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Quantifying the differences in structure and mechanical response of confectionery products resulting from the baking and extrusion processes

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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

Extrusion has potential advantages over baking in terms of throughput, asset cost and flexibility. However, it is challenging to achieve through extrusion the “light, crispy” texture of a more traditional baked confectionery. This study compares and contrasts for the first time confectionery products produced through these two processes, i.e. baking and extrusion. The microstructural differences are measured using imaging techniques, i.e. Scanning Electron Microscopy (SEM) and X-Ray Tomography (XRT) whereas mechanical characterisation is used to highlight differences in the resulting mechanical properties. Crucial information is presented which shows that the two technologies result in different mechanical properties and microstructures, even if the level of porosity in the two products is kept constant. In addition, confectionery products whether they are produced through baking or extrusion, have irregular geometries. The latter makes mechanical characterisation a real challenge. Therefore this study also presents rigorous methods for measuring true mechanical properties such that meaningful and valid comparisons may be made. The accuracy of the chosen methodologies is verified through experiments using flat and tubular extruded geometries as well as testing the products in various directions. It was concluded that the manufacturing method and, in the case of extrusion, the initial moisture content influences the microstructure and mechanics of confectionery products, both of which have an impact on consumer sensory perception.

1. Introduction

Oven baked wafers are intermediate components used in the manufacture of several popular confectionery products and have been manufactured and marketed successfully for decades (Sundara, 2012). A more recent method of producing similar lightweight and crispy products is the extrusion process. Extrusion gives many advantages over the conventional cooking processes in terms of throughput, asset cost and flexibility; it is a continuous process with the flexibility of on-line process adjustments for achieving the desired product characteristics (Karwe, 2008). However, attaining a similar ‘light’, crispy texture through extrusion as in a traditional baked confectionery wafer is problematic. This study aims to understand why products produced through these two processes are different, quantify any differences both microstructurally and mechanically and therefore pave the way for optimising extruded processes and products.

Consumers base their perception and appreciation of acceptable foods on characteristics such as crispness or crunchiness of the food. A review by Luyten et al. (Luyten et al, 2004) reported the absence of an officially accepted definition and measurement of crispness, or the characterisation of properties of crispy foods. However, a large proportion of experiments and studies (Sandoval et al., 2008; Arimi et al., 2010; Roudaut et al., 1998) in this field appear to use the fundamental mechanical properties, namely Young's Modulus and fracture stresses, as a means to characterise and compare the mechanical properties of crispy food products. Typical mechanical tests that are popular in food testing include tensile, compression, bending and puncture tests (Duizer, 2001, 2003). It is a general consensus that both ‘crispy’ and ‘crunchy’ sensations relate to the fracture properties of food materials (Luyten et al, 2004). It is suggested that ‘crunchy’ foods exhibit a complex fracture behaviour correlating to frequent drops in the force during compression or indentation loading, i.e. frequent fracture events. These mechanical ‘signatures’ (or indeed their associated acoustic emission traces) have also been analysed so that their ‘ruggedness’ was quantified in numerical terms using Fast Fourier transform analysis as well as fractal analysis (Roudaut et al., 2002; Pamies et al.,

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2000) in an effort to draw correlations to sensorial measurements. The presence of such frequent fracture events implies that the morphology plays an important role in the crunchiness of the material as fracture events are expected to correlate to fracture of 'layers' in the microstructure, typical of the fracture behaviour of cellular materials (Luyten et al, 2004).

The morphology of cellular materials can be characterised by the porosity, relative density, the size and shape of the cells and their distribution in the microstructure as well as the amount of solid material present in the cell faces and edges (Ashby, 2006). The latter is used to classify the foam as an 'open' or 'closed' celled structure and affects the interconnectivity of the cells. Microstructure in this study will refer to the arrangements of the pores and cell walls, not the supramolecular level of the solid material. A number of authors have developed analytical models in order to determine the solid material properties of the foams. These models treat the porous microstructure as complicated shapes, for example, Chen and Lake developed a model for closed cell foams based on tetrakaidecahedral unit cell shape (Butt, 2016), the Halpin-Tsai model is a commonly used model for composites (Williams, 1980), the Christensen model considers open celled foams as a three dimensional network of struts (Christensen, 1986) and the Gibson and Ashby model treats the foam as an array of simple cubic cells (Ashby, 2006).

Therefore, mechanical (texture) properties heavily influence the quality of a food product as perceived by the consumer. Now, in the engineering field of mechanics of materials, it is a well-known fact that these macroscopic properties are affected by the food structural organisation at the smaller length scale (Clarke and Eberhardt, 2002). Hence, it is of great importance and interest to study the food structure at the microscopic level and determine its associated effect on the properties at the macroscopic level. The microstructure of food foams can give crucial information in combination with the results from the mechanical tests (Mohammed et al., 2013a; Agbisit et al., 2007). Agbisit et al. (2007) suggested that there is a moderate to strong association of the mechanical properties of the food foams with their cellular structure. The Young's modulus of cellular foams can be correlated to cell dimensions and the cell wall thickness (Gao and Tan, 1996). It is worth noting here that the porous nature of food foams necessitates the definition of two densities; one of the solid material and another of the bulk foam. The solid density, ρ_s, and bulk foam density, ρ^*, can be used to determine the relative density of the foam (ratio of air space to solid material) which can in turn be related to the foam porosity (Nussinovitch, 2005).

Some literature relates to baked bread, biscuit, wafer and extruded foods (Agbisit et al., 2007; Chanvier et al., 2013; Yven et al., 2010; Chevallier et al., 2014; Livings et al., 1997), however, this study is the first to investigate the products made via these two processes in comparison with each other; most importantly all the materials in this investigation were produced using manufacturing facilities at one location and ingredients sourced from the same place. This can give crucial information about whether the two technologies result in different types of products they can produce or whether they are producing an end product of similar mechanical properties and therefore sensory and textural attributes. It also aims to expand the knowledge and understanding of food foams and their link to sensory properties, an area with a great deal of scope for further research.

Lastly, the irregular and complex geometry of confectionery extruded and baked products require rigorous experimental characterisation methodologies; this study will therefore also highlight such methods to enable valid comparisons between the mechanical response of several products to be made. Such rigorous methods are generally lacking in the food research literature, with geometry dependent tests based on Texture Profile Analysis (TPA) often used in the form of penetration and puncture experiments which though they may at best be able to rank various materials or products, they are not able to result in fundamental, geometry independent, mechanical properties. For samples of highly variable geometry which often is the case with food products, the accuracy and meaning of the resulting TPA data is doubtful. Finally, rigorous fundamental mechanical properties are also needed as inputs to computational predictive models of other downstream processes such as cutting, packaging or indeed of the food oral process.

2. Materials and methods

2.1. Samples

Because of the inherent nature of the two manufacturing processes, baking within hot plates produces flat sheets whereas extrusion often leads to cylindrical shapes, as is the case in this study. Therefore, in an effort to study the effect of the product's geometry, the extruded shapes were rolled upon exit of the die to produce a flatter shape (called a 'flatbread' in this work) to provide a more direct comparison with the baked sheets. Additionally, the water content in the pre-extrusion mix was also studied as this could affect the density of the extruded shape, though it is not easy to predict the outcome. This is because expansion of starchy melts during the extrusion process is a complex phenomenon; several parameters such as temperature, moisture content and die geometry affect the different mechanisms related to expansion, i.e. bubble nucleation, growth, coalescence shrinkage and finally setting (Kristiawan et al., 2016). As it will later be discussed, in the current study the higher moisture content led to a higher density product and vice versa. Hence the effect of water content is studied by comparing 'standard' (SD) and 'high density' (HD) tubes corresponding to lower and higher water contents respectively.

Therefore the materials required for this study consisted of four samples: a standard density (SD) extruded tube, a high density (HD) extruded tube, a high density (HD) extruded flatbread (all three produced via the same extrusion process), and a wafer product made via the baking process (Fig. 1). All samples were provided by Nestlé Product Technology Centre Confectionery, York and their formulations are summarised in Table 1. The wafer batter ingredients consist primarily of wheat flour and water while the mixture used for the extrusion process is made by varying the quantities of the same ingredients and adding cocoa powder, sugar and starch.

In the baking process, liquid batter is spread and then baked between in a single plate Haas oven (Haas Food Equipment GmbH, Austria). The oven plates have engravings, known as 'reedings,' which allow the batter to spread evenly when the hot plates are closed and

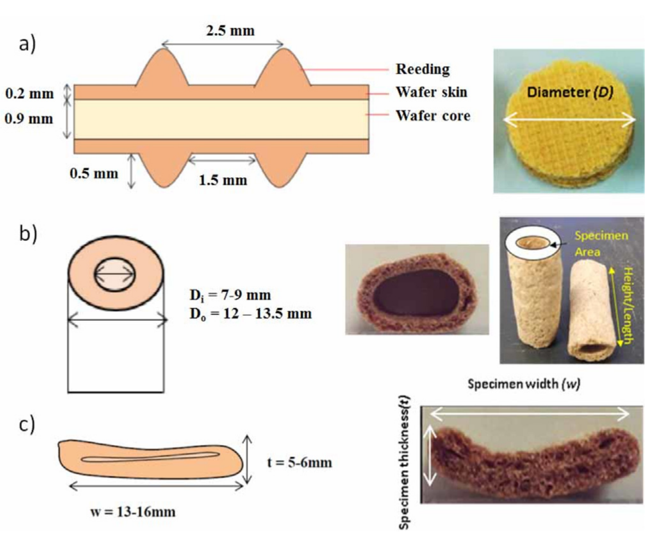

Fig. 1. Schematic and photos of (a) Baked wafer (b) Extruded tube (c) Extruded flatbread [schematics not drawn to scale].