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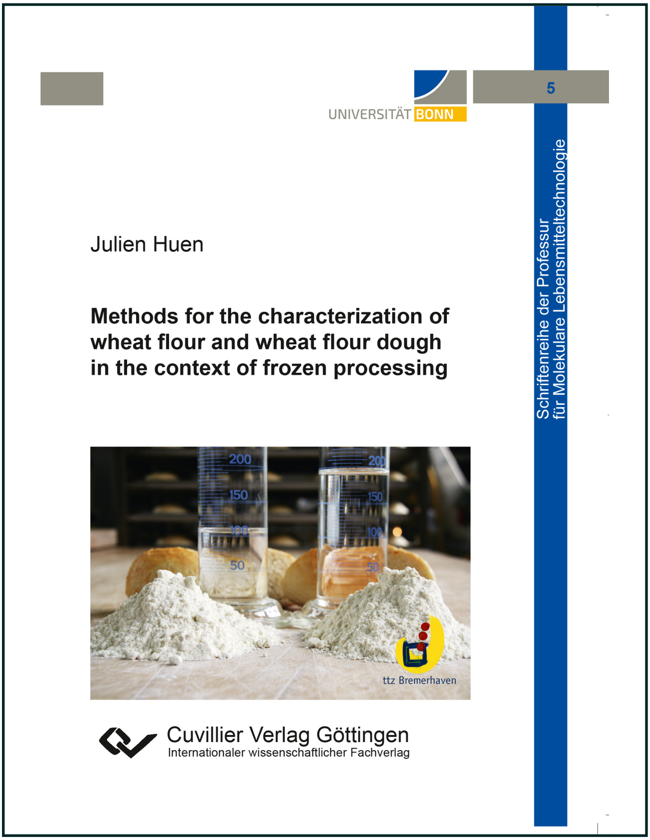

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Methods for the characterization of wheat flour and wheat flour dough in the context of frozen processing

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Chapter 1 – General introduction

This thesis deals with the use of deep-cooling processes in the bread supply chain and its impact on bread quality. To understand the need for deep-cooling, it is necessary to briefly describe the bread market and the related production and distribution schemes.

The worldwide bread market

Bread is a basic foodstuff in most parts of the world. The worldwide annual bread production is estimated to 125 million tons (IndexBox Marketing & Consulting, 2017). The main cereal used as a basis for bread-making is wheat, the annual worldwide production of which accounts for about 750 million tons (FAO, 2018).

In western countries, bread is nowadays available to consumers in a large variety of formats, adapted to different consumption situations. This includes fresh bread and rolls (1 to 5 days of shelf life), pre-packed long-life bread (up to 4 weeks of shelf life), and composed products for immediate to short-term consumption such as sandwiches (Fremaux, 2015). Local traditional bread types co-exist with products inspired from other countries like bagels, buns, pita, ciabatta, products based on ancient grains (emmer, spelt, quinoa, chia) and products with special nutrition claims (low-carb, protein-rich). These products are offered by a heterogeneous sales structure including traditional bakeries, supermarkets, bakery and sandwich stores, restaurants and gas stations (Eichholz-Klein, 2016).

Changes in the way of life in society in the last decades (e.g. increase in out-of-home consumption, diet trends) have not led to a decrease in bread consumption but rather to a higher variety of products and to changes in the modes of production and distribution (Fremaux, 2015). Despite high growth rates, gluten-free bakery products still represent a niche market that until now do not significantly impact the volumes of wheat-based bread (Technavio, 2017).

Modern bread-making processes – use of deep-cooling

The history of bread-making goes back to antiquity (Jacob, 2014). The basic process of bread-making involves kneading flour and water to a dough, proofing by endogenous or added microorganisms for aeration, and baking to improve digestibility related to starch gelatinisation. Although these principles have remained unchanged through the ages, the conditions of bread production have considerably evolved.

Traditionally, bread-making was performed in small businesses carrying out all production steps as well as selling at one place and in one run within a few hours (night production followed by day sale). This model is still being practiced nowadays, but its market share has considerably decreased in the last decades, while production and distribution at larger scale has gained importance: Between 2000 and 2015, the number of bakery companies in Germany has decreased from 20,302 to 12,155, while the corresponding turnover has increased from 15.7 to 19.8 billion euros (Detmers, 2017). Large scale manufacturing in factories implies that sales have to take place in separated stores, with a transportation step in-between. In addition, the manufacturing process itself may be decomposed in different segments performed at different times and places (Cauvin, 2015).

In contrast to wheat grains and wheat flour which may be stored at ambient conditions for months with only minor alteration (Fierens et al. 2015), bread dough is very unstable due to microbiological activity, and fresh bread has a limited shelf life. In this context, freezing represents a possibility to gain operational flexibility. Freezing can be performed both with bread dough and with (pre-) baked bread. Figure 1.1 gives an overview of the production process of bread with its most common variations and the points where freezing, frozen storage and thawing are typically performed.

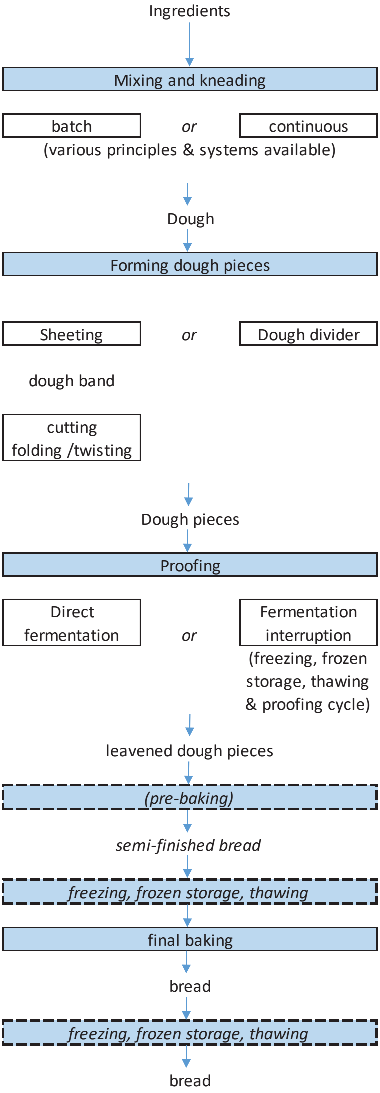

Figure 1.1: Schematic representation of the bread-making process with the different possible positions of the freezing process (based on Lösche, 2003, Cauvin, 2011 as well as own observations in European bakery companies). It should be noted that freezing is usually used once (maximum) in the production process.

In Germany, next to traditional bakeries, two main models of bread production and sales co-exist on the market: the subsidiary model and the industry model (German: “Filialisten” vs. “Zulieferbetriebe” according to the nomenclature of the German Association of Plant Bakers VDG). In the subsidiary model, bread is produced at one site and distributed once to several times a day to a network of typically 10 to 50 self-owned local points of sales (POS). The main part of the range is delivered to the POS as finished products. On top of this, a few products may be delivered as fresh dough pieces, with final baking occurring at the POS (e.g., wheat rolls and brezels). In the subsidiary model, products delivered to the POS are intended for selling on the same day. Freezing is typically used at the production site with dough pieces which are kept frozen for a few hours or a few days to increase flexibility in the production process (reducing night work, making larger dough batches, producing in advance for Sundays and bank holidays). This process is usually called fermentation interruption.

In contrast, in the industry model, bread is produced centrally and intended for national or international distribution in the frozen state (with the exception of pre-packed long-life bread), mainly to other companies (supermarkets, bakery and sandwich stores, restaurants, gas stations). In this case, frozen storage is typically performed for several months, with shelf lives of around one year. In this model, there is a high need to keep the handling at the point of sale as easy as possible, as the sales staff is seldom specialized in baking. While in earlier times, this model was often practiced with frozen dough pieces that needed to be thawed, proofed and baked at the POS, the main current practice involves (part)-baking the bread in the factory and freezing after baking. In this way, at the POS, only thawing and final baking are necessary. In the case of products with soft crust like bagels, a final baking is not even necessary, which further simplifies operations.

The subsidiary model is characterised by relatively small batches, as dough pieces are produced only a few days in advance. The production processes are typically of the batch or semi-batch type, with manual handling between the single steps as well as partly manual work in the single processes.

In contrast, the industry model typically involves continuous processes at high throughput (several tons per hour on each production line, corresponding to several thousand pieces per hour). As production is entirely disconnected from sale and consumption in time, very large batches can be produced.

Of course, the boundaries between the subsidiary and the industry model are open and in the single companies, different variations or combinations of these models may be practiced. For instance, companies operating primarily according to the subsidiary model may choose to integrate some industry products in their range, enabling them to offer a higher diversity of products.

As described above, freezing has become a major process in the bread production and distribution chain. Although low temperatures stop microbiological growth and considerably delay chemical reactions, the processes of freezing, frozen storage and thawing often lead to quality deterioration. In order to gain a better understanding, it is necessary to describe the composition of flour and bread dough, the main quality attributes of bread products, and the physical processes occurring during freezing and thawing.

Wheat flour composition and characterization

The wheat flour supply chain is mainly composed of wheat breeders, farmers, cereal traders and millers. All members of this supply chain have an influence on the composition of the flour finally delivered to bakery companies. Each wheat variety as developed by the breeders and approved by the responsible national authorities (in Germany: Bundessortenamt) has a certain genetic potential to synthetize specific grain components (Henry & Wrigley, 2018). The growing conditions (soil, climate, fertilisation) have a major effect on gene expression and thus on the grain composition (Koga et al, 2016, Hawkesford et al, 2014). After harvest, single grain batches are stored together in silo cells. In most cases, this occurs at the facilities of grain trading companies (VDM, 2016). The decision about which grain batches will be stored together directly impacts the quality that is delivered to the mill. The mill, in turn, influences the flour composition through (i) blending different grain batches, (ii) setting the milling parameters, (iii) combining milling fractions in a specific way (Brütsch, 2017) and (iv) including additives like ascorbic acid and malt flour (common in Germany) as well as enzymes (common e.g. in France).

Wheat flour is mainly composed of starch (70 - 75 %), water (≈ 14 %), proteins (10 - 13 %), non-starch polysaccharides (arabinoxylan 2 - 3 %), fat (≈ 2 %), endogenous enzymes (≈ 1 %) and minerals (≈ 0.5 % depending on the selected extraction rate) (Goesaert et al., 2005).

Analytical investigations usually conducted on flour include the quantification of single components and the description of functionality, especially based on rheology. Methods appropriate for measurements in the processing companies are described in the ICC and AACC standards. Measurements performed in mills typically include water content, minerals (ash), total proteins, gluten (dry and wet), falling number, sedimentation value and damaged starch (ICC 104/1, 105/2, 107/1, 110/1, 116/1, 155, 172). In addition, dough kneading and stretching properties, gluten aggregation properties and starch gelatinization may be assessed by specific instruments and methods (ICC 114/1, 115/1, 121, 126/1, 173, AACC 56-11). Cereal traders and mills also use NIR spectroscopy for the fast determination of humidity and protein in grains at delivery.

In research, more sophisticated techniques are used for quantifying single components, including HPLC, SDS-PAGE and LC-MS for gluten analysis (Wrigley, 1996, Wrigley et al., 2006, Schalk, 2017), HPSEC, HPAEC and X-ray diffraction for starch analysis (Grant et al., 2002, Yoo et al., 2002, Jane et al. 1999) and HPSEC and HPAEC for non-starch polysaccharides (Courtin and Delcour, 2002, Ordaz-Ortiz, 2005).

From flour to bread dough

Next to flour, the main ingredients of bread dough are water, yeast or sourdough and salt. Optionally, sugar, fat, malt extracts, vital gluten, ascorbic acid, emulsifiers, acidity regulators, hydrocolloids and enzymes may be added to improve processability and/or baked good quality (Wassermann, 2009). It should be noted that, while rationalization of bread-making has first led to an increased use of additives and enzymes in bread-making, the market now increasingly demands “clean label” products (Fremaux, 2015). The satisfaction of this demand in large-scale production implies a better process expertise and the use of flours with improved functionality.

Dough kneading is essentially characterised by the homogenisation of dough components and the hydration of starch granules (especially damaged starch), gluten and non-starch polysaccharides. In addition under mechanical shear, a 3-dimensional gluten network is formed. During network formation, new disulfide bonds are being created by the oxidation of S-H groups, existing disulfide bonds are being exchanged among each other (so-called disulfide interchange reactions), and hydrogen bonds are being formed between different parts of the glutenin polymer as well as with gliadins. The glutenin polymer is believed to be responsible for the elastic properties of the dough, while gliadins and starch increase viscosity (Wrigley et al., 2006).

Quality attributes of bread

Bread products are characterised by a number of physical and sensory attributes. The main physical attributes include weight, specific volume, dimensions, colour of crust and crumb, pore size and distribution in the crumb, hardness and elasticity of crumb (Scanlon and Zghal, 2001). Sensory attributes include appearance, smell, taste and texture/mouthfeel, for each of which a number of descriptors are used (Callejo, 2011).

In b2b (business to business) trading, a detailed specification is issued for each product. In these specifications, typically only a narrow corridor is defined for the main attributes. Therefore, a high degree of reproducibility is required in industrial production.

In traditional bakeries and in subsidiary bakeries, which operate in the b2c (business to consumer) model, no specification is agreed with the customer. Therefore, a higher degree of variability is possible. Nevertheless, these companies must offer a level of organoleptic quality comparable or superior to industrial companies, as they are in direct competition with them and have higher per-piece production costs.

Conditions of freezing, frozen storage and thawing

Two scenarios have to be differentiated here. In the case of fermentation interruption, freezing, frozen storage, thawing and proofing may be performed in a single fermentation interruption cabinet according to a programmed temperature and humidity profile if the storage time is only a few hours. Typical freezing temperatures are in the range of -20 °C to -10 °C. In contrast, if the dough pieces have to be stored for several days, freezing will occur in a shock freezer at -40 to -30 °C, storage in a cold room at -20 to -18°C, followed by controlled thawing and proofing in a fermentation interruption cabinet (Lösche, 2003).

In industry production, freezing of bread typically takes place in continuous freezing tunnels operating in with air temperatures of -40 °C to -30 °C. Storage and transportation occur at -20 to -18°C. Thawing at the point of sale occurs at room temperature without particular equipment (Lösche, 2003).

Phenomena occurring in bread dough during freezing, frozen storage and thawing

Scientific literature and experience reported by bakery companies describe negative effects related to the use of freezing with bread dough. These are mainly a reduction in volume, a coarser crumb structure and a loss of dough firmness leading to flatter products (Gélinas et al., 1996, Lu and Grant , 1999, Esselink et al, 2003, Frauenlob et al., 2017). So far, the underlying phenomena are only partially understood.

The most obvious effect when freezing bread dough is the transformation of liquid water into ice. In bread dough, some water molecules are involved in the hydration of macromolecules (gluten, starch or non-starch polysaccharides) by hydrogen bonds. Another part of the water molecules acts as a solvent for water-soluble substances like mono- and disaccharides and minerals.

Ice formation may be monitored quantitatively by differential scanning calorimetry (DSC). DSC measurements show that, when decreasing the temperature of bread dough, ice formation does not start at 0 °C but at temperatures around -5 °C (the exact temperature depending on the formulation). This can be related to the substances dissolved in water. When decreasing temperature further, more ice is created, while a liquid water phase remains. Because ice is composed only of water molecules, the concentration of solutes increases in the water phase as the proportion of ice rises. At even deeper temperatures (-44°C in the experiments of Baier-Schenk et al., 2005a and 2005b), the remaining liquid water phase undergoes a glass transition, visible in the DSC through a change in heat capacity. The glassy state is an amorphous solid state.

Next to this, there is a glass transition of gluten, occurring at around -13 °C in the dough (Kalichevsky et al., 1992, Noel et al., 1995, Baier-Schenk et al., 2005a).

Ice has a crystalline structure. Crystallization is an exothermic process, as ice has a lower internal energy than liquid water. Ice formation implies the creation of crystal nuclei. A high activation energy is necessary for homogeneous nucleation (Koop et al., 2000). Once a nucleus is present, further water molecules can join the existing crystalline structure with a relatively lower activation energy (crystal growth). Experiments on pure water and on aqueous solutions show that in the case of high temperature gradients, leading to a high undercooling, nucleation is facilitated. This favours the creation of a high number of small crystals. In contrast, in the case of a low temperature gradient, leading to a low undercooling, a limited number of larger crystals are created (Petzold and Aguilera, 2009). During frozen storage, ice crystals may undergo transformations. This recrystallization leads to a smaller number of larger crystals, which are thermodynamically more stable than small crystals. Recrystallization involves migration of water molecules between crystals. There are several mechanisms for this, depending on whether the transfer of water molecules occurs via the liquid, the gas or the solid phase. Temperature variations during storage favours recrystallization through the liquid phase. In addition, recrystallization is temperature-dependant and is slower at lower temperatures. During thawing, recrystallization may occur as temperature increases, leading to the short-time formation of larger crystals, before these finally melt (Petzold and Aguilera, 2009).

In the case of pure water and aqueous solutions, these phenomena can well be monitored, as crystal boundaries can be observed via light microscopy. Freezing experiments on vegetal and animal tissue (in the case of food: fruit, vegetables, fish and meat) show that the phenomena described above also apply to cellular systems. In addition, it was shown that larger crystal sizes are responsible for higher cell damages (Martino et al., 1998, Delgado et al., 2005, Otero et al., 2000, Sun, 2003, Do et al., 2004). This justifies the use of shock freezers operating at low temperatures, in order to create high temperature gradients and small crystals.

In bread dough, ice crystals are difficult to observe, and there are only few publications showing ice crystals either directly or indirectly. Baier-Schenk (2005a) published pictures obtained by cryo SEM (scanning electron microscopy), showing ice crystals of several hundred micrometres in diameter in the pores of the dough after 197 days of storage at -22°C. These crystals had a very regular shape with a clearly identifiable hexagonal basal face and prismatic faces. Such large crystals were not found in the pores of freshly frozen dough, evidently showing a recrystallization effect over time. This observation, however, does not provide any information on the structure of ice contained in the dough matrix itself. In pores, ice crystals can grow without any mechanical constraints, which can explain the regular shape observed.

In the case of vegetal and animal tissues and of microbial cells, freezing damage is mainly explained by damage to cell components, especially cell membranes, due to ice crystals. In bread dough, the observed quality losses are believed to the effect of ice crystals on yeast cells and on gluten. The latter, however, is more based on the fact that gluten is responsible for dough strength and gas holding capacity than on tangible knowledge on the interaction of gluten with ice.

Reduction of deep-cooling damage in bakery products

Developing strategies for reducing freezing damage implies understanding the underlying phenomena. From a practical point of view, the options open to the baker are to improve either the recipe or the production process. On the recipe side, specific ingredients may be added. These include substances that decrease the freezing point and substances that increase the temperature of glass transition (Levine and Slade, 1990). Bakery improvers combining several of these substances, especially mono- and disaccharides as well as the hydrocolloids guar gum and carboxymethylcellulose CMC are available on the market with the specific claim of improving fermentation interruption performance.

On the process side, one may reduce the freezing temperature, reduce frozen storage temperature, avoid storage temperature variations, and improve thawing conditions. Shock freezing is commonly used with bread dough and bread without evidence of its impact on crystal structure.

Interestingly, so far, strategies on the ingredient size mainly consist in adding extra substances to the dough. Little is known about flour qualities more appropriate for freezing processes and no flours are marketed with the specific claim of being particularly suitable for this purpose.