X-ray micro-tomography to study the baking of bread: a dynamic approach to follow crust and crumb formation

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Aims

In bakery products, quality attributes of the crust such as crispy texture and colour and of the crumb as softness and springiness are important attributes for consumer's perception. These attributes mainly set up during the baking stage and are influenced by baking conditions. Many physical and chemical changes occur to lead to a porous structure wrapped in a crust. The objective of this work is to follow the setting of a bread structure with focuses on the crust on one hand, and on the crumb on the other hand, by X-ray micro-tomography.

Method

Samples preparation

Baking was performed in a traditional oven (Miwe condo, Arnstein, Germany) at 250°C. Steam (300 mL of water) was added just before and after loading dough. The baking of a whole deck was interrupted at different baking durations: after 4, 12 and 23 min. The oven door was opened and breads were immediately dived into liquid nitrogen in order to stop the baking evolution: bread structure was fixed. Cylindrical samples of 22 mm diameter were then taken in the center of bread over the entire height of the bread. Three samples were prepared for each partial baking time. Samples were stored at -20°C and defrosted before X-ray micro-tomography measurement. The same operation was done for dough just after the proofing to get the initial structure, but these samples were scanned frozen in a dedicated sample holder.

X-ray micro-tomography

The characterization of the cellular bread structure by X-ray micro-tomography was performed using the Skyscan 1174 (Skyscan, Kontich, Belgium). The sample was inserted in a plastic tube of 22 mm diameter which has a very low absorption coefficient and scanned either frozen or defrosted. The source and the detector were fixed, while the sample was rotated during measurement. The acquisition parameters are reported in Table 1.

Table 1 Microtomography parameters for acquisition and reconstruction

<table>
<thead>
<tr>
<th>Acquisition parameters</th>
<th>Value</th>
<th>Reconstruction parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image size (pixels)</td>
<td>1024*1304</td>
<td>Image size (pixels)</td>
<td>1200*1200</td>
</tr>
<tr>
<td>Expo.time (ms)</td>
<td>1800</td>
<td># of sections</td>
<td>700 to 2000</td>
</tr>
<tr>
<td>Pixel size (µm)</td>
<td>22.14</td>
<td>Smoothing</td>
<td>2</td>
</tr>
<tr>
<td>Rot. step (°)</td>
<td>0.7</td>
<td>Ring artifact reduction</td>
<td>10</td>
</tr>
<tr>
<td>Frame averaging</td>
<td>2</td>
<td></td>
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</tbody>
</table>

The porosity and the size of the gas cells were analyzed from reconstructed sections after an automatic thresholding to get binary images. Porosity was determined from the pixel ratio (void surface in the area of interest) for each section in the 2D image analysis and was calculated from the voxel ratio (void volume in the volume of interest) in the 3D image analysis. The size
of the gas cells was derived from the local thickness calculation, i.e. the diameter of the largest sphere which encloses a point in the void and which is entirely bounded within the solid surfaces. The connectivity density provides a measure of the number of redundant connections between structures per unit volume.

**Results**

**Validation of the sample holder for frozen samples**

Samples like fermented dough continue to evolve even during the scan: it’s impossible to have good results for this type of product. So they need to be scanned in the frozen state. A sample holder inspired from the sample mount presented by Van Dalen et al. (2014) was designed (Figure 1), in order to scan frozen sample. A plastic tube containing the sample is inserted between 2 plates containing dry ice. Top and bottom plates were machined in aluminum to enhance heat transfer by conduction. The system was validated by recording the temperature during a standard acquisition that lasted 22 min. The temperature of the sample was kept under -25°C throughout the acquisition procedure.

![Figure 1. Left: sample holder made of a plastic tube containing the sample inserted between 2 metal plates containing dry ice. Right: temperature recording during a standard acquisition](image)

**The bread structure at the end of baking**

At the end of baking, bread samples measured 42 mm in height. Figure 2 presents the porosity of the bread at the end of the baking stage. A drastic change in porosity from around 0.5 at both surfaces to 0.75 inside the samples occurs within one or two millimeters. From these data, four volume of interest have been defined within the samples. The mean porosity of the crumb could be represented by the envelope created by the data weighted by their standard deviation, therefore creating a range of porosity between 0.63 and 0.83. Outside of this range, areas of interest are assigned to the bottom crust (5% of the total height or 2.1 mm) and the upper crust (5% of the total height or 2.1 mm) whose thickness is in the range of values reported in the literature. The crumb is divided in two equal volumes, bottom crumb and upper crumb, presenting a mean porosity of 0.73.

Images analyses were conducted on these volumes of interest to calculate the porosity, the cell size distributions within these specific volumes (data not shown) as well as the connectivity density (table 2). The porosity is significantly lower in the crust (0.61) than in the crumb (0.73). Moreover there is no discrepancy between the bottom and the upper regions of the bread. The higher values of connectivity density in the crust indicate that the structure has more connections in the crust than in the crumb, suggesting that, conversely, the pores are more interconnected in the crumb than in the crust.
Figure 2. Porosity from the bottom crust to the upper crust of bread at the end of the baking stage.

Table 2 Calculated parameters on the 3D images of the baked bread. Data are mean values of three replicates and standard deviation is reported in parenthesis.

<table>
<thead>
<tr>
<th></th>
<th>Porosity</th>
<th>Connectivity density (mm$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper crust</td>
<td>0.606 (0.076)</td>
<td>26.2 (4.6)</td>
</tr>
<tr>
<td>Upper crumb</td>
<td>0.732 (0.013)</td>
<td>13.3 (0.9)</td>
</tr>
<tr>
<td>Bottom crumb</td>
<td>0.730 (0.017)</td>
<td>15.7 (0.4)</td>
</tr>
<tr>
<td>Bottom crust</td>
<td>0.605 (0.013)</td>
<td>33.6 (4.2)</td>
</tr>
<tr>
<td>Whole sample</td>
<td>0.726 (0.014)</td>
<td>15.3 (0.4)</td>
</tr>
</tbody>
</table>

Dynamic monitoring of the bread structure during baking

Figure 3 exhibits the calculated porosity for the different volumes of interest as a function of position in the sample and at different times of baking. At the end of the fermentation step, the porosity of the dough is 0.537 and then it increases during the baking step. This study highlights significant local differences in porosity in the sample according to the volume considered.

A monotonically decrease in porosity is observed from the upper surface towards the bottom surface, probably due to the gravity forces. Indeed, a study on the stability of bread dough reported variations in dough shape ratios according to the mixing conditions, which underlines the importance of the rheological behavior of the dough. These disparities in porosity according to the relative height are consistent with the fragile structure of the dough bubbles walls. Others studies on bubble growth and bubble size distributions in dough did not report such observations, mainly because they consider the dough in its entirety and focus on its modifications with the proofing time.

After 4 min of baking, the samples are homogeneous in porosity, which reaches the same value in the 4 volumes of interest studied. During this first step of the baking stage, CO$_2$ inside the dough is released promoting bubble expansion and coalescence; with the slowly increasing temperature, rheological properties of the dough change to lead to a very fragile structure that can be easily disrupted. A coalescence of the largest bubbles is reported, resulting in the disruption of the crumb structure after 150 s to 250 s of baking, which
corresponds to temperature inside the samples of 30°C to 35°C (figure 4). The crust is not yet formed.

Figure 3. Porosity of the different volumes of interest (bottom crust and crumb, upper crumb and crust) at different baking times (0 min, 4 min, 12 min and 23 min).

The crust and the crumb become differentiated after 12 min of baking. While the porosity stays steady in the upper volume, it increases significantly in the other volumes, particularly in the crumb. At that time, the important temperature increase (up to 70°C – figure 4) promotes starch gelatinization and protein denaturation that contribute to the setting of the crumb. At the upper surface of the bread, a drying process occurs that contributes to the crust formation. From an engineering point of view, the dough evolves from a very viscous liquid to a semi rigid elastic solid. At that time the structure of the bread is settled down; samples have reached their maximum height (45 mm) and the following increase in porosity during the second half of the baking stage (from 12 min to 23 min) should be attributed to a decrease in the volume of the matrix rather than an increase of the pore volume since the height reached by the samples at the end of baking is 42 mm. Obviously, the important water loss occurring during the period contributes to this evolution (Figure 4).
Figure 4. Temperature and water content during baking measured in the different volumes of interest.

Conclusion
A sample holder has been successfully developed for the study of dough samples in the frozen state. It allowed the acquisition of 3D images with a higher resolution by reducing the movements inside the samples.

X-ray micro-tomography has proven to be a powerful tool in characterizing the microstructure of dough and its transformation in bread during baking. It gives access to the 3D structure that can be analyzed and gives access to the porosity, the size distributions of the pores and the matrix and the connectivity to describe the cellular structure. Further work will complete these results with other partial baking times as well as the investigation of the pore size distributions within the volumes of interest at different baking times. The 3D model that can be built from the data set can be a really helpful tool for different applications and, particularly, the simulation of the heat and mass transfers occurring during baking and the understanding of the implementation of structure during food processing.

Acknowledgements
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References