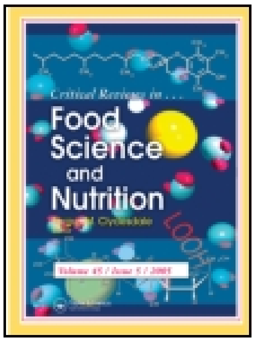

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Par-baked Bread Technology: Formulation and Process Studies to Improve Quality

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Extending the shelf-life of bakery products has been an important requirement resulting from the mechanization of this industry and the need to increase the distance for the distribution of final products, caused by the increase in production and consumer demand. Technologies based on the interruption of the breadmaking process represent an alternative to overcome product staling and microbiological deterioration. The production of par-baked breads is one of these technologies. It consists of baking the bread in two stages, and due to the possibility of retarding the second stage, it can be said that the bread can always be offered fresh to the consumer. The technology inserts logistics as part of the production process and creates the "hot point" concept, these being the locations where the bread is finalized, such as in the consumers' homes or sales locations. In this work, a review of the papers published on this subject was carried out, and aspects related to both the formulation and the process were considered. This technology still faces a few challenges, such as solving bread quality problems that appear due to process modifications, and these will also be considered. The market for these breads has grown rapidly and the bakery industry searches innovations related to par-baked bread technology.

Keywords Par-baked bread, baking, refrigeration, freezing, storage, modified atmosphere

INTRODUCTION

The greatest challenge in bakery has always been the same: how to preserve those special qualities of aroma, taste, and texture of a product that has just been taken from the oven (Cauvain, 2001). Physical–chemical changes (staling and hardening) and microbiological deterioration, such as "rope" and mold growth, are the most limiting factors for bread shelf-life. Considering the importance of bread in terms of nutrition and consumption, this limited stability leads to great economic losses throughout the world (Karaoglu et al., 2005).

The extension of bread shelf-life has been achieved by applying adequate anti-staling strategies (Cauvain, 2001). The use of additives and processing aids, such as enzymes, emulsifiers, and preservatives in bread formulations represents one of these strategies. However, new technologies based on interruption of the breadmaking process have also been successful when the idea is to supply freshly baked bread to consumers. These technologies include refrigerated or frozen dough, frozen proofed dough, par-baked bread and fully baked and frozen bread (Best, 1995).

Frozen dough technology has been extensively studied. Nevertheless, there are great difficulties when using this technology. The problems associated with frozen bread dough include long dough proofing times, reduced volume, and undesirable bread texture. Yeast is necessary to provide sufficient gas production for the increase in dough volume, and its destruction during freezing results in a reduction in gas production, which adds to the problem caused by a reduction in dough gas retention capacity as a result of a weakening of the dough structure through damage to the gluten network (Kenny et al., 1999).

Thus the par-baked bread technology appeared as an alternative to offer better quality products to consumers, also solving the problem of bakery product shelf-life. The process consists of producing bread in a similar manner to the conventional process, but in the baking stage, the product is only baked up to a certain point, instead of being completely baked, and after this stage, it is stored and re-baked after storage to

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complete the process. Due to the possibility of retarding this last re-baking stage, it can be said that the process allows one to obtain fresh products at any time. Re-baking can be carried out in bakery shops, supermarkets, hotels, restaurants, etc. ("hot points") or in the consumers' homes, moments before consumption.

The typical characteristics of par-baked bread, that differentiate it from conventional bread, are its pale crust color, high crumb moisture content, thin crust, and lower specific volume (Leuschner et al., 1997; Sluimer, 2005). Of the different types of par-baked bread, differences with respect to quality characteristics, such as specific volume, crust mechanical properties, firmness, and crumb structure exist (Altamirano-Fortoul and Rosell, 2011).

Par-baked bread technology has given an impulse to the growth of "hot points," a trend in which the bakery (central production) opens a branch to which it sends packaged and frozen bread to be re-baked. Receiving the product ready to be put in the oven means the shop does not need specific areas for production and raw material storage. The process reduces the space necessary for bread processing by up to 70%, just requiring the counter, the oven and a small space to store the product (freezer). Since there is no production sector in these places, nor large storage areas, and since the stock is only for reposition, there is also an expressive economy in electric energy and an improvement in hygiene levels. Another advantage is that the company does not depend on specialized professionals to produce the bread, and the products are of high standardized quality—the bread is the same every day (Nutrinews, 2010). There is also a drastic reduction in bread preparation time (Lucas et al., 2005a; Rosell and Gómez, 2007)—falling from four hours in the conventional process to only 10 minutes with this new concept. Amongst other advantages, the reduction in preparation time allows for the availability of fresh bread the whole day, and also the shop has total control of production, with no risks of losses or lack of product (Nutrinews, 2010). Moreover, par-baked technology can offer a diversity of bakery products (Rosell, 2010) and the nutritional value of breads can be changed due to partial baking (Kopec et al., 2011). The market for such bread has grown rapidly (Rosell and Gómez, 2007) and par-baked bread is leading in terms of innovation in the bakery industry (Carr et al., 2006).

FORMULATION

The formulations must be carefully checked according to the breadmaking process that will be used (Rosell and Santos, 2010), and some adaptations must be made to par-baked bread formulations so as to achieve good results. According to Sluimer (2005), medium strength flour must be used for the final product not to have a very high specific volume and tend to collapse. The addition of emulsifiers that act by improving bread texture is also recommended. Since the bread goes through two baking stages, more water must be added than usual. However, for the dough to be able to incorporate this extra amount of water, substances that retain it, such as hydrocolloids, can be used.

According to Mandala et al. (2008), stabilizing hydrocolloids (xanthan gum, hydroxypropylmethylcellulose, guar gum, or LBG) influenced the final characteristics of par-baked bread. The moisture content of the crust of such bread was 11–19% higher than that of the control bread (fresh bread).

Bread improvers can act effectively in par-baked bread processes involving frozen storage. The presence of improvers (α-amylase, sourdough, κ-carrageenan, and hydroxypropylmethylcellulose) minimized the negative effect of frozen storage, showing an increase in retrogradation temperature. Regarding the staling of par-baked bread before frozen storage and re-baking, all the improvers reduced the retrogradation enthalpy of the amylopectin, retarding staling (Bárcenas et al., 2003b).

In a study carried out by Bárcenas and Rosell (2006a), the incorporation of hydroxypropylmethylcellulose (HPMC) into the formulation of par-baked bread resulted in re-baked products with better quality and a lower crumb staling rate, without affecting the sensory attributes. The beneficial effect of HPMC was more evident in the samples of frozen par-baked bread, which showed microstructures with no damage due to the growth of ice crystals. The authors explained that HPMC had a protective effect against the damage caused by freezing and frozen storage, due to a strong interaction between the HPMC chains and the constituents of the bread crumb. Bárcenas et al. (2004) showed that the addition of HPMC to the formulation improved the texture of the bread obtained by par- baking, frozen storage, and re-baking. Apart from this, the presence of HPMC also improved the specific volume and general product quality during long periods of frozen storage, minimizing the negative effects of the process conditions. On the other hand, κ-carrageenan was not an appropriate improver for the interrupted baking process with frozen storage, since it did not retard the staling mechanism. For par-baked bread stored at low temperatures (2°C), Bárcenas and Rosell (2007) observed that the addition of HPMC retarded staling of this bread and the same effect was observed in re-baked bread. HPMC reduced the crumb hardness of both par-baked and re-baked bread, and also promoted a reduction of amylopectin retrogradation.

In a study by Rosell and Santos (2010), the addition of fiber (resistant starch, high methoxyl pectin and a mixture of inulin/oat fiber) was not capable of maintaining the structure of the crumb during storage, and the functionality of the pectin was negatively affected in the interrupted baking process. The inclusion of resistant starch and an inulin/oat fiber mixture led to a reduction in bread specific volume and to an increase in hardness.

Carr and Tadini (2003) verified that greater additions of yeast and vegetable fat promoted, respectively, greater specific volume and reduced firmness and chewiness in re-baked par-baked French rolls. Cohesiveness and elasticity were not significantly influenced by the addition of different amounts of yeast and vegetable fat.

Addition of 15 and 22.5% sourdough positively affected the specific volume and crumb firmness of partially baked frozen gluten-free bread. Moreover, sourdough addition decreased the glycemic index (Novotni et al., 2012).

Ferreira and Watanabe (1998) evaluated the specific volume of frozen par-baked French rolls produced with added ascorbic acid (0 and 100 ppm, flour basis), vegetable fat (0, 1%, and 2%, flour basis), and sugar (0 and 0.5%, flour basis). The authors recommended the addition of 100 ppm (flour basis) ascorbic acid and 2% (flour basis) vegetable fat to obtain the best results.

Ribotta and Le Bail (2007), studying the addition of enzymes (fungal alpha-amylase, hemicellulose, and protease) showed that they failed to produce any notable differences in the water properties of the crumb of fresh (not frozen) par-baked bread, but seemed to reduce the intensity of the changes in the water properties as measured by DSC, during freezing of the par-baked bread.

Jiang et al. (2008) found that xylanase could be used to improve the quality of frozen par-baked bread (FPBB). The presence of xylanase minimized the negative effect of frozen storage in relation to the control sample (without xylanase). Xylanase reduced the dependence of bread volume on frozen storage, and promoted a significant increase in bread volume. FPBB with xylanase showed greater volume and a softer crumb when compared to the control sample (without xylanase). In the presence of xylanase, crumb firmness and amylopectin recrystallization were reduced during the storage period, suggesting an anti-staling effect of the xylanase in FPBB. The addition of xylanase significantly reduced total shrinkage and crumb shrinkage during the freezing process.

Xylanase was also used in par-baked French rolls substituted with whole wheat flour together with two other enzymes: glucolipase and hexose oxidase. It was shown that the enzymes had a satisfactory performance in formulations of this type of product. Concentrations of 30–75 mg/kg flour for glucolipase, 91–359 mg/kg flour for xylanase, and 30–120 mg/kg flour for hexose oxidase, used together in the base formulation, were the values indicated for obtaining desirable characteristics, such as good tolerance to proofing, good oven spring, good specific volume, a rounded shape and good cut opening and cut height after baking (Almeida and Chang, 2012).

The use of an anti-microbial agent in par-baked bread is very important, since if one is not used, the bread must be stored at a temperature of 4 ± 2°C (Karaoglu et al., 2005). The addition of calcium propionate as an anti-microbial agent significantly reduced the crust moisture content, baking loss, specific volume, hydration capacity, and softness values of white par-baked loaf bread stored at 4 ± 2°C, while the crumb moisture content, acidity and color increased significantly (Karaoglu and Kotancilar; 2006). The addition of calcium propionate had a significant effect on the amylogram readings (pasting temperature, bump area, peak, holding-end, and cooling-end viscosities), water activity, volume yield, and crumb softness values of re-baked bread prepared with wheat bran and stored at 4 ± 2°C (Karaoglu, 2006).

PROCESS

In principle, par-baked bread technology does not differ much from traditional breadmaking technology, since before storage the product passes through all the stages necessary to transform dough into bread (Fik and Surówka, 2002). Figure 1 shows a flow-chart of the par-baking process. The technique uses the same steps of mixing, intermediate proof, and make-up (Baking Business, 2005). However, the time between the end of mixing and the beginning of molding is frequently shorter than that employed in the straight dough method. Also, the intensity and degree of mixing must be adapted and low speed mixers are frequently used (Sluimer, 2005).

There is divergence in the literature with respect to final proof time. According to Almeida (2014), the final proof time is the same as that used in the conventional process because if it is higher, structure collapse occurs. However, Ferreira et al. (1999) showed that this step should be shorter in the production of French rolls. According to the latter authors, using the same proof time for par-baked breads as for conventional breads rendered par-baked breads with lower specific volume.

PAR-BAKING

As mentioned before, the main difference between completely baked bread and partially baked bread is how they

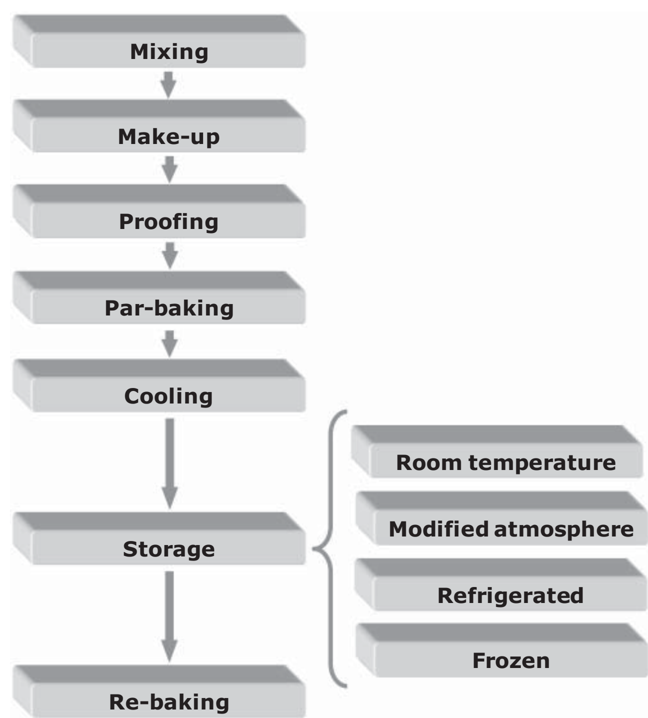

Figure 1 Par-baked bread process flow-chart.

are baked (Hillebrand, 2005). In the par-baking step, bread baking is carried out until the crumb is formed but the crust color has still not developed, that is, the process is ended before the *Maillard* reaction occurs in the crust (Fik and Surówka, 2002; Bárcenas and Rosell, 2006a, 2006b). After partial baking, or par-baking, the bread should already present its definitive size and shape (Ferreira et al., 1999). The crumb structure of bread is fully formed during the par-baking stage (Majzoobi et al. (2011). However, due to the low water content of the dough, the starch is partially gelatinized during the par-baking process. Thus, some starch granules remain and will melt during the final baking (Bárcenas et al., 2003b; Almeida and Chang, 2013a), suggesting that bread structure is not completely formed at the end of the par-baking stage.

During baking, the rheological characteristics of bread dough undergo profound changes between 55 and 75°C. It is around this temperature range that starch gelatinization and protein coagulation occur. In this stage the dough viscosity increases various orders of magnitude, but the product is not "baked" at this point. If it is removed from the oven at this moment it will not support its own weight and will collapse under the influence of gravity. Practical observations have shown that it is necessary to continue baking many types of bread until the temperature of the center reaches between 92 and 96°C, in order to a sufficiently rigid structure to be formed (Cauvain, 2003; Almeida and Chang, 2013a). Also, according to Pyler (1988), when it leaves the oven, the temperature on the inside of par-baked bread must exceed 76.7°C and preferentially reach 82.2°C, otherwise its volume will shrink excessively during cooling.

According to Paid and Walker (2001), the par-baking conditions (temperature and time) have a great effect on the par-baked bread quality characteristics. The par-baking time before freezing of the products considerably influences their quality after thawing and re-baking. This parameter has a significant effect on how the bread will be commercialized in the future (Karaoglu and Kotancilar, 2006). The par-baking time and total baking time, depend a lot on the type of dough and shape of the product, as well as on the thermal conditions of the oven (Fik and Surówka, 2002). In the first stage of baking, the baking temperatures are lower and the times are longer than in conventional production processes, and steam can be used to help control oven-spring (Cauvain and Young, 2000).

Karaoglu and Kotancilar (2006) showed that the par-baking time of white pan bread had a significant effect on the moisture content, specific volume, hydration capacity, softness, total titratable acidity, and color of the bread. The authors concluded that in relation to crumb softness, a short par-baking time was recommended for white pan bread baked in two stages (re-baking after par-baking and storage). Ten minutes of par-baking proportioned a softer crumb than the other times tested (15 and 20 minutes at 230°C), even though longer par-baking times proportioned higher volumes.

Fik and Surówka (2002) found that the optimum par-baking time was between 74 and 86% of the time necessary for complete baking. In their study, they found that by employing a fraction of 71% of the baking time to par-bake bread before freezing and final re-baking after frozen storage under industrial conditions, it was possible to obtain a product with sensory and textural qualities close to those of fresh bread. It was shown that a fraction of baking equal to 43% was too short to impart the desirable sensory and textural aspects to breads after frozen storage and re-baking.

Ferreira et al. (1999) verified that the higher the temperature, the shorter the time necessary for par-baking French rolls. The authors found that, amongst the temperatures studied (150, 175, and 200°C), the temperature of 200°C could be defined as the best one, since par-baking occurred more rapidly and the breads baked at this temperature presented a specific volume not differing from those baked at 175°C, and higher than that of those baked at 150°C.

Pérez-Nieto et al. (2010), on considering the values obtained for dough temperature, mass loss, height increase, and crumb structure, observed that at a certain point of the baking stage, the dough reached a condition that remained almost invariable when baking continued. This baking stage (when the bread temperature and height remain practically constant) could be considered as an appropriate final time for par-baking of the dough. However, the aspects of the crumb structure should be analyzed to ensure that no further change in crumb structure occurred when baking continued.

To fulfill the requirements of the par-baking process, the use of superheated steam is quite common. Superheated steam substitutes the hot air used in the traditional process. Due to the steam, the crumb is formed as rapidly as or more rapidly than in normal baking. At the beginning of par-baking, the surface of the dough absorbs the steam and hence the sharp increase in temperature induces heat transport in the dough, forming the crumb structure. On the other hand, moisture absorption delays crust formation and prevents moisture loss. As the oven temperature is much lower than in regular baking, the development of the crust color is retarded, resulting in a pale crust. However, after par-baking a crust with a certain thickness is a prerequisite to obtain a stable volume, and if the dough is baked in saturated steam at 100°C, the volume is obtained but without the crust. Under this condition, the crumb will begin to collapse during the second half of the baking process, and will continue shrinking during cooling (Sluimer, 2005).

According to Cauvain and Young (2000), during the preparation of par-baked rolls in a rack oven, only a "few seconds" were required, and longer steaming led to severe wrinkling of the product. Steaming times of 18 s were recommended for par-baked French-type breads, since extending the steaming period led to product collapse and severe wrinkling.

COOLING

Bread cooling after the par-baking step is necessary. However, par-baked bread is more vulnerable in this step because it does not have an established crust, making the structure fragile. Moisture of ambient air can condense on the bread, which can cause the formation of a shriveled crust and shrinkage of the crumb. Forced convection should be avoided as it leads to greater condensation on the crust (Sluimer, 2005). An alternative method for cooling is the use of vacuum. Vacuum cooling stabilizes par-baked structure without producing wrinkling or shriveling of the loaf, as it avoids condensation on the crust (Rosell, 2010). The use of vacuum is very quick and permits cooling down the bread within a few minutes (Wiggins, 1999). However, Le Bail et al. (2011) found that the staling rate of re-baked bread, after it was cooled after par-baking by vacuum, was almost two times that of par-baked bread cooled at ambient temperature. According to these authors, the kinetics of pressure drop and of depressurization for vacuum cooled bread could have some impact on the final quality of the bread and could therefore be optimized.

STORAGE

Special attention must be given to the storage conditions of par-baked bread, since they have a fundamental role in the technological quality of bread and its staling behavior (Rosell and Santos, 2010). After par-baking, the bread can be stored in four different ways before re-baking: at room temperature, under a modified atmosphere, under refrigeration or frozen (Bárcenas and Rosell, 2006a; Deschuyffeleer et al., 2011; Leuschner et al., 1997). The main difference that the different storage conditions can provide to the par-baked bread is in its shelf-life, which can vary from a few days to months.

Storage at Room Temperature

The shelf-life of well packaged bread stored at room temperature is limited (Sluimer, 2005). The microbial count increases significantly during the storage of bread at room temperature, without the addition of anti-microbial agents (Karaoglu et al., 2005). After about five days, molds are visible on the crust, marking the end of the product shelf-life. During these five days, the difference in moisture content between crust and crumb tends to balance out, making the crust become softer and the crumb more crumbly, and the fresh bread aroma mostly disappears (Sluimer, 2005). However, the second baking stage after storage at room temperature causes a reduction in the microbial count and promotes bread freshness again (Karaoglu et al., 2005).

Storage under a Modified Atmosphere

Packaging par-baked bread under a modified atmosphere extends the microbiological shelf-life of this product for a few months. Aspects such as product contamination after par-baking, gas composition, packaging material characteristics and packaging technology must be verified (Sluimer, 2005).

Doulia et al. (2000) showed that preservation of par-baked baguettes under a modified atmosphere (70% CO_2 and 30% N_2 in PA/EVOH//PE) was the treatment permitting the greatest shelf-life extension amongst all those tested (ethanol, chemical preservatives, ultraviolet radiation and pasteurization). The authors also noticed that the shelf-life increased when the temperature at which the modified atmosphere packaged products were stored was reduced. A microbiological shelf-life period above 100 days was obtained with storage at 27°C, while a period of only 71 days was obtained for storage at 35°C, as compared to the control bread which had a shelf-life of only 4.6 days.

Leuschner et al. (1999) observed swelling of all par-baked bread samples stored under a modified atmosphere (40% CO_2 and 60% N_2 in Multiflex PA/PE 20/70C) after 2 weeks when stored at 28°C. The storage of bread at 37°C resulted in packaging swelling after 3 days.

Refrigeration (4°C) combined with packaging under a modified atmosphere could be useful to extend the shelf-life of par-baked bread (par-baked brown soda bread and par-baked yeast rolls). The storage of par-baked bread at 4°C under a modified atmosphere was not associated with package swelling (Leuschner et al., 1999). These authors found that par-baked Irish bread (Irish Brown Soda) stored under a modified atmosphere (40% CO_2 and 60% N_2 in Multiflex PA/PE 20/70C) at 4°C was microbiologically stable for 13 weeks.

According Deschuyffeleer et al. (2011), modified atmosphere packaging (100% CO_2) alone was not enough to ensure sufficient shelf life for the product. Therefore, other conservation strategies that do not affect the fresh and natural character of par-baked breads are needed, such as natural anti-fungal components. Early spoilage of commercial par-baked breads were caused by *P. anomala* and *S. fibuliger* (chalk mould defect).

Refrigerated Storage

Refrigerated storage is an adequate alternative to preserve par-baked bread (Lainez et al., 2008), since it extends the shelf-life with a lower energy requirement when compared to frozen storage (Bárcenas and Rosell, 2006a; Rosell and Santos, 2010). It is crucial to prevent the growth of *Bacillus* sp. (Leuschner et al., 1999).

Karaoglu et al. (2005) showed that the microbial count of par-baked bread stored under refrigeration (4°C) was lower than that of bread stored at ambient temperature. Par-baked bread stored at 7°C presented mold growth on the ninth day, while the product stored at 1°C did not present mold growth for 28 days (Lainez et al., 2008).

The storage of bread at low temperatures is generally not recommended since it increases the bread staling rate, thus reducing the quality and freshness. In the case of par- baked bread, storage at low temperatures can be considered, since staling is reverted during re-baking (Leuschner et al., 1999).

Crumb hardness and bread staling of re-baked bread were progressively accelerated during storage (Rosell and Santos, 2010). Bárcenas and Rosell (2007) also showed that during the storage of par-baked bread at low temperature (2°C), a progressive increase in crumb firmness and rapid crystallization of the amylopectin occurred. However, the heat applied during the re-baking process reverted these phenomena, the extension of this improvement depending on the storage time of the par-baked bread. In relation to the staling of re-baked bread, the storage time of the par-baked bread did not significantly affect the staling process of the resulting re-baked bread (Bárcenas and Rosell, 2007). The fully baked bread obtained from par-baked bread stored at 1°C presented greater firmness values and changes in crumb firmness than par-baked bread stored at 7°C (Lainez et al., 2008).

Re-baked white pan bread, which had been par-baked for 10 minutes and stored for 7 and 14 days under refrigeration, provided softer crumbs than the control bread (non par-baked bread) (Karaoglu and Kotancilar, 2006). Regarding crumb softness, Karaoglu (2006) showed that the refrigerated storage period of par-baked bread prepared with wheat bran determined the firmness during storage.

Refrigerated storage had little impact on specific volume (Rosell and Santos, 2010), but an increase in storage time of the par-baked bread under refrigeration (4°C) led to a reduction in quality of the resulting re-baked bread, which was related to losses in moisture content and softness and an increase in baking loss, specific volume (Karaoglu and Kotancilar, 2006). However, Lainez et al. (2008) found that the moisture content, specific volume and width/height ratio in completely baked bread was not affected by the storage time and temperature. Completely baked bread obtained from par-baked bread stored at 1°C had inferior sensory quality than that from par-baked bread stored at 7°C (Lainez et al., 2008).

Comparing refrigerated storage to storage at room temperature, it can be seen that moisture diffusion from crumb to crust occurred at a much lower rate at 0°C than at 25°C. During the storage of a packaged volume at ambient temperature, the crust became soft after one day of storage, but under refrigerated storage, the crust maintained a certain crunchiness for more than two days. These crusts were re-formed more rapidly during re-baking than the soft crust. The re-baked crust from refrigerated storage gives a better impression of freshness than the crust from storage at room temperature. Also, the development of off-flavors was much lower under refrigeration than under ambient conditions (Sluimer, 2005).

As compared to frozen storage, refrigerated storage seems to be a good alternative. The crumb microstructure of bread stored under refrigeration (2°C) was almost intact as compared to that of bread stored frozen. Positive temperature storage led to bread with better specific volume, low crumb hardness and a slower hardening rate during staling, than the bread stored frozen. With respect to sensory quality, par-baked bread stored under refrigeration did not differ in aroma, but received lower scores for taste and texture when compared to bread from frozen storage. Additional studies on the performance of sensory quality and microbiological safety during long storage periods under refrigeration are required (Bárcenas and Rosell; 2006a).

Frozen Storage

Frozen storage is the process most used to preserve par-baked bread. This technique allows for storage for long periods, but is an expensive process due to the high maintenance costs of the cold chain (Lainez et al., 2008). A comparison between the frozen par-baked bread process and conventional bread showed that, under industrial conditions, the frozen par-baked bread process demands about 2.2 times more electrical energy than the conventional process (without considering the energy used to cool the par-baked bread, for frozen storage and for thawing of the frozen par-baked bread before the final baking (Le Bail et al., 2010).

Freezing

Freezing converts the water present in a food into a non-active compound, and in this way, together with the low temperature, prevents the growth of microorganisms and the development of the chemical and enzymatic reactions responsible for food deterioration (Bárcenas and Rosell, 2006b).

There is a lot of information available in the literature concerning the freezing of foods, but few data concerning high porosity foods such as bread (Hamdami et al., 2004c, 2004d). The freezing of a moist, porous matrix represents a very specific problem. In fact there is coupling of heat transference with moisture diffusion, further complicated by transition of the water into ice (Hamdami et al., 2004b). Recently various researchers have focused their studies on the properties and thermo-physical changes that occur during the freezing of par-baked bread (Grenier et al., 2002; Hamdami et al., 2003, 2004a, 2004b, 2004c, 2004d, 2004e, 2006; Lucas et al., 2005a, 2005b).

Bread can be frozen, stored in the frozen state and thawed more easily than the dough. After freezing, bread no longer requires the activity of the yeast nor the gas retention properties, which are quality factors important in non-baked dough. However, the success of freezing bread also requires care and attention in all aspects of the operation. Inadequate freezing, frozen storage, and thawing of the bread can increase staling (Inoue and Bushuk, 1996), which was, indeed, confirmed by Cauvain (2004), Kennedy (2000), and Vulicevic et al. (2004). According to these authors, since the greater part of staling results from passing through the range from 0 to 5°C, with the maximum rate occurring around 4°C, a badly executed freezing-thawing cycle can tremendously increase the degree of staling undergone by the bread, since it passes through the optimum staling temperature twice. The effect of the freezing-thawing cycle on bread staling will be more significant the longer it takes to pass through the critical temperature range (Cauvain, 1998). Thus during cooling of the par-baked bread, it must pass through this temperature range as quickly as possible, so that its quality during frozen storage is preserved (Vulicevic et al., 2004).

The freezing process adopted by companies that process this type of product in Brazil is that of mechanical refrigeration using the convection of low temperature (−40°C) air at high speed as the heat exchange principle. Cryogenic processes, using liquid nitrogen or carbon dioxide, are also adequate for the frozen bread process (Pinheiro, 2005).

Hamdami et al. (2007) studied the conditions of freezing for par-baked bread. They showed that the temperature, speed, and relative humidity of the cold air were, in order of importance, the air parameters with greater influence on weight loss, ice concentration at the crust-crumb interface, and freezing time. For bread freezing in a single step, the authors concluded that the freezing time and weight loss decreased with reduction in temperature and increase in air speed, whereas the ice concentration below the crust decreased with reductions in both temperature and air speed. Consequently, quick freezing (233 K and 5 m/s) should be used when the objective is to minimize weight loss and freezing time and slow freezing (233 K and 0.5 m/s) should be used when the objective is to minimize the ice concentration at the crust-crumb interface during the freezing process of par-baked bread.

Although the freezing of bread is generally carried out in a single-staged process, Hamdami et al. (2007) proposed a two-staged process where the temperature and air velocity suffered changes between the two stages. Slow freezing (0.5 m/s and 253 K), applied at the start of the freezing process, tends to minimize the amount of ice at the crust-crumb interface during the initial period, and can be combined with quick freezing (5 m/s and 233 K) during the second stage. By way of slow freezing in the first stage and quick freezing in the second stage, there was a considerable reduction (13.5%) in the ice concentration at the crust-crumb interface as compared to the use of a single stage process, in detriment of an increase in freezing time and loss of weight.

Ota (2006) showed that the temperature of the air in the freezing tunnel was the factor which most influenced the quality of the final product, the lower temperatures being the most prejudicial. For par-baked bread with no additives to maintain physical and structural characteristics similar to those of traditionally baked bread with no additives, the bread should be frozen at intermediate air temperatures (from 14.5 to 21°C) with greater flexibility for the air speed (3.5 to 6.0 m/s). For par-baked bread with additives to present characteristics similar to reference bread with additives, it should also be frozen at intermediate air temperatures (from 14.5 to 21°C), but with low air speeds (from 2.1 to 4.7 m/s).

Non-packaged bread freezes considerably faster than packaged bread. It has been demonstrated that the freezing rate of non-packaged bread responds to differences in the air speed and orientation, as also to the freezing temperatures. The moisture loss from non-packaged bread during freezing is negligible. Consequently it is recommended that bread be frozen in the non-packaged form, to minimize the loss of quality during freezing (Jeremiah, 1996).

Freezing and thawing processes negatively influenced crust hardness. The crust penetration test showed that conventional bread had the hardest crusts, followed by frozen bread baked from non-fermented dough, frozen completely baked bread and finally frozen par-baked bread. Frozen par-baked bread presented a significantly harder crumb than conventional bread (Curic et al., 2008).

Image analysis of the crumb showed that the ratio of total cell area and total measured area of the fully baked and frozen bread was similar to conventional bread, but in the unfermented frozen dough and partially baked and frozen bread it was lower.

However, number of crumb cells per cm^2 was higher in partially baked and froze bread and unfermented frozen dough than in conventional bread but the cells were smaller. This indicates that freezing influenced the cell distribution such that they were greater in number but smaller in size (Curic et al., 2008). Freezing of the par-baked bread influenced the properties of the water as measured by DSC (Ribotta and Le Bail, 2007).

Time of Frozen Storage

Various problems can increase with the frozen storage of par-baked bread for a prolonged period of time under controlled conditions (Ribotta and Le Bail, 2007). The quality of the bread can suffer changes with the increase in storage time of par-baked bread such as a reduction in specific volume, a loss of moisture content, an increase in crumb hardness and loss of aroma, resulting in product deterioration (Bárcenas et al., 2004; Vulicevic et al., 2004; Bárcenas and Rosell, 2006b).

Carr et al. (2006) showed that frozen par-baked French bread had a smaller specific volume and weight than the fresh bread, although frozen storage did not influence the moisture content, porosity, elasticity or cohesiveness of the crumb.

The profound effects of storage temperature on the rate of staling have long been known. A fall in the storage temperature increases the degree of crumb firmness resulting from starch retrogradation (Cauvain, 1998). Long periods of frozen storage appear to be associated with a greater rate of staling (Bárcenas and Rosell, 2006b).

Pyler (1988) reported that when the product was maintained from −9.4 to −6.7°C, that is, just below its freezing point, a perceptible loss in softness and aroma occurred within a week. According to this researcher, a storage temperature of −18°C would be necessary for the crumb softness to remain relatively stable for a month.

Using differential scanning calorimetry (DSC), Bárcenas et al. (2003a) studied modification of the amylopectin during the baking process. No retrogradation of the amylopectin was detected during storage of the par-baked bread. However, an analysis of the staling of these baked samples showed that the time of frozen storage produced a progressive increase in the range of retrogradation temperature of the amylopectin, and a large amount of energy was required to melt the amylopectin after long storage periods, indicating that structural changes in the amylopectin occurred during frozen storage. Bárcenas et al. (2003b) also showed that the frozen storage of par-baked bread produced an increase in the temperature range for amylopectin retrogradation. With respect to the fresh bread quality after re-baking, Bárcenas et al. (2003a) showed that the crumb hardness increased with frozen storage time, and that the rate of hardening during staling was dependent on the time. DSC studies and the determination of crumb hardness showed that some changes occurred during frozen storage. The increase in crumb hardness was more evident after 14 days of storage. Bárcenas and Rosell (2006b) observed that the crumb hardness of par-baked bread after different periods of frozen storage remained constant, whereas the hardness of the re-baked bread increased with frozen storage time. For both types of bread, the enthalpy of amylopectin retrogradation did not vary with the period of frozen storage. Fik and Surówka (2002) found no effect of the period of frozen storage (77 days) on the crumb hardness of re-baked par-baked bread.

Novotni et al. (2011) found that the oxidative stability and the total phenolic content of par-baked bread decreased during frozen storage (22 days), but that the oxidative stability was greater than that of frozen fully baked bread, although lower than that of the frozen dough. The researchers also reported that the oxidative stability was better in blue colored high-density polyethylene (PE-HD) packaging than in transparent polyester-polyethylene-ethylene-vinyl alcohol copolymer (PET-PE/EVAL/PE) packaging, probably due to the blue color and low light transparency. The period of frozen storage and packaging material did not affect the firmness of the par-baked bread.

The more pronounced changes in bread quality were observed at the start of the storage period, and a marked difference could be noted in the values of the parameters before freezing and after one week of frozen storage. In the following weeks, the sensory and textural changes were only slight. It was confirmed that the freezing process itself had the greater effect on the quality of frozen bread, whereas the storage time under optimal conditions only slightly affected the quality (Fik and Surówka, 2002). Moisture content (crust and crumb), elasticity and mouth feel were the most sensitive quality attributes, which deteriorated significantly after 4 weeks of storage (Vulicevic et al., 2004). Results obtained in the difference from control test showed that the judges perceived a slight difference between the frozen par-baked bread and fresh bread after the third day (Carr et al., 2006).

During frozen storage, an increase in size of the crystals is important and can reduce product quality (Reid, 1983). Results for microstructure observed by Low Temperature Scanning Electron Microscopy indicated that the physical damage suffered by the crumb constituents of par-baked bread during frozen storage was caused by a progressive growth of ice crystals. This damage appears to be the main factor responsible for the loss in quality and greater rate of staling (Bárcenas and Rosell, 2006b).

The phenomenon of recrystallization during frozen storage, involving changes in the number, size, and form of the ice crystals, damages the product structure (Bárcenas and Rosell, 2006a). Reid (1983) mentioned that even at constant temperature a process occurred in which small crystals become even smaller, whereas larger crystals grow in size. With time the number of crystals decreases and the mean size increases—in part, a reversal of the initial effect of quick freezing occurs.

Based on the physical properties and sensory scores, the period of frozen storage of par-baked bread is between 8 and 20 weeks (Vulicevic et al., 2004; Majzoobi et al., 2011).

Defects of Par-baked Bread Stored under Frozen Conditions

Frozen storage is one of the most efficient methods to retard the bread staling process (Mandala and Sotirakoglou, 2005) and moisture equilibration between the crust and the crumb. In addition it preserves the aroma of fresh bread (Sluimer, 2005). Nevertheless it causes some changes in the bread structure which result in prejudice to the product. The defects in frozen bread cited in the literature are a reduction/contraction in specific volume, the collapse (shrinkage) of the structure, the appearance of discoloration immediately under the crust, commonly known as snow-white discoloration, separation of the crust from the crumb and flaking of the crust.

Reduction/Contraction in Specific Volume

Frozen par-baked bread shows a statistically smaller specific volume than that of conventional bread (Curic et al., 2008). Frozen storage results in a progressive reduction in bread specific volume, more marked during the first month of storage (Rosell and Santos, 2010).

Ferreira et al. (1999) observed a decrease in specific volume of French bread during the first 24 h of frozen storage (−18°C), and after this period this parameter remained practically unaltered during the rest of the storage time (10 days). The authors showed that this parameter was reduced due to contraction of the volume (16%).

Bárcenas et al. (2003a) and Carr and Tadini (2003) observed that the frozen storage period (between 7 and 42 days and between 7 and 28 days, respectively) had no effect on the specific volume of the re-baked par-baked bread.

Bárcenas et al. (2004) also showed that the specific volume of re-baked par-baked bread was not affected by the duration of frozen storage (between 7 and 42 days).

Almeida (2006) and Almeida et al. (2013b) showed a statistically significant fall in specific volume of the re-baked par-baked bread after 32 and 62 days of frozen storage in relation to conventional bread, caused by a reduction in volume of the bread. Nevertheless, there was no significant difference between the volume and specific volume of the bread with 32 and 62 days of frozen storage, showing that the period of frozen storage evaluated did not influence these characteristics of the re-baked par-baked bread.

Carr and Tadini (2003) showed that during frozen storage, the specific volume of the bread probably decreased because crystallization of the water damaged the bread structure.

Shrinkage of the Structure

In the study of Ribotta and Le Bail (2007), the freezing process caused significant contraction of the par-baked bread, showing that the product was submitted to great mechanical shock during processing. The study confirmed the shrinkage during cooling and freezing.

Dynamic mechanical analysis in the controlled force mode was capable of accompanying the shrinkage of the par-baked bread crumb during freezing. The crumb shrank during cooling and the whole freezing process, the curves showing a heat contraction phase followed by a rapid fall in crumb height, which could be related to the freezing matrix. In general the freezing of par-baked bread altered the thermo-mechanical profile. The frozen samples presented a smaller contraction rate during cooling, but greater deformation during the freezing process. Since the total retraction did not show significant alterations as a consequence of the cooling and freezing of the par-baked bread, the tension developed in the matrix during the whole process was greater in the frozen samples due to the fact that they showed quicker deformation during crystallization of the ice (Ribotta and Le Bail, 2007).

Crystallization of the amylose during cooling and partial recrystallization of the amylopectin during freezing and frozen storage could explain the crumb contraction and the increase in the fraction of non-freezable water (Ribotta and Le Bail, 2007). The use of specific enzymes combined with appropriate processing conditions (specific cooling and freezing rates) could probably allow for a reduction in crumb contraction (Ribotta and Le Bail, 2007). Almeida and Chang (2012) found that the problem of structure of par-baked bread during the cooling and freezing steps (shrinkage) could be circumvented through joint adoption of the following measures: carrying out a more open modeling, stopping the proofing stage when the dough is resistant to touch (with the objective of the dough not losing its power to support the structure, achieving greater volume in a fragile structure), establishing the par-baking stage well: only a few seconds of steam at the beginning of baking, appropriate baking time versus temperature curve, last moments carried out in dry conditions (steam elimination) and ending only when the center of the bread reaches 93–96°C.

Snow-white Discoloration

One of the prejudices caused by frozen storage is the appearance of snow-white discoloration of the crumb. The occurrence of this white ring or freezing ring is a consequence of the drying out of the crumb just below the crust during frozen storage (Sluimer, 2005). Researchers have shown that the white rings that start to appear under the crust are caused by the transference of moisture by sublimation and diffusion from the highly moist center of the crumb to the low moisture content region of the crust (Pyler, 1988). The appearance of discoloration occurs after a relatively long time in the freezer. After thawing the ring becomes weaker but does not disappear (Sluimer, 2005).

Separation of the Crust from the Crumb

Not all bakery products can be frozen with success. This is especially true for crisp bread (for example baguettes) in which the most obvious manifestation of the quality problem is the separation of the crust from the rest of the product. In crispy bread there is a considerable difference in moisture content between the crust and the crumb, which means that they freeze and thaw and expand and contract at different rates. This puts considerable pressure on the structural architecture of the product, and the final result of various tensions and deformations is the separation of the crust from the crumb. This problem could be solved by the migration of moisture from the crumb to the crust, which would subsequently leave it softer and more flexible, but in this case the nature of the product would be changed to a degree which could be unacceptable for a crisp product (Cauvain, 1998).

Crust Flaking

One of the biggest problems occurring with the quality of frozen par-baked bread is crust flaking (Ribota and Le Bail, 2007). The non-systematic occurrence of flaking on a production scale suggests that this phenomenon must be conditioned by factors related to the production environment (Lucas et al., 2005a). Crust flaking sometimes appears during the last stage, seriously compromising the sensory quality of the bread. Industrial practices suggest that the freezing step is responsible for flaking, and no flaking occurs in the final baking step if the bread is not frozen (Lucas et al., 2005a).

It was found that crust flaking increased with freezing of the bread if the bread was completely baked and frozen, and frozen par-baked bread showed considerably more flaking than conventionally baked bread (Curic et al., 2008).

Le Bail et al. (2005) showed that the relative humidity during fermentation and pre-cooling was the key factor in the control of the amount of flaking. To obtain better crust characteristics for re-baked frozen par-baked baguettes (minimizing flaking), a final fermentation under moist conditions (relative humidity between 90 and 95%) was better than dryer conditions (relative humidity between 50 and 55%), and similarly cooling after par-baking carried out under moist conditions (relative humidity between 90 and 95%) was better than under dry conditions (relative humidity between 50 and 55%). Other factors that helped minimize crust flaking of baguettes were the application of steam at the start of par-baking, and maintaining the temperature of the product not too high at the start of freezing. The results obtained with a temperature of 35°C at the center, the lowest temperature investigated, were better than those obtained with a temperature of 55°C.

Crust flaking can be explained by a synergic effect of a multiple group of parameters (Ribotta and Le Bail, 2007). Three factors are cited as causing flaking: thermo-mechanical shock (Hamdami et al., 2007; Lucas et al., 2005b; Ribotta and Le Bail, 2007), drying out of the crust (Hamdami et al., 2007; Curic et. al., 2008) and an accumulation of ice under the crust (Hamdami et al., 2007).

Crust flaking could be related to mechanical changes due to thermo-mechanical shock occurring during cooling-freezing and final baking. The crust and crumb are two different materials, and depending on the degree of hydration of the crust at the end of par- baking, the crust will be more or less susceptible to the thermo-mechanical stress imposed during the freezing process (Hamdami et al., 2007). According to Lucas et al. (2005b), if the volume cannot deform itself as a response to the compression force of the gas phase during cooling, or to the retraction of the protein network, tension forces will develop within the structure. These forces associated with the tension and stress act in a very narrow domain (crust–crumb interface) in which extreme gradients in terms of temperature, moisture, and frozen water occur (Ribotta and Le Bail, 2007). This will weaken it and make parts of the structure separate more easily from the whole, that is, the crust will flake (Lucas et al., 2005b).

The processing conditions can influence the quality of frozen par-baked bread, which could be related to the excess of drying out at the surface during cooling after par- baking, and the freezing process itself. Such excessive drying out could be responsible for flaking and/or for the color with no shine of the crust (Hamdami et al., 2007; Curic et al., 2008).

An accumulation of ice under the crust during freezing can also contribute to the crust flaking and thus this can be considered as a quality indicator (Hamdami et al., 2007).

RE-BAKING

The main objectives of the second phase of oven baking are the reversal of bread staling, formation of the crust, provision of a brown color to the crust and aroma development (Leuschner et al., 1997, 1998, 1999; Sluimer, 2005). Almeida and Chang (2013a) found that during the re-baking step the bread structure continues to be formed. The starch gelatinization process beginning in the par-baking step continued in the re-baking step in three parts (inner crumb, outer crumb, and crust) of the French rolls made with whole wheat flour, mainly in the inner and outer crumbs.

In order to obtain an acceptable color during re-baking, the oven temperature should be high, for example, above 250°C. Thus in order to maintain the water loss low, the re-baking time should be kept short, about 10 minutes for rolls and 25 minutes for loaves (Sluimer, 2005). Nevertheless, Leuschner et al. (1997) found that it was possible to establish bread re-baking at lower temperatures. These authors showed that browning of the crust occurred quicker at 200°C than at 180°C. A re-baking time of 20 minutes in an oven at 180°C was sufficient to revert the firmness of bread staling and recover the crumb softness of fresh bread.

During re-baking, contraction of volume and specific volume can occur. For French rolls substituted with whole wheat flour, the mean reduction in volume of the re-baked rolls, as compared to the par-baked rolls, was 5.8%, and that of the specific volume was 5.0% (Almeida and Chang, 2012), while for French rolls elaborated with refined wheat flour, volume reductions of 7.5% and specific volume reductions of 3.9% for re-baked bread as compared to par-baked bread were found (Ferreira et al., 1999). Leuschner et al. (1997) also found a volume loss of the bread (10%) during storage and re-baking, but it was not dependent on the re-baking time. However, there was a linear increase in weight loss with re-baking time, which was slightly higher at 200°C than at 180°C.

The loss of moisture due to evaporation of water is another aspect related to re-baking (Bárcenas and Rosell (2006b). Working with loaves made with 850 g portions of dough, Leuschner et al. (1997) showed that the moisture loss only occurred in the crust area (up to 10 mm below the crust), the rest of the loaf being unaffected. The moisture content of the crust decreased from 40 to 20% whereas that of the crumb remained constant at 45%. Almeida and Chang (2013a) also verified that moisture of the inner and outer crumbs remained high even after the two steps of baking in French rolls, whereas the crust lost a significant amount of moisture. These authors and Carr et al. (2006) found that high moisture content in crumb is retained due to steam application during re-baking.

With respect to color, crumb color usually is not affected by the second phase of re-baking (Almeida and Chang, 2013a; Leuschner et al., 1997).

Karaoglu and Kotancilar (2006) concluded that in relation to crumb softness, a long re-baking time is recommended for white loaves baked in two steps (re-baking after par-baking and storage). However, in relation to specific volume, a short re-baking time is recommended.

CONCLUSIONS

With the change in life style of the population and consequent need for products that are more and more convenient, par-baked bread has demonstrated great success, since it requires almost no time and effort for finalization. In addition it represents an alternative for industries with large-scale production which need more useful time for their product to allow for commercialization at great distances. From the studies cited above, it can be seen that care with the formulation and process are necessary to overcome structural defects of the bread and offer quality products. There are still many opportunities for further study, with the expectation that par-baked bread can become impossible to differentiate from conventionally produced fresh bread by the consumer.

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