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Compression behaviour of bread crumb up to densification investigated using X-ray tomography and finite element computation

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ABSTRACT

We propose to shed more light on deformation and structural changes of bread crumb submitted to severe compression. The analysis of such behaviour refers to an adequate approximation of human mastication of airy and spongy products. X-ray microtomography is coupled to mechanical testing of soft bread characterised by a fine cellular architecture. Structural attributes, namely, relative density, cell size and cell wall thickness distributions are determined using image analysis and related to the load level. Kinetics of pore shrinkage is also studied depending on its shape and size. Finite element model is developed to assess mechanical anisotropy induced by deformed airy structure. Results show that the pore content decreases from 72% to 24% after more than 89% of reduction in height. An irregular trend of pore shrinkage is also revealed which depends on deformation stages. Finite element results show a heterogeneous stress distribution but only a minor mechanical anisotropy is revealed as a result of the deformed airy structure.

1. Introduction

Instrumental analysis of bread texture is a constant field of interest through the past decades (Bourne, 1978; Gambaro, Gimenez, Ares, & Gilardi, 2006; Hibberd & Parker, 1985; Lasztity, 1980; Nussinovitch, Steffens, Chinachoti, & Peleg, 1992; Rizzello, Calasso, Campanella, De Angelis, & Gobbetti, 2014; Scanlon, Fahloul, & Sapirstein, 1997). The subject evolved from basic testing procedures (Ofelt, MacMasters, Lacaster, & Senti, 1958; Ponte, Titcomb, & Cotton, 1962) to more sophisticated protocols to sense bread deformation (Moussawi, Xu, Nouri, Guessasma, & Lubineau, 2014). Pioneer contributions aimed at the determination of product firmness using simple mechanical descriptors (Bice & Geddes, 1949; Ofelt et al., 1958; Ponte et al., 1962). Among the mechanical testing possibilities that have been explored, one can mention indentation (Lasztity, 1980; Liu, Chuah, & Scanlon, 2003; Platt & Powers, 1940), shearing (Baruch & Atkins, 1989), compression (Cornford, Axford, & Elton, 1964; Hibberd & Parker, 1985; Keetels, Visser, vanVliet, Jurgens, & Walstra, 1996b) and tension (Chen, Whitney, & Peleg, 1994; Nussinovitch et al., 1992; Scanlon, Sapirstein, & Fahloul, 2000). Resistance to compression is among the best candidates to evaluate bread texture (Martin, Zeleznak, & Hoseney, 1991; Ofelt et al., 1958; Ponte et al., 1962). This quantity represents the firmness of the product. It can be defined as the force required to achieve a certain level of compression.

Other mechanical parameters are extracted from compressive force–displacement curves such as hardness, softness, springiness, cohesiveness, chewiness and resilience (Bice & Geddes, 1949; Gambaro et al., 2006; Rozylo et al., 2014). As pointed out in an earlier work by Bourne and co-worker (Bourne & Comstock, 1981), the degree of compression has a significant effect on texture profile parameters. This effect becomes more pronounced at higher compression levels.

Studies related to direct exploitation of bread force–displacement response are limited since confrontation with other studies is inconclusive if testing conditions or sample dimensions are not the same. Most of the contributions correct such lack of universality by trying to match the result of instrumental testing with sensory evaluation (Brady & Mayer, 1985; Gambaro et al., 2006).

But reaching a standing alone approach is a target for many other studies seeking representative mechanical parameters by a conversion of force–displacement signal to stress–strain equivalent response (Rohm, Jaros, & deHaan, 1997; Scanlon & Zghal, 2001; Scanlon et al., 2000).

Basic mechanical parameters that can be determined from stress–strain response are stiffness, yield stress, strength, deformation at break, recoverable work and toughness (Hibberd & Parker, 1985; Nussinovitch et al., 1992; Scanlon et al., 1997). These mechanical parameters are defined in many research works. Some of them are cited in this paper. Although, these mechanical parameters depend

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significantly on aging (Cornford et al., 1964; Keetels et al., 1996b; Persaud, Faubion, & Ponte, 1990; Piazza & Masi, 1995), the airy structure modulates significantly their magnitude (Zghal, Scanlon, & Sapirstein, 2002). The air content is a typical example of structural attribute that controls nonlinearly the elasticity of airy products (Babin, Della Valle, Dendievel, Lassoued, & Salvo, 2005; Keetels, vanVliet, & Walstra, 1996a; Nussinovitch et al., 1992; Ponte et al., 1962). Bounds can be defined for representative mechanical quantities based on literature work (Babin et al., 2005; Cornford et al., 1964; Keetels et al., 1996a; Lasztity, 1980; Ofelt et al., 1958; Persaud et al., 1990; Piazza & Masi, 1995; Rohm et al., 1997; Scanlon & Zghal, 2001; Scanlon et al., 1997, 2000; Zghal et al., 2002) as follows:

- Under tensile conditions: stiffness (7–18 kPa), yield stress (0.4–1 kPa), strength (0.5–3.0 kPa), and toughness (4–12 J/m^2).
- Under compression conditions: Poisson's ratio (0.17–0.28), stiffness (0.3–176 kPa), and yield stress (4–17 kPa).

The role of bread structure is tackled for different objectives (Chabot, Hood, & Liboff, 1979; Gan, Ellis, Vaughan, & Galliard, 1989; Hayman, Hoseney, & Faubion, 1998; Sandstedt, Schaumburg, & Fleming, 1954). For some studies, the airy structure of the bread reveals textural information that can be approached using image analysis tools (Bertrand, Leguerneve, Marion, Devaux, & Robert, 1992; Sapirstein, Roller, & Bushuk, 1994). Arguments supporting this viewpoint refer to the customer visual evaluation of the product as a genuine sensory attribute. Other contributions focus on microstructural effects that are implied by the transformation process (Chabot et al., 1979; Gan et al., 1989; Martin et al., 1991; Sandstedt et al., 1954). Different structural descriptors can be extracted from image analysis such as relative density, cell density, cell area, cell size and cell wall thickness distributions (Sapirstein et al., 1994; Shimiya & Nakamura, 1997).

A number of these structural descriptors are related to the mechanical behaviour of bread thanks to evolution of instrumental analysis and theoretical background related to the mechanics of cellular solids (Liu et al., 2003).

Despite this accumulated knowledge about structure–mechanical behaviour of bread, such knowledge relates to correlations between overall quantities assuming certain deformation mechanisms to be accurate. The design of experimental set-ups, which combine simultaneously image acquisition and mechanical testing, has led to a clearer view of involved deformation mechanisms. For instance, 2D video recording allows change in lateral expansion (Poisson's ratio) to be captured (Rohm et al., 1997). Also, the emergence of 3D imaging techniques such as X-ray μ-tomography opens new routes to study microstructure and mechanical properties of bread. Measurement of structural attributes such as porosity content is statistically more representative compared to any classical 2D slicing methodology. Indeed, the 3D image can be viewed as a stack of a thousand (in a typical acquisition) of cross-sections. The statistical weight of this measurement is much larger than typical replicates associated with 2D scanners.

From the mechanical viewpoint, virtual testing of bread crumb validates some of the hypothesis about airy structure effect (Babin et al., 2005; Guessasma, Babin, Della Valle, & Dendievel, 2008). X-ray μ-tomography is used, in this work, to study changes in the airy structure including deformation of cell walls and contraction of cells in a large range of compression levels. Finite element computation is used to predict the structural anisotropy induced by deformation. We apply here a recently developed technique that allows handling structural information through the conversion of grey levels into material properties (Guessasma & Hedjazi, 2012; Hedjazi, Guessasma, Della Valle, & Benseddiq, 2011; Mamlouk & Guessasma, 2013; Moussawi et al., 2014). This method becomes meaningful when any change in the resolution induces major structural changes as it is the case for airy structures (missing walls, discontinuities, etc.) (Guessasma et al., 2008). In the former study (Moussawi et al., 2014), mechanical behaviour of bread crumb was investigated at relatively small load levels (i.e., 2% reduction of the sample height). At such levels, conclusions of the study were limited to the elasticity stage. In the present work, severe compression conditions are rather appointed to carry out a comprehensive study including all deformation stages up to the crumb densification. Both works share the same microstructural analysis aiming at quantifying the cell wall thickness and cell size distribution evolutions with respect to the load level. However, in the present work, the large number of load levels reshapes completely the time evolution of all structural attributes. Moreover, anisotropic effects inferred to cell morphology evolution are expressed and discussed.

2. Experimental procedure

Market white bread rated as soft and fluffy is studied. This product is characterised by a large number of fine cells surrounding few large cells. The cell size mixture remains well above the resolutions needed to perform X-ray μ-tomography analysis. The density of the product is 0.46 g/cm^3. Cylinders ($\phi = 23$ mm and $h = 2.44$ mm, where ϕ and h refer to diameter and height, respectively) from freshly baked bread are sectioned. The initial moisture content of samples is close to 50% wb. X-ray μ-tomography acquisition is performed at different compression levels. The heating of the sample induced by X-ray exposition is not an issue when few acquisitions are planned. However, sample heating becomes a serious concern when a large number of compression levels are needed. Preliminary observations show that water content loss after 8 h is 33%. Testing duration is adapted to allow 3D images to be acquired below 20 min per compression level. A micromechanical machine from Deben is used to apply compression simultaneously to X-ray μ-tomography acquisition. Because of the small weight of the airy samples, a risk of structural displacement is possible during X-ray μ-tomography acquisition. This risk is inferred to the rotation of the sample to realize radiographic images. The upper stage of the testing equipment is displaced to apply a minor compression to the sample. This is used as an initial configuration prior real loading of the sample. Maximum microtest travel is 10 to 20 mm depending on the testing configuration. This allows achieving severe compression of the sample while maintaining an accurate displacement level. In the present case, a maximum displacement (Δh) of 8.44 mm is obtained, which represents 68% of the initial height. We define the reduction in height with respect to the original height as an imposed displacement ratio (e), which writes

$$e(\%) = \Delta h / h \tag{1}$$

where h is the height of the unloaded sample. e refers also to the load level or overall engineering strain.

The displacement rate of the micromechanical equipment is in the range (0.1–1) mm/min. The maximum displacement rate (1 mm/min) is selected to lower the acquisition duration. Up to 13 different levels of compression are used. The control of displacement is as accurate as 10 μm. The displacement increment varies between 0.12 mm and 1.48 mm.

A previous study indicates that an increment of 0.5% is a lower bound to detect microstructural changes (Moussawi et al., 2014). The minimum level selected in this study is 1%. Images are acquired using X-ray μ-tomography equipment (Metris XTH225 industrial CT scanner). A microfocus X-ray source is used which offers a spot size of about 3 μm. The voxel size used in this study is 15.556 μm. The resolution is fixed and corresponds to 3.25×10^9 voxels. If compared to classical 2D imaging techniques, the resolution of 3D images corresponds to 1918, 1918 and 883 cross-sections in X, Y and Z directions. The beam energy is 55 KeV.

Both standard and advanced image analyses are performed using programed macros in public software ImageJ from NIH, USA. Part of