical deformation and stress maps under given loading conditions (Mamlouk & Guessasma, 2013; Singh et al., 2010; Zhang et al., 2012). Those techniques rely on two aspects: predicting numerically the stress–strain relationship and assuming that the solid material properties remain homogeneous. In this study, we aim at achieving experimental deformation maps using an advanced image processing technique that is able to determine local heterogeneities.

Digital volume correlation (DVC) is a way to capture the heterogeneous kinematics (typically the heterogeneous displacement field) of a complex structure during testing. Using this technique, a sampling of the displacement can be obtained over the whole structure by cross-correlation of the structure image in different configurations (typically, different levels of loading). Image based techniques are very appealing due to three features: (1) they cover a wide variety of scales (from nano tomography, AFM, SEM and microscopy to classical digital cameras), making them useful at almost all engineering scales, (2) they belong to the family of “non-contact” measurement techniques, and sensitive bodies can be observed *in-situ* with minimal perturbations and (3) they strongly capture the heterogeneity of the displacement. These make them the perfect tool for studying complex, heterogeneous structures and a path to identify local material parameters in the structures (Moussawi, Lubineau, Florentin, & Blaysat, 2013).

In this study, a DVC algorithm is used in order to study the deformation of a bread crumb subjected to uniaxial compression. A previous published paper by the same research group (Babin, Della Valle, Dendievel, & Salvo, 2005) related numerically Young's modulus of bread crumb to its relative density. In this work, we are more concerned with local properties through the the experimental determination of displacement maps of bread crumb.

The amount of compression selected is small enough to guarantee linearity between the generated stress and strain in the airy structure. A prevailing cell wall bending deformation mechanism is then expected. Large overall strain values would mean a shift to cell collapse plateau stage, where large modification in the void structure is expected. Bread crumb is known to present a complex airy structure that is closely related to the texture. A typical proof of such relationship is the sensory perception of bread exhibiting distinct relative densities. The local kinematic field should be understood to evaluate the quality of the bread.

The mapping functions used allow for both rigid body motions as well as for displacement gradients within each subset. The interpolation of the deformed image is performed using a bilinear interpolation. Since the predictable displacement can be a fraction of the voxel size, interpolation is needed to evaluate the grey level at positions that are not multiples of a voxel. Interpolation guarantees, by the way, sufficient accuracy in the determination of the displacement components. The initial guess for the iterations over each subset is obtained from neighbouring subsets which have already been analysed. We produce maps of the approximated displacements, densities and residuals for each of the subsets in the bread crumb foam in order to evaluate the relationship between the porosity and the deformation characteristics.

2. Experimental layout

The raw material is a soft white bread from the market. The product is selected based on a homogeneous and small size open porosity. Roughly, the cell size is less than 1 mm for a slice size of about 100 mm and an overall density of 0.19 ± 0.04 g/cm^3. Freshly baked bread is sliced as regular cylinders using a circular sectioning tool. Typical sections of 23 mm in diameter are obtained. Sample height varied from 10.7 to 22.5 mm. Samples are conditioned to avoid excessive drying prior to loading. The initial moisture content is around 49% wb. After sectioning, samples are wrapped in plastic bags to retain moisture. In addition, experiments are performed shortly after sectioning. The moisture loss achieves 5% wb at the end of mechanical testing. Loading is performed using a Deben Microtest Tomography tensile/compression stage especially designed to cope with the X-ray microtomography requirement (Fig. 1). The system is able for example to sustain rotation whilst testing the specimen. Maximum microtest travel is 10 to 20 mm depending on the testing configuration whilst the displacement rate range is 0.1 mm/min to 1 mm/min. The control of displacement is as accurate as 10 μm. The maximum displacement rate (1 mm/min) is selected for all experiments. Compression is performed in the elastic regime up to a maximum average deformation of 2% about the compression axis. The purpose of using small deformation steps is in line with avoiding substantial changes in the airy structure whilst testing the specimen. Different compression levels are performed up to 2%. For the purpose of determination of the displacement field, 3D images are acquired using X-ray microtomography equipment (Metris XTH225 industrial CT scanner). The equipment is based on a microfocus X-ray source offering a spot size as small as 3 μm. A small spot size reduces the number of source–detector paths intersecting in a single point (blurry effect). A finer resolution can be achieved if the equipment has a small focal spot size. But, spatial resolution is also weighted by the source–object–detector distances. Voxel size as small as 3 μm is not achieved in our case because of an optimal source-to-sample distance requirement needed to build the whole sample. We use intermediate resolutions allowing a voxel size ranging from 13 to 17 μm. Note that the displacement control accuracy is lower than the voxel size. Each scan has an average duration of 17 min. The achieved voxel count for the acquired CT volumes varies between 1.13 × 10^9 and 4.67 × 10^9. The following parameters are selected for beam energy of 55–70 keV/ 13.4–14.0 W. We vary the source energy to obtain an optimal

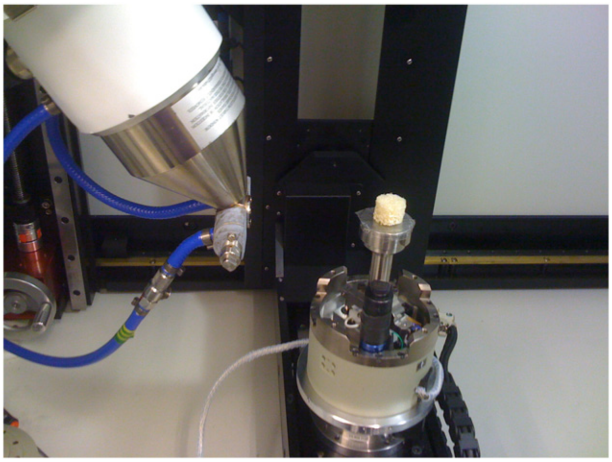

Fig. 1. Experimental set-up used for bread crumb compression with X-ray microtomography (CT scanner).