TEXTURE OF BREAD CRUST: PUNCTURING SETTINGS EFFECT AND ITS RELATIONSHIP TO MICROSTRUCTURE

R. ALTAMIRANO-FORTOUL ¹, I. HERNANDO ², C.M. ROSELL ^{1*}

¹ Institute of Agrochemistry and Food Technology. CSIC. Avenida Agustin Escardino,
7. Paterna 46980. Valencia. Spain.

² Department of Food Technology, Universitat Politècnica de Valencia, Camino de Vera
14, 46022 Valencia, Spain.

Running head: Texture and microstructure of bread crust

*Corresponding author: croSELL@iata.csic.es

Tel +34 963900022

Fax +34 963636301

Funding sources:

Spanish Ministerio de Ciencia e Innovación (Project AGL2008-00092/ALI and AGL2011-23802) and the Consejo Superior de Investigaciones Científicas (CSIC).

Conflict of interest

This manuscript has not been published previously and neither is under consideration for publication elsewhere. The publication is approved by all authors and tacitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright-holder.

ABSTRACT

The effect of the puncturing settings (crosshead speed and punch cross section) on the crust mechanical parameters was investigated using breads with two different crust thickness. Results showed that, greater punch cross section was associated to compression behavior, which reduced the sensibility to detect changes in the crust structure. Moreover, low crosshead speed (0.5 mm/s) puncture test provided information about the cellular structure of the crust. The relationship between the puncturing parameters and the water activity and moisture content together with the crust microstructure analysis revealed that for obtaining reliable information about the structural ruptures related to crispiness texture, it is necessary to use low crosshead speeds (0.5 mm/s) and low punch cross section (3 mm²). Crust microstructure observations indicate that the crust layers and the size and shape of the air cells are responsible of the puncturing behavior.

Key words: bread; crust texture; puncturing; water activity; moisture content; microstructure.

PRACTICAL APPLICATIONS:

Texture of the bread crust is an important parameter used to define the quality of crispy breads and their freshness. Consequently, the extension of crust crispiness is still a priority for the baking industry. Different methods have been proposed for assessing the mechanical properties of the bread crust, although punching is a common feature in all of them. However, there is no information about the incidence of punching settings on the bread crust mechanical parameters. Water activity and moisture content of the crust, besides scanning electron microscopy of the crust section were used to confirm the reliability of the mechanical parameters. The study allows defining the best conditions to study the crust mechanical properties providing information about the internal cell structure. Results could be very useful at research level and also for the baking industry when investigating crust freshness.

INTRODUCTION

Texture is an important component for the consumer's perception of bread quality. Any food's texture is largely connected to its mechanical properties, which in principle are a direct consequence of the internal food microstructure. Texture is considered a multidimensional attribute that comprised a number of different textural properties (Bourne, 2002). In a more specific definition, texture is primarily the response of tactile senses to physical stimuli that result from contact between some part of the body and the food. In case of bread the textural attributes that better defined its quality and even freshness are crust crispness and crumb firmness. Different methods have been proposed to measure food mechanical features, which involve techniques like compression, penetration, acoustical procedure and sensory analysis (Van Vliet and Primo-Martín 2011). Texture evaluation in crispy food is a complex subject, because of that the combination of techniques involving sensory analysis, acoustical procedure and instrumental analysis has been performed. Many authors use these techniques, for instance to evaluate the relationship between texture and sensory attributes on potato chips (Jaworska and Hoffmann 2008). On the other hand, Duizier (2001) and Varela *et al.* (2008) used the combination of acoustic analysis with mechanical testing for analyzing crispness. Nevertheless, instrumental measurements are generally preferred to evaluate objectively the attributes related to the mechanical properties (Valles Pamies *et al.* 2000). In fact, loudness, crispness and firmness are correlated with peak force, slope, force-deformation and Young's Modulus (Vickers and Christensen 1980, Sauvageot and Blond 1991; Valles Pamies *et al.* 2000; Carr *et al.* 2006; Mazumder *et al.* 2007).

Regardless the instrumental technique used to characterize food texture, the puncture test is one of the most widely applied for texture evaluation and its application in food texture measurement has been comprehensively studied (Georget *et al.* 1995; Van Hecke *et al.* 1998; Cheng *et al.* 2007; Arimi *et al.* 2010; Altamirano-Fortoul and Rosell 2011). Considering that the textural properties of a food depend on its structural elements, the puncture test has been used for defining the texture in cellular foods (Van Hecke *et al.* 1998; Valles Pamies *et al.* 2000). From the recorded force-displacement plots, obtained after fracture, it can be calculated the average of the so-called puncturing force (integral of force–time), the number of spatial ruptures, the average specific force of structural ruptures and the crispness work (Van Hecke *et al.* 1998; Valles Pamies *et al.* 2000). The puncture test measures the force required to push a punch or probe into a food. The test is characterized by (a) the force measuring instrument, (b) penetration of

the probe into the food causing irreversible damage or failure results, and (c) the depth of penetration (Bourne 2002).

Regarding crust mechanical properties, different instruments and settings have been used without applying any objective criteria for selecting those. Van Nieuwenhuijzen *et al.* (2008) used a texture analyzer (TA-XT Plus, Stable Micro Systems Ltd., Surrey, UK) to evaluate a model crust, where the pieces were punctured with a cylinder of 2 mm diameter at a speed of 0.1 mm/s. While, Primo-Martin *et al.* (2009) used a 32 mm diameter probe and a compression speed of 40 mm/s. The crust of crispy breads obtained from part-baked has been investigated by puncturing with a cylindrical probe (4 mm diameter) at crosshead speed of 40 mm/s (Altamirano-Fortoul and Rosell 2011) or 50 mm/min (Mandala 2005). Despite the wide use of puncturing for assessing crust features, there is no information about the incidence of punching settings on the bread crust mechanical parameters and neither the impact of the crust microstructure on those measurements.

The texture of food is a result of its core structure and the mechanical properties of this, being that some crispy foods are cellular solids, and they contain holes filled with gas or liquid (bread or vegetables and fruit). Nevertheless, it must be in mind that the mechanical behavior of the crispy food crusts is affected by their morphology and structure. Consequently, the use of instrumental methods and microstructure analysis would certainly be an alternative for providing more information about the texture of crispy food crust.

The objective of this study was to determine the effect of the puncturing settings (crosshead speed and punch cross section) on the crust mechanical parameters. Moreover, the study aimed to select the appropriate puncturing settings for identifying crust features based on water activity and moisture content of the crust and also its relationship to microstructure analysis. Scanning electron microscopy (SEM) of the crust section was used to confirm the reliability of the mechanical parameters. With that purpose breads with two different crust thicknesses were used.

MATERIALS AND METHODS

Materials

Two different specialties of part-baked frozen breads provided by Forns Valencians S.A. (Valencia, Spain) were used. Those specialties were selected for giving breads with

different crust section, thus hereafter they will be referred as thin and thick crusts. Chemical proximate composition of bread with thin crust was 30.1 g/100g moisture content, 60 g/100g carbohydrates, 2.74 g/100g fats and 6.41 g/100g proteins. The composition of the one with thick crust was 34.3 g/100g moisture content, 59 g/100g carbohydrates, 0.72 g/100g fats and 5.41 g/100g proteins.

Full baking process and storage

Part-baked breads were removed from the freezer (-18°C) and thawed at room temperature till the center of the loaf reached 5°C. Then, they were baked in an electric oven (Eurofours, France). Baking conditions varied with specialty and were as follows: 180°C for 11 min in the case of bread with thick crust, 180°C during 18 min for the one with thin crust. Both specialties required a preheated oven at 220°C.

For each specialty, two sets of samples were used, which were baked in separate days. Fresh Loaves (0.5 h after baking) were tested for textural characteristics (mechanical properties), water activity, moisture content, crust section and structure.

Physicochemical analysis

Moisture content and water activity were determined in the crust and crumb of breads. Crust and crumb were separated using a razor blade based on white versus brown color. Moisture content was determined following ICC standard method (1994) (ICC 110/1). Water activities were measured using a water activity unit (Aqua Lab Series 3, Decagon devices, Pullman, USA) at 25°C.

Crust section analysis was performed by scanning cross section of bread sample, 10 mm thick, in a flat bed scanner equipped with the software HP PrecisoScan Pro version 3.1 (HP scanjet 4400C, Hewlett-Packard, USA). The default settings for brightness (midtones 2.2) and contrast (highlights 240, midtones 2.2, shadows 5) of the scanner software were used for acquiring the images. The crust section was calculated from the scanned samples at the upper and bottom side using an image analysis program (UTHSCSA Image Tool software, TX, USA).

All determinations were carried out in triplicate for each set of samples.

Puncture tests

Loaves were puncture tested using a texture analyzer with a 5 kg load (TA XTplus, Stable Micro Systems, Surrey, UK). The analysis consisted in recording the force

required to penetrate the bread crust by punching the sample at three different points of bread surface: in the middle of the crust area and at 2 cm distance on both sides. Experiments were carried out using cylindrical probes with diameters 2 mm (punching area=3 mm²), and 6 mm (punching area= 28 mm²) at varied crosshead speed that included 0.5, 1, 10, 20, 30 and 40 mm/s.

The data were analyzed using the method proposed by Van Hecke *et al.* (1998). This method is based on the peak analysis of the force-deformation curves. From the force-deformation curve the following puncturing parameters were determined:

$$\text{Average puncturing force } F_m(\text{N}) = \frac{A}{d} \quad \text{Eq. (1)}$$

$$\text{Spatial frequency of structural ruptures } N_{wr}(\text{m}^{-1}) = \frac{No}{d} \quad \text{Eq. (2)}$$

$$\text{Average specific force of structural ruptures } f_{wr}(\text{N}) = \sum \frac{\Delta F}{No} \quad \text{Eq. (3)}$$

$$\text{Crispness work } W_c(\text{N.m}) = \frac{F_m}{N_{wr}} \quad \text{Eq. (4)}$$

Where No : is the total number of peaks, d is the distance of penetration (mm), ΔF is the individual force drops for each peak (N) and A is the area under the force-deformation curve.

Four breads from each set were used for carrying on the puncture test, obtaining 24 individual measurements for each experimental point.

SEM of bread crust

Scanning electron microscopy (SEM) was used to examine the crust of bread. Slices of bread were freeze-dried previously to the microscopy analysis. Sample cubes (1cm³) were fixed with the aid of colloidal silver and then coated with gold (Baltec SCD005) at 10⁻² Pa and an ionisation current of 40 mA. The observation was carried out in a JEOL JSM-5410 scanning electronic microscope at 10 kV.

Statistical analysis

Data were presented as mean of sample sets. Statistical analysis of the results was performed using Statgraphics Plus V 7.1 (Statistical Graphics Corporation, UK). In

order to assess significant differences among samples, a multiple sample comparison was performed. The analysis of variance was carried out to decompose the variance of the data into two components: a between-group component and a within-group component. When the P-value of the F-test was lesser than 0.05, there was statistically significant difference between the means of the 2 groups at the 95.0% confidence level. Multiple range test was used to determine which means were significantly different from which others and Fisher's least significant difference (LSD) procedure was used to discriminate among the means. A correlation matrix was established to analyze the relationship among variables. The correlation matrix shows Pearson product moment correlations between each pair of variables (Rodgers and Nicewander 1988).

RESULTS AND DISCUSSION

Physicochemical characteristics of fresh bread

The crust section was initially determined in the specialties selected to confirm that they obey the criteria of significant different crust width. The upper crust of the sample identified as thick crust had a section of 5.10 mm, which was significant ($P < 0.05$) different than that in the bread with thin crust (2.94 mm). Sluimer (2005) reported that in the case of a soft bun or pan bread, the thickness of the crust is restricted to 2-5 mm on the top crust and the side and bottom crust are thinner.

Numerous studies have been carried out stating the importance of the moisture content and water activity on the crust mechanical properties (Van Hecke *et al.* 1998; Kawas and Moreira 2001; Lewiki 2004; Varela *et al.* 2008). Water is a constituent of food which affects food stability, quality and textural properties; because of that, special emphasis was put in assessing moisture content in the loaves. A significant difference was determined at a confidence level of 95% between the water activity and moisture content of the two breads. In the bread with thin crust, the water activity of the crust was 0.522 and 0.971 for the crumb. On the opposite side, the bread with thick crust exhibited the highest (0.540) water activity in the crust with also high values in crumb (0.976). Castro-Prada *et al.* (2009) reported that increment in water activity of crispy products induces the transition from brittle to ductile fracture behavior. Water leads to plasticization and thus alters the mechanical properties of the product. Previous studies in bread reported that a_w of 0.68-0.69 would be the point where the mechanical

transition (brittle to tough) of crust occurs (Altamirano-Fortoul and Rosell 2010). In the present study, the water activity values for both crust thickness were lower than that range, which ensures that experimental assessment of crust mechanical properties were carried out when they behave as crispy material.

Similarly, moisture content in the crust and in the crumb showed significant differences; being 11.46 g/100 g and 40.89 g/100 g for the bread with thick crust and 9.67 g/100 g and 39.16 g/100 g for the bread with thin crust, respectively. Those values were within the range of previous findings for breads (Baik and Chinachoti 2000; Altamirano-Fortoul and Rosell 2011).

Effect of punching settings on the puncturing parameters of thin and thick bread crust

Bread crust texture was measured by a puncture test and the method proposed by Van Hecke *et al.* (1998) was used for assessing puncturing parameters from the force-time or deformation curves. A multiple comparison analysis was performed to determine the possible effect of the punch cross section (probe) and crosshead speed and to have greater understanding of the factors that influence the puncturing parameters. The puncturing conditions (punch cross section and speed) affected significantly ($P < 0.05$) all mechanical parameters used to characterize the bread crust in two types of samples (breads with thin and thick crusts).

The first parameter defined from the force-time or deformation curve was the average puncturing force (F_m), which represents the mechanical resistance that has a product when a force is applied. Figure 1 shows the influence of punch cross section and test speed on F_m parameter when the texture of crust was determined in two types of breads which differed on the crust thickness.

In general, higher values were observed with larger punch cross section (28 mm²) in both samples. Therefore, regardless the thickness of the crust, F_m parameter was dependent on the punch cross section. With major probe section higher number of cells is compressed leading to wider force-deformation curve, where the maximum force is an indication of the peak resistance offered by crust during compression. An increase in the section to be compressed enhances the force and consequently the other parameters related to the force. In fact, Van Hecke *et al.* (1998), when studied the mechanical parameters in extruded products, found that at higher punch cross section the compression acquires major importance. In addition, the average puncturing force was

crosshead speed dependent, obtaining higher values for F_m at lower speed, and that effect was more noticeable with thick crust. The speed of travel of the punch is an important factor when testing viscoelastic foods because they are strain-rate sensitive (Bourne 2002). As expected, thick crust required great force (F_m) for puncturing than thin crust, but that was only correct for puncturing test carried out at crosshead speed up to 10mm/s, and beyond that speed the trend was reversed.

In thin bread crust, the average puncturing force was more dependent of the probe than the speed, obtaining higher F_m values at higher punch cross section, but values were barely constant when modifying the crosshead speed. In the case of thick bread crust, independently of the punching section, the maximum F_m values were obtained at lower speeds, and a progressive decreased of this parameter was observed when increasing the speed. The low speed produced a jagged force displacement plots, resulting slow speed of deformation, where the molecules presented conformational changes in direction of applied force, resulting in higher mechanical resistance. These results agree with the explication of Tsukakoshi *et al.* (2008) that observed differences in force-deformation curves based on the plunger or probe speed.

The N_{wr} parameter, or spatial frequency of structural ruptures, is related to the number of peaks caused during the fracture of the sample. Therefore, a highly jagged curve profile with many peaks due to numerous fracture events is often produced by products that are perceived as crispy. In fact, if the sample is undergoing a large amount of fracture events, this is related to a more crispy texture (Vicent 1998). Considering the above, if during the fracture events there is major number of structural ruptures (high value of N_{wr}), it indicates that the sample is more crispy. In the Figure 2 it is shown the effect of the punch cross section and speed on N_{wr} parameter. The effect of the puncturing conditions on the N_{wr} was dependent on the crust section. In the thick bread crust, the N_{wr} versus speed plot showed a bell shape trend, with maxima values within 20 mm/s to 30 mm/s speeds, and significantly higher values were obtained when using lower punch cross section (3 mm²). Those results demonstrate that a greater punch cross section caused the decrease of the jaggedness of the force-deformation curve as well as the peaks presents, and consequently there were fewer structural ruptures. Considering that a thickness of more than 5 mm is a good level for crusty bread (Sluimer 2005); this thick bread crust might have more cellular structure, therefore there were more structural ruptures in short time.

In thin bread crust, the highest value of this parameter was obtained when using greater punch cross section (28 mm^2), but the tendency reversed with increasing speed (puncturing speed $\geq 20 \text{ mm/s}$). With low punch cross section (3 mm^2) the N_{wr} parameter showed the same bell shape plot that was observed with the thick bread crust.

Overall results suggest that with smaller punch cross section, major number of peaks corresponding to structural ruptures can be detected within less deformation and thus causes greater values of N_{wr} parameter.

Concerning the f_{wr} parameter that relates the specific force with the structural ruptures,, higher values were obtained with great punch cross section (28 mm^2) (Figure 3). Therefore, greater punch section caused a major structural rupture because it encompasses fractures in the walls and small microscopic structures. Since, it is difficult to attribute one observed fracture to a single wall beneath the center of the plunger, as was observed by Tsukakoshi et al. (2008) when studied mechanical properties of snacks by using a wide plunger.

In the thin bread crust, f_{wr} parameter increased significantly when using the punch cross section of 28 mm^2 at speed higher than 1 mm/s speed. Nevertheless, with smaller punch cross section (3 mm^2) this parameter exhibited a slightly different behaviour; it showed maximum value at 0.5 mm/s crosshead speed and after a steep decrease, it showed a steady increase from 20 mm/s . In the thick bread crust, a more erratic behavior was observed, but it was possible to detect that the values obtained with the low punch cross section were less dependent on the crosshead speed than those obtained with the punch cross section of 28 mm^2 . Therefore, results on average specific force with the structural ruptures show that independently of crust thickness, at higher speeds and punch section the mechanical resistance in the cell walls increases.

The parameter crispness work, W_c , was significantly dependent on the punch cross section and the crosshead speed used for carried out the assessment (Figure 4). Crispness work decreased with the crosshead speed of puncturing assay, excepting when thin bread crust was punctured with large punch cross section (28 mm^2). With the large punch cross section, W_c parameter showed a steady increased with the crosshead speed when assessing thin bread crust mechanical properties. Dan and Kohyama (2007) found that the increase in fracture work associated with the test speed is due to higher fracture force. However, present results indicate that large punch cross section can be

responsible of that behaviour, where pure compression force could mask the real fracture force. Crispness work results suggest that only by using low puncturing speed is possible to assess this parameter, independently of the punch cross section used, reducing the interference of the compression.

High value of crispness work indicates that the structure is difficult to fracture. Considering that thick bread crust has a more crispy texture, with stiff structure that collapse with a brittle fracture, the fracture of the crust would need more work. Therefore, puncturing settings play a fundamental role when determining the mechanical parameters of bread crust. Crosshead speed of the puncture test and the punch cross section affected the mechanical parameters and the effect was largely noticeable with thick bread crusts.

Relationship between crust puncturing parameters and water activity and moisture content

It has been previously stated the role of water in the mechanical properties of foodstuff. However, since the values of the mechanical parameters are greatly dependent on the setting conditions, a possible relationship between the puncturing parameters and the water activity and moisture content must be established.

A multivariate analysis was applied to determine the possible correlation among the water and the puncturing parameters that defined the mechanical properties of the crust (Table 1 and 2) using the two punch cross section tested and the lowest (0.5 mm/s) and highest (40 mm/s) crosshead speeds used.

Using the experimental data obtained at the low speed and punch cross section, regardless of the crust thickness (Table 1), a significant positive relationship was obtained between the F_m parameter and water activity and moisture content. A significant negative relationship was observed with the spatial frequency of structural ruptures (N_{wr}) and the water activity and moisture content. In addition, a significant positive relationship was obtained between the crispness work, W_c parameter, and moisture content/water activity. No significant relationships were observed between f_{wr} and neither water activity or moisture content.

Some divergences were obtained when the experimental data obtained at high speed and punch cross section were used for obtaining the correlation matrix (Table 2). Again, the F_m showed a significant positive relationship with the water activity and moisture

content and no relationship were observed with f_{wr} . Conversely to results obtained at low speed and low punch cross section, a significant positive relationship was observed with the spatial frequency of structural ruptures (N_{wr}) and the water activity and moisture content and the correlation coefficients indicated a moderately strong relationship between the variables. Whereas W_c parameter showed a significant negative relationships with water activity and moisture content.

According to the results presented in Table 1 and 2, it should be remarked that water influences the mechanical properties of bread crusts as well as it affected their response to force required for crust fracture. The positive relationship F_m with the water activity and moisture content independently of the test conditions might be consequence of the strong interaction of water molecules with the rest of the macromolecules that constitute the bread crust. Conversely, the frequency of structural ruptures (N_{wr}) and the crispness work were more sensitive to experimental settings. Taking into account that water molecules act as plasticizer and soften the starch–protein matrix, besides that an increase in water activity or in the moisture content decreases the frequency of structural ruptures (N_{wr}) (Van Hecke *et al.* 1998), it seems that mechanical properties of bread crust might be only accurately determined when low crosshead speed and low punch cross section are used (Table1), where N_{wr} and W_c show negative relationship with the water activity and water moisture content.

Crust structure

In order to support the puncturing parameters results, the microstructure of the cross-section in each bread was analyzed by SEM. Micrographs confirmed microstructure differences between thin and thick crusts of bread (Figure 5). Two different structural zones were detected in the so-called bread crust, a dry crust and a sub-crust. The sub-crust is of great importance because it gives rise to chemical transition between the crust and the crumb and also allows to show where ends the crust and where begins the crumb. Figure 5a and 5b show the micrographs of crust zones in both samples. The swollen granules and partially solubilized starch as well as proteins act as essential structural elements of bread. Therefore, bread crust is formed by a network of gluten protein with starch granules (Cuq *et al.* 2003). Thin bread crust presented a small section of zone 1 than the thick bread crust. In addition, thin bread crust showed a smooth zone 2 (Figure 5a), whereas thick bread crust exhibited an irregular zone 2 with cracking structure (Figure 5b). Therefore, the differences observed when assessing the

mechanical parameters responded to microstructural differences. The puncture plot of the thick bread crust displayed irregular peaks in the force curves, which is characteristic of a crispy product. This crust presented multiple fracture events, which could be the result of cracks and irregular morphology.

In zone 1, it was possible to detect the layers and air cells with varying dimensions, where the differences in the cellular structure were readily apparent. The thin bread crust showed few layers (Figure 5c), whereas the thick bread crust had more layers and contain more irregular and larger cells (Figure 5d). That observation is accordance with the puncturing results, since greater values were obtained for thick bread crust, because the presence of air cells more fully stretched required greater force to fracture them.

At higher magnification, in the inner zone of the crust, the thin crust showed a homogeneous structure, where starch granules were embedded in a lipoprotein network and covered by a coating (Figure 5e). However, thick crust showed some loose starch granules on the matrix surface, giving place to a more heterogeneous starch structure with the presence of cells and discontinuous phase (Figure 5f). This effect might be responsible of the mechanical behavior of thick crust, which was much less resistant to the compression and collapsed as a result of the compression force on the surface, therefore the fracture occurred rapidly. The morphology of the crust in crispy foods determines the mechanical properties behavior (Luyten *et al.* 2004). Sam *et al.* (2001) found that chips with thicker cell walls and larger internal voids were judged crispier, which is consistent with the thick crust results.

Possibly, the differences in the structure between the samples were ameliorated by the water molecules present in the breads due to a plasticizing effect. Martinez-Navarrete *et al.* (2004) found that water leads to plasticization and softening of the starch-protein matrix and thus alters the strength of the product. On the other hand, the starch granule may therefore contribute to the product architecture in different ways.

CONCLUSION

When studying the mechanical properties of bread crust by puncturing, the test settings, namely crosshead speed and punch cross section, exert great influence in the data recorded, and that effect is magnified when increases crust thickness. The relationship between the puncturing parameters and the water activity and moisture content together with the crust microstructure analysis allow selecting the most appropriate texture

settings for obtaining reliable mechanical parameters. Strong positive relationship is observed between the average puncturing force (F_m) and the water activity and moisture content. However, for obtaining reliable information about the cellular structure of the crust, that is the amount of fracture events or structural ruptures related to crispiness texture, it is necessary to use low crosshead speeds (0.5 mm/s) and low punch cross section (3 mm²), which will reduce the incidence of the compression. Crust microstructure observations indicate that the crust layers and the size and shape of the air cells are responsible of the puncturing behavior.

ACKNOWLEDGEMENTS

Authors acknowledge the financial support of Spanish Ministerio de Ciencia e Innovación (Project AGL2008-00092/ALI and AGL2011-23802) and the Consejo Superior de Investigaciones Científicas (CSIC). Altamirano-Fortoul would like to thank her PhD grant (JAE pre) to CSIC. The authors also thank Forns Valencians S.A. (Spain) for supplying commercial frozen partially baked breads.

REFERENCES

- ARIMI, J.M., DUGGAN, E. O’SULLIVAN, M., LYNG, J.G. and O’RIORDAN, E.D. 2010. Development of an acoustic measurement system for analyzing crispiness during mechanical and sensory testing. *J. Texture Studies* 41, 320-340.
- ALTAMIRANO-FORTOUL, R. and ROSELL, C. M., 2011. Physico-chemical changes in breads from bake off technologies during storage. *LWT - Food Sci. Technol.* 44, 631-636.
- ALTAMIRANO-FORTOUL, R. and ROSELL, C.M. 2010. Alternatives for extending crispiness of crusty breads. *Proceedings of International Conference on Food Innovation, FoodInnova, Spain* (pp. 631–636). ISBN978-84-693-5011-9.
- BAIK, M.Y., and CHINACHOTI, P. 2000. Moisture redistribution and phase transitions during bread staling, *Cereal Chem.* 77(4), 484–488.
- BOURNE, M.C. 2002. *Food Texture and Viscosity: Concept and Measurement*, 2nd Ed., Academic Press, London/San Diego.

- CARR, L.G., RODAS, M.A.B, DELLA TORRE, J.C.M. and TADINI, C.C. 2006. Physical, textural and sensory characteristics of 7-day frozen part-baked French bread. *LWT - Food Sci. Technol.* 39, 540-547.
- CASTRO-PRADA, E.M., PRIMO-MARTÍN, C., MEINDERS, M.B.J., HAMER, R.J. and VAN VLIET, T. 2009. Relationship between water activity, deformation speed, and crispness characterization. *J Texture Studies* 40, 127–156.
- CHENG, E.M, ALAVI, S., PEARSON, T., and AGBISIT, R. 2007. Mechanical-acoustical and sensory evaluations of cornstarch-whey protein isolate extrudates. *J. Texture Studies* 38, 473–498.
- CUQ, B., ABECASSIS, J., and GUILBERT, S. 2003. State diagrams to help describe wheat bread processing. *Int. J. Food Sci. Technol.* 38, 759-766.
- DUIZER, S. 2001. A review of acoustic research for studying the sensory perception of crisp, crunchy and crackly texture. *Trends Food Sci. Technol.* 12, 17-24.
- GEORGET, D. M. R., PARKER, R., and SMITH, A. C. 1995. Assessment of a pin deformation test for measurement of mechanical properties of breakfast cereal flakes. *J. Texture Studies* 26, 161–174.
- ICC. International Association for Cereal Science and Technology. 1994. General principles of the available ICC standard methods. International Association for Cereal Science and Technology.
- JAWORSKA, D. and HOFFMANN, M. 2008. Relative importance of texture properties in the sensory quality and acceptance of commercial crispy products. *J. Sci. Food Agric.* 88, 1804-1812.
- KAWAS, M.L., and MOREIRA, R. 2001. Characterization of product quality attributes of tortilla chips during the frying process. *J. Food Eng.* 47, 97-107.

- LEWIKI, P.P., JAKUBCZYK, E., MARZEC, A., DO CARMO CABRAL, M., and PEREIRA, P.M. 2004. Effect of water activity on mechanical properties of dry cereal products. *Acta Agrophysica* 4(2), 381-391
- LUYTEN, A., PLUTER, J.J., and VAN VLIET, T.V., 2004. Crisp/Crunchy crusts of cellular solid foods: a literature review with discussion. *J. Texture Studies* 35 (5), 445–492.
- MANDALA, I.G. 2005. Physical properties of fresh and frozen stored, microwave-reheated breads, containing hydrocolloids. *J. Food Eng.* 66, 291-300.
- MARTÍNEZ-NAVARRETE, N., MORAGA G., TALENS P., and CHIRALT A. 2004. Water sorption and the plasticization effect in wafers. *Int. J. Food Sci. Technol.* 39, 555-562.
- MAZUMDER, P., ROOPA, B.S., AND BHATTACHARYA, S. 2007. Textural attributes of a model snack food at different moisture contents. *J. Food Eng.* 79, 511–516.
- PRIMO-MARTIN, C., SÖZER, N., HAMER, R.J. and VAN VLIET, T. 2009. Effect of water activity on fracture and acoustic characteristics of crust model. *J. Food Eng.* 90, 277-284.
- RODGERS J. L. and NICEWANDER W. A. 1989. Thirteen ways to look at the correlation coefficient. *The American Statistician*, 42, 59–66.
- SAUVAGEOT, F. and BLOND G. 1991. Effect of water activity on crispness of breakfast cereals. *J. Texture Studies* 22, 423-442.
- SLUIMER, P. 2005. *Principles of Breadmaking: Functionality of Raw Materials and Process Steps*. Ed. American Association of Cereal Chemists. St.Paul, Minnesota.

- TSUKAKOSHI, Y., NAITO, S., and ISHIDA, N. 2008. Fracture intermittency during a puncture test of cereal snacks and its relation to porous structure. *Food Res. Int. 1*, 909-917.
- VALLES PAMIES, B., ROUDAUT, G., DACREMONT, C., LE MESTE, M., and MITCHELL, J.R. 2000. Understanding the texture of low moisture cereal products: mechanical and sensory measurements of crispness. *J. Sci of Food and Agriculture 80*, 1679-1685.
- VAN HECKE, E., ALLAF, A.K., and BOUVIER, J.M. 1998. Texture and structure of crispy-puffed food products part II: Mechanical properties in puncture. *J. Texture Studies 29*, 619-632.
- VAN NIEUWENHUIJZEN, N.H., PRIMO-MARTIN, C., MEINDERS, M.B.J., TROMP, R.H., HAMER, R.J. and VAN VLIET, T. 2008. Water content or water activity, what rules crispy behaviour?. *J. Agric. Food Chem. 56 (15)*, 6432–6438.
- VAN VLIET, T. and PRIMO-MARTÍN, C. 2011. Interplay between product characteristics, oral physiology and texture perception of cellular brittle foods. *J. Texture Studies 42*, 82-94.
- VARELA, P., SALVADOR, A., and FISZMAN, S.M. 2008. Methodological developments in crispness assessment: Effects of cooking method on the crispness of crusted foods. *LWT- Food Sci. Technol. 41*, 1252-1259.
- VICKERS, Z.M., and CHRISTENSEN, C.M. 1980. Relationships, between sensory crispness and other sensory and instrumental parameters. *J. Textural Studies 11*, 291-308.

FIGURE CAPTIONS

FIGURE 1. EFFECT OF TEXTURE SETTINGS (CROSSHEAD SPEED AND PUNCH CROSS SECTION) ON THE AVERAGE PUNCTURING FORCE (F_m) OF THICK (OPEN SYMBOLS) AND THIN (CLOSED SYMBOLS) CRUST BREADS. Legends: 3 mm² punch cross section (●), 28 mm² punch cross section (▼).

FIGURE 2. EFFECT OF TEXTURE SETTINGS (CROSSHEAD SPEED AND PUNCH CROSS SECTION) ON THE FREQUENCY OF STRUCTURAL RUPTURES (N_{wr}) OF THICK (OPEN SYMBOLS) AND THIN (CLOSED SYMBOLS) CRUST BREADS. Legends: 3 mm² punch cross section (●), 28 mm² punch cross section (▼).

FIGURE 3. EFFECT OF TEXTURE SETTINGS (CROSSHEAD SPEED AND PUNCH CROSS SECTION) ON THE AVERAGE SPECIFIC FORCE OF STRUCTURAL RUPTURES (f_{wr}) OF THICK (OPEN SYMBOLS) AND THIN (CLOSED SYMBOLS) CRUST BREADS. Legends: 3 mm² punch cross section (●), 28 mm² punch cross section (▼).

FIGURE 4. EFFECT OF TEXTURE SETTINGS (CROSSHEAD SPEED AND PUNCH CROSS SECTION) ON THE CRISPNESS WORK (W_c) OF THICK (OPEN SYMBOLS) AND THIN (CLOSED SYMBOLS) CRUST BREADS. Legends: 3 mm² punch cross section (●), 28 mm² punch cross section (▼).

FIGURE 5. SCANNING ELECTRON MICROGRAPHS OF CRUST CROSS SECTION. Images correspond to cross section of breads with thin (a, c, e) and thick (b, d, f) crusts. Micrographs of zones of cross section of bread crust (a, b), inner zone 1 (c, d) at high (750x) magnification (e, f) are shown.

TABLE 1. CORRELATION MATRIX. Correlation coefficients and P -value within the physical and puncturing parameters of the thin and thick crust determined at crosshead speed of 0.5 mm/s and with 3 mm² punch cross section.

Parameters	Parameters				
	N_{wr} (mm ⁻¹)	f_{wr} (N)	W_c (Nmm)	a_w	Moisture content (%)
F_m (N)	-0.3935 *	0.7144 ***	0.9703 ***	0.5044 **	0.7309 ***
N_{wr} (mm ⁻¹)		-0.4157 *	-0.4244 *	-0.456 **	-0.5272 ***
f_{wr} (N)			0.7559 ***	0.1636	0.2274
W_c (Nmm)				0.4852 **	0.695 ***
a_w					0.6083 ***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

TABLE 2. CORRELATION MATRIX. Correlation coefficients and P -value within the physical and puncturing parameters of the thin and thick crust determined at crosshead speed of 40 mm/s and with 28 mm² punch cross section.

Parameters	N_{wr} (mm ⁻¹)	f_{wr} (N)	W_c (Nmm)	a_w	Moisture content (%)
F_m (N)	-0.6131 ***	0.3102 *	0.9686 ***	0.6572 **	0.9837 ***
N_{wr} (mm ⁻¹)		0.4424 *	-0.6232 ***	0.5139 **	0.8138 ***
f_{wr} (N)			0.3488 *	0.1725	0.2553
W_c (Nmm)				-0.4111 *	-0.6541 ***
a_w					0.6083 ***

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

FIGURE 1.

FIGURE 2.

FIGURE 3.

FIGURE 4.

FIGURE 5.