Understanding potato chips crispy texture by simultaneous fracture and acoustic measurements, and sensory analysis

A. Salvador, P. Varela, T. Sanz, S.M. Fiszman*

Instituto de Agroquímica y Tecnología de Alimentos (CSIC), Apartado de Correos 73, 46100 Burjassot, Valencia, Spain

ABSTRACT

The fracture and acoustic properties of six commercial potato chips that differ in sensory hardness and sensory crispness were analysed and related in this work. Principal component analysis showed a correlation among the sensory attributes and the instrumental parameters (both mechanical and acoustic). Two components mainly explained the behaviour of the different potato chips. The first component was positively related to the number of force and sound events, to sound pressure level maximum, to the area under the force curve, and to sensory crispness, and negatively related to fat content; and the second component was positively related to the gradient (slope of the first part of the curve), the potato chip thickness, and to sensory hardness and sensory crispness. The behaviour of the different potato chips was explained by either one of the two components or by both components. Results indicate that certain degree of sensory hardness is necessary for higher crispness perception.

© 2008 Published by Elsevier Ltd on behalf of Swiss Society of Food Science and Technology.

1. Introduction

Potato chips, also known as potato crisps, are popular salty snacks. A potato chip is a thin slice of potato, deep fried or baked until crisp. Potato chips serve as an appetizer, side dish, or snack. Commercial varieties are packaged for sale, usually in multilayered bags. The simplest chips of this kind are just cooked and salted, but manufacturers can add a wide variety of seasonings (mostly made using herbs, spices, cheese or artificial additives). Potato chips are an important part of the snack food market in many countries.

The characteristic crispy texture of potato chips is one of the most important quality indicators of the finished product, apart from colour, odour and flavour. Potato chips texture is often described in terms of crispness, hardness and crunchiness. This crispy/crunchy character is an important sensory characteristic on which consumers base their appreciation.

Raw potato properties as well as manufacturing conditions are important factors determining crispness of potato chips. Segnini, Dejmek, and Öste (1999a) highlighted the significance of potato starch content, position of the sample within the tuber, and final moisture content on the texture of potato chips. Pre-drying after blanching was found to decrease oil absorption and to significantly increased crispness of potato chips (Pedreschi & Moyano, 2005). Also, soaking in NaCl at 25 °C for 5 min after blanching was found to increase crispness (Pedreschi, Moyano, Santis, & Pedreschi 2007).

Fat content and texture of potato crisps are also influenced by frying temperature and the type of oil used for frying (Kita, Lisinska, & Golubowska, 2007).

Texture of potato chips can be evaluated using sensory and instrumental methods (Szcesniak, Brant, & Friedman, 1963). Among the instrumental tests, the puncture test placing the entire potato chip in a three-point support has been widely employed. The maximum breaking force was proposed to quantify the texture of the samples (Pedreschi & Moyano 2005; Pedreschi et al., 2007; Segnini, Dejmek, & Öste 1999a, 1999b). This fracture force seemed to be a good predictor of all the sensory texture attributes (hardness, crunchiness, chewiness, and tenderness) as measured by a trained panel, while deformation at fracture did not significantly correlate with any of the sensory attributes Segnini et al. (1999b).

Vincent (1998) fractured the potato chips and extracted the number of drops in force and the size of the drops from the force–deflection curves. The frequency curves obtained provided a mechanical signature of the crisp food.

Kita, Lisinska, and Golubowska (2007) measured the texture of potato chips using a rectangular share blade and determined the maximum shear force necessary to cut one slice of chips.

The above mentioned methods evaluated texture of the entire potato chip. To be able to obtain fundamental parameters, Rojo and Vincent (2008) evaluated potato chips crispy texture in homogeneous specimens carefully obtained from the potato chips. The mechanical strength was found to be related both to the intrinsic material properties and to the texture of chips. The centrally loaded

* Corresponding author. Tel.: +34 963 90 0022; fax: +34 963 63 6301.
  E-mail address: sfiszman@iata.csic.es (S.M. Fiszman).

plate tests provided a qualitative evaluation of crispness (Rojo & Vincent, 2008).

In general, crispness is characterized by a brittle fracture at low fracture force, and distinguishable fracture events, with the concomitant emission of sound (Duizer, 2001; Luyten, Plijter, & van Vliet, 2004). Vickers (1987) related sensory crispness with acoustic attributes of potato chips measured with an oscilloscope and found that measurements indicating the loudness of the sounds correlated most closely with crispness. Duizer (2001) reviewed the main aspects of acoustic research for studying the sensory perception of crisp, crunchy and crackly textures. Srisawas and Jindal (2003) developed a method for evaluating the sensory crispness of snack food products based on direct application of frequency domain spectra of acoustic signals and the use of neural network models; this study measured the perception of air-conducted sounds and their correspondence with the sensation of crispness; the authors concluded that the precise interpretation of acoustic data was difficult.

A new approach to investigate the acoustic nature of crispness has recently emerged; it is based on the simultaneous recording of the sound and fracture/mechanical events produced during the application of a force to a crisp product. To do so an Acoustic Envelope Detector (AED) was attached to a Texture Analyser. Little research has been done by applying this technique. Recently, Chen, Karlsson, and Povey (2005) and Varela, Chen, Fiszman, and Povey (2006) found a very good connection between some recorded sound parameters, the instrumental texture measured, and the sensory assessment of crispness in biscuits and roasted almonds, respectively.

The aim of this work was to assess the crispness of six different commercial potato chips by using force/displacement measurements in combination with the corresponding acoustic emission, and to relate these results with some compositional and sensory characteristics associated to crispness.

2. Materials and methods

2.1. Samples

Six kinds of commercial potato chips of different characteristics have been studied: "Traditional potato chips" ("T"), "0% salt potato chips" ("0%"), "Extra-crunchy potato chips" ("Extra C"), "Wavy potato chips" ("W"), "Light potato chips" ("L"), and "Potato-based snack" ("Snack"). Their specific composition is shown in Table 1. All

the samples came in their original package (PET-met/PE) of 200 g and were kept at room temperature (21 °C) until testing. For each sample a selection of chips with similar shape and size was made. The potato chips were measured immediately after opening the package.

2.2. Thickness of potato chips

Thickness of potato chips was measured using an electronic digital calliper (range 0–150 ± 0.01 mm). Twenty potato chips of each kind were measured.

2.3. Moisture and fat content

Moisture was determined by vacuum drying at 95 °C to constant weight (standard technique, method 950.46, AOAC, 2000). Total fat content was determined by direct extraction with ethyl ether for 12 h in a Soxhlet extractor (AACC, 1967). Four determinations were performed for each kind of potato chip.

2.4. Texture and sound emission analysis

A TA-XT plus Texture Analyser (Stable Micro Systems, Godalming, UK) was used for force/displacement measurements with a 25 kg load cell, using a spherical probe (P/0.25S) of ¼-inch diameter; the samples were placed on the HDP/CFS (Crisp Fracture Support Rig and corresponding platform, SMS) (Fig. 1). The test settings were: test speed 1 mm/s, trigger force 5 g, travel distance of the probe 3 mm. An AED described in detail elsewhere (Chen et al., 2005; Varela et al., 2006) was used for sound recording, with the corresponding software (Texture Exponent 32). The gain of the AED was set at one. A Bruel and Kjaer free-field microphone (8-mm diameter), calibrated using an Acoustic Calibrator Type 4231 (94 dB and 114 dB SPL-1000 Hz) was positioned at 4 cm distance with an angle of 45° to the sample. Ambient acoustic and mechanical noise was filtered by the use of a high pass filter of 1 kHz. A low pass filter set the upper calibrated and measured frequency at 16 kHz. The AED operates by integrating all the frequencies within the band
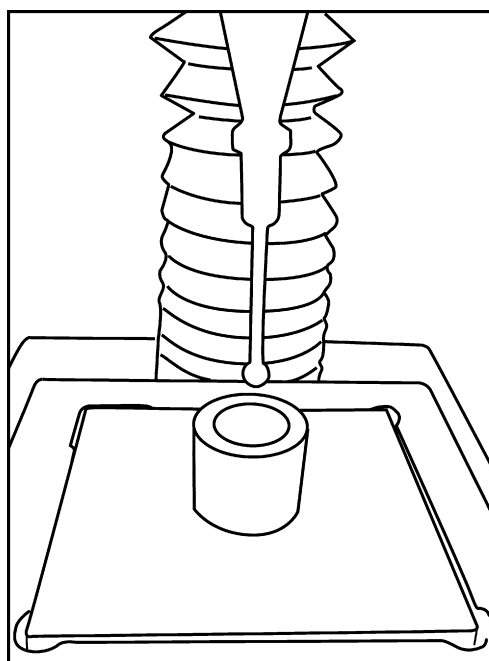
Table 1
Characteristics of the commercial potato chips per 100 g, as described by the manufacturer in the package and the nomenclature adopted in the text.

Sample	Ingredients	Protein (g)	Carbo-hydrates (g)	Fat (g)	Fibre (g)	Sodium (g)	Caloric content (Kcal)
"T"	Potato, vegetable oil and salt	6.0	52.0	37.0	ND	ND	568
"0%"	Potato and vegetable oil	6.5	48.0	35.0	4.5	0.06	530
"Extra C"	Potato, vegetable oil and salt	6.0	48.0	32.0	5.0	1.20	505
"W"	Potato, vegetable oil and salt	6.6	48.6	36.2	ND	ND	547
"L"	Potato, vegetable oil and salt	7.0	60.0	21.0	5.5	0.70	460
"Snack"	Dehydrated potatoes, vegetable oil, and fat, corn flour, wheat starch, maltodextrin, emulsifier: E 471, salt, rice flour and dextrose	6.0	51.0	34.0	4.0	0.50	535

ND: composition not declared.

Fig. 1. Schematic diagram of the Crisp Fracture Support Rig and corresponding platform.

pass range generating a voltage proportional to the sound pressure level (SPL). The data acquisition rate was 500 points per second for both force and acoustic signals. All tests were performed in a laboratory with no special soundproof facilities at room temperature. Fifteen replications were performed for each kind of potato chip. Force/displacement and SPL/displacement curves were simultaneously plotted. From the force curve the following parameters were extracted: area below the force curve, number of force peaks (drop in force higher than 0.049 N), and gradient (slope of the curve up to the first major peak). From the sound curves, the number of sound peaks (drop in sound pressure level higher than 10dB) and the sound pressure level (average of the ten higher peaks, $SPLmax_{10}$).

2.5. Sensory analysis

A panel of 9 assessors with experience in the descriptive evaluation of crispy products was used to evaluate the six samples of potato chips. Testing was carried out in a sensory laboratory equipped with individual booths (ISO, 1988). A balanced complete block experimental design was carried out to evaluate the samples. The intensities of sensory attributes "hardness" and "crispness" were scored on 10 cm unstructured line scales labelled from "low" (0) to "high" (10). To evaluate hardness the instruction was to bite the whole chip with the incisors until fracture and to score the material resistance. To score crispness the instruction was to evaluate altogether during mastication, amount and quality of the sound produced, deformability and brittleness. The samples were served in random order, each on a separate plastic tray, identified with a three digit random code. Panellists were instructed to rinse their mouths with water between sample evaluations.

2.6. Statistical analysis

One-way analysis of variance (ANOVA) was performed on the instrumental and on sensory parameters to evaluate differences among the chip samples. Besides, principal component analysis (PCA) was done to correlate sensory and instrumental parameters. In this analysis the rotation method used was Varimax with Kaiser normalisation and correlations were taken into account if higher than 0.6. Statistical analysis was performed using the SPSS 12 package program (SPSS Inc., Chicago).

3. Results and discussion

3.1. Thickness, moisture and fat content of potato chips

The different potato chips showed significant differences in the values of thickness, moisture and fat contents (Table 2). Potato chips "W" and "Snack" showed significantly the highest thickness values, while potato sample "T" and "0%" showed significantly the lowest. The fat content of potato chips "T" and "0%" was significantly higher than all the other potato chips. As can be expected for being a "light" product, "L" potato chips had the lowest fat content. No relationship among the moisture and fat content could be established, due to the unknown but expected differences in the raw potatoes characteristics and in the manufacturing process of the different potato chips.

The influence of the raw potato characteristics and of the production conditions on the fat content of potato chips was studied by several authors. Kita (2002) studied fat content of chips made from potato tubers of five varieties; he found significant differences among the samples and related fat content to dry mass content: higher dry mass content produced chips with lower fat content. In another study (Kita et al., 2007), the quantity of fat absorbed in potato chips was related to the type of oil and frying

Table 2
Thickness, moisture and fat contents of the potato chips studied.

Sample	Thickness (mm)	Moisture (%)	Fat (%)
"T"	1.2[a]	1.8[a]	35.9[a]
"0%"	1.2[a]	1.6[a]	36.9[a]
"Extra C"	1.3[b]	2.7[b]	29.6[b]
"W"	1.5[c]	1.5[a]	30.7[b]
"L"	1.3[b]	2.2[ab]	18.7[c]
"Snack"	1.4[bc]	3.0[b]	28.7[b]

[abc] For the same column means without a common letter differ ($p < 0.05$) according to Tukey's test.

temperature. Lower temperature was associated to higher fat content. Pedreschi and Moyano (2005) studied the effect of predrying on fat content of potato chips. They found that a pre-drying process increased the crispness of potato chips and reduced significantly the oil absorption of blanched potato slices after frying. However, the relation between fat and moisture content of potato chips and their crispy texture remains unclear. A possible relationship among moisture and fat content of potato chips and their crispy texture is analysed further in this article.

3.2. Texture and sound emission analysis

A representative profile of the force and the simultaneously recorded sound during the probe displacement in the potato chips is shown in Fig. 2.

The force–displacement curves show a jagged appearance with several fracture events, typical of crispy food (Chen et al., 2005; Varela et al., 2006; Vincent, 1998).

Two well differentiated regions were observed in the curves. A first region, starting from the first contact between the probe and the potato chip until the first major drop in force, was associated with a major structural breakdown; in this first region, the probe mainly deformed the potato chip and the force increased nearly linearly with time. During this first region, not much structural breakdown took place and the acoustic emission was also quite low. The second region started from the first major structural breakdown; in this region, higher force and acoustic events were recorded in comparison to the first region.

In order to compare objectively the behaviour of the different potato chips, specific parameters were extracted from the force and sound curves. The parameters evaluated were: 1) the gradient (slope of the first part of the force curve), which is related to the
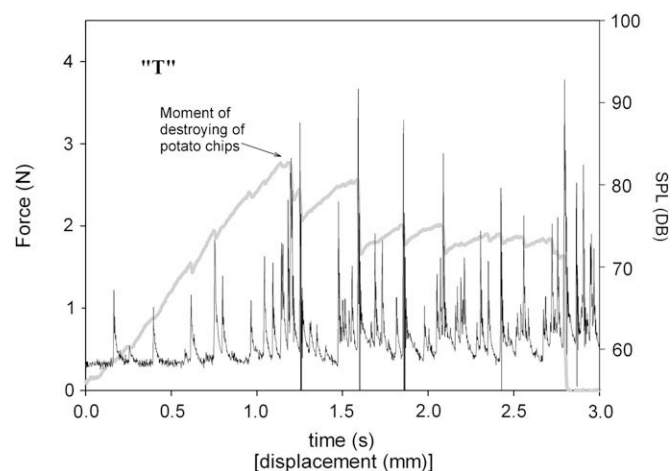

Fig. 2. Force (grey line) and Sound Pressure Level (SPL, black line) versus probe displacement. Potato chip "T".

Table 3
Mean values of the instrumental texture and sensory parameters.

Chip Sample	Instrumental texture parameters					Sensory parameter scores	
	Area (Ns)	Gradient (N/s)	Number of force peaks before breaking	Number of force peaks after breaking	Number of total force peaks	Hardness	Crispness
"T"	4.5[a]	3.3[a]	2.1[ab]	6.3[a]	8.4[ab]	2.7[ab]	4.9[ab]
"0%"	2.1[b]	3.9[ab]	0.4[b]	1.6[b]	2.0[c]	2.6[a]	5.2[ab]
"Extra C"	2.8[ab]	4.7[ab]	2.1[ab]	3.6[ab]	5.7[abc]	5.9b[cd]	7.7[bc]
"W"	3.7[ab]	6.5[b]	2.8[ab]	3.0[ab]	5.8[abc]	6.1[cd]	8.7[c]
"L"	3.6[ab]	4.2[ab]	3.8[b]	5.3[ab]	9.1[a]	4.1abc	7.3[bc]
"Snack"	2.6[b]	4.4[ab]	1.4[ab]	2.2[b]	3.7[bc]	7.4[d]	2.7[a]

[abc] Different letters for the same column means there is a significant difference ($p < 0.05$) according to Tukey's test.

stiffness; 2) the area under the force versus displacement curve, which is related to the total work involved in the test; 3), 4) and 5) the number of force peaks before and after the first main structural breakdown, and the number of total force peaks, which are an index of the jaggedness of the curve; 6) and 7) the number of acoustic events before and after the first main structural breakdown, and the number of total sound peaks, and 8) the sound pressure level (average of the ten higher peaks, $SPLmax_{10}$); this last parameter was found more representative of the maximum sound pressure level than the value of just the maximum peak, which could have a more unpredictable value.

The parameters obtained are shown in Table 3 (force/displacement plot parameters) and Table 4 (sound/displacement plot parameters).

Samples "Snack" and "0%" had a significantly lower area than any other sample, which showed no significant differences among them.

Sample "W" presented the highest gradient and was therefore the stiffest. On the contrary sample "T" showed the lowest gradient.

In general, the higher number of total force peaks was associated with higher number of total sound peaks and to $SPLmax_{10}$. As expected, in all the potato chips the number of force and acoustic peaks was lower in the first region (before breaking) than in the second region (after breaking), which confirms the fact that the main structural breakdown occurs in the second region. Samples "L", "T", and "Extra C" showed the higher number of force peaks, sound peaks and $SPLmax_{10}$. A high number of force and sound peaks have been associated to a high sensory crispness (Chen et al., 2005; Varela et al., 2006). In potato chips "Extra C", "L", "Snack", and "0% salt" this positive relation among number of peaks and sensory crispness was also found. However, in samples "W" and "T" this relation was not found. The discrepancy in the behaviour of these two samples is discussed in the next section, where the correlation among the different parameters evaluated will be studied.

Table 4
Mean values of the instrumental parameters extracted from sound/displacement plots.

Chip Sample	Number of sound peaks before breaking	Number of sound peaks after breaking	Number of total sound peaks	Max SPL (dB) (average of 10 peaks)
"T"	5.2[a]	22.2[a]	27.4[ab]	85.1[ab]
"0%"	2.6[a]	9.6[b]	12.1[ac]	82.6[ad]
"Extra C"	8.0[ab]	12.8[ab]	20.8[abc]	86.7[b]
"W"	2.3[a]	7.8[b]	10.2[c]	84.6[ab]
"L"	12.4[b]	23.4[a]	35.8[b]	91.8[c]
"Snack"	1.2[a]	8.3[b]	9.6[c]	80.4[d]

[abc] Different letters for the same column means there is a significant difference ($p < 0.05$) according to Tukey's test.

3.3. Sensory analysis

Values of sensory attributes evaluated are shown in Table 3. Significant differences in the attributes "hardness" and "crispness" were found among the different potato chips samples. "Extra C", "W" and "Snack" chips were the samples with higher sensory hardness and "Extra C", "W" and "L" were the samples with higher sensory crispness.

3.4. Correlation between sensory and instrumental analysis

To evaluate the correlation among the different instrumental and sensory parameters a PCA was carried out. The rotation method used was Varimax with Kaiser Normalisation and rotation converged in 5 iterations. Three components were extracted that together explained 87.7% of the variance. The first two components that explained together 68.9% of the variance are represented in Fig. 3. The first component explained 39.5% of the variance and showed a positive correlation with the instrumental parameters "area", "number of force peaks", "number of sound peaks", "$SPLmax_{10}$", and sensory crispness, and a negative correlation with the fat content.

Behaviour of samples "L" and "Extra C" was explained by the positive part of PC1. As previously stated, these samples are characterized by high number of force, sound peaks and $SPLmax_{10}$ and with high sensory crispness. In the opposite situation appears sample "Snack", which behaviour is explained by the negative part of PC1, characterized as a sample with low number of force, sound peaks, $SPLmax_{10}$, and low sensory crispness.

The second component explained 29.4% of the variance and showed a positive correlation with the thickness, the gradient, sensory hardness and sensory crispness.

The positive part of PC2 explained the behaviour of sample "W", which was the thicker sample with a high gradient value and also with high sensory hardness.

The third component explained 18.8% of the variance and showed a positive correlation with the moisture content and sensory hardness. The positive part of PC3 explained the behaviour of sample "Snack", which was the sample with the higher moisture content and the highest sensory hardness (data not shown).

Unlike other samples, sample "W" despite having a low number of force and sound peaks showed a high sensory crispness; this differential behaviour may be explained due to the way this potato chip fractured during the instrumental texture test, which failed to simulate the way the trained panel evaluate crispness. Upon contacting with the spherical probe, potato chips "W" broke very easily into two parts (following exactly one of the waves of their surface). These two broken parts fell apart and the probe did not continue breaking them. As a consequence of this fracture pattern, the number of fracture and sound events registered was low (see the force–sound/displacement plot in Fig. 4). The panellists scored sensory crispness during mastication, which implied that they also evaluated the crispness provided by biting the two broken pieces of the potato chip, which failed to be registered by the texture analyser. Therefore, potato chips "W" were scored with high sensory crispness, despite their low instrumental crispness in terms of force and acoustic events.

Finally, the behaviour of samples "T" and "0% salt" is explained by both components. Sample "T" was related to the positive part of PC1 (high number of force peaks, sound peaks and $SPLmax_{10}$) and to the negative part of PC2 (low gradient, low thickness, and low sensory hardness). The relation of sample "T" with the negative part of PC2 explained its low sensory crispness, despite its high number of force and sound peaks, revealing its very brittle and weak structure, so the crispness perception is very short in the mouth. Sample "0% salt" was related to the negative part of both
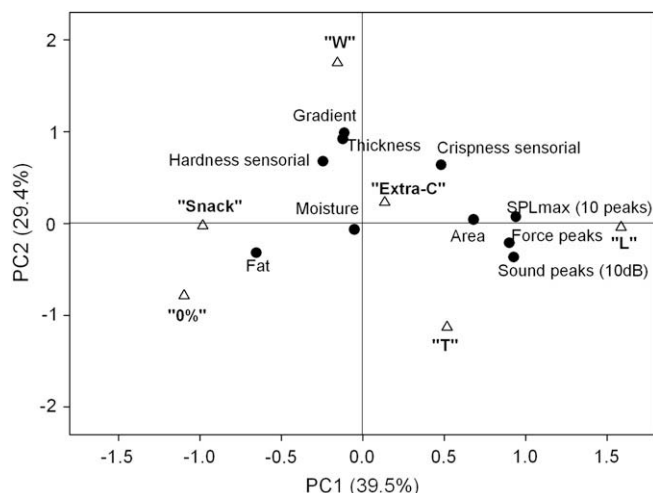
Fig. 3. PCA. 2D-loading plot of the samples in the two principal components explaining 68.9% of the variance.

components and it is characterized as a sample with both low sensory crispness and low sensory hardness. Another reason that could explain the low sensory crispness of both "0% salt" and "T" is their significantly higher fat content (Van Vliet, Visser, & Luyten, 2007), as fat content was related to the negative part of PC1 and therefore negatively related to sensory crispness.

Previous work on potato chips texture studied parameters such as potato variety (Blahovec, Vacek, & Patocka, 1999; Kita, 2002; Lefort, Durance, & Upadhyaya, 2003), starch quantity (Lefort et al., 2003), position of the slice within the tuber (Segnini et al., 1999b), temperature of the frying oil (Kita et al., 2007; Pedreschi & Moyano, 2005; Segnini et al., 1999b), kind of oil (Kita et al., 2007), all of them interesting factors influencing potato chip texture. However, there is little research on the relationship among crispness-related sensory attributes and physical properties of the potato chips. The instrumental test described in this article was able to evaluate, to discriminate and to predict quite reasonably sensory crispness. In addition, the following specific advantages make it suitable for industrial application: 1-The samples can be analysed as it, no regular geometry is necessary; 2-industries are familiarized with the main machinery employed, a texture analyser, as it is an instrument widely employed for quality control of a wide variety of food items; 3-No soundproof facilities are needed for sound recording; 4- The analysed parameters can be easily obtained from the curves using the instrumental software.

4. Conclusions

Information from the force/deformation and simultaneously sound recording during fracturing of potato chips constitutes an effective instrumental tool to predict sensory crispness. However, careful interpretation of the results has to be done.

In general sensory crispness is positively related to the number of fracture and acoustic events, to SPLmax$_{10}$, and to the area below the force curve. In addition, results indicated that certain degree of sensory hardness is necessary for crispness perception. On the other hand, a low number of force and acoustic events normally are taken as an index of low crispness; however, a careful observation and analysis of the fracture pattern is necessary.

Acknowledgements

References

AACC. American Association of Cereal Chemists. (1967). *Cereal laboratory methods.* Method 30–20.

AOAC. Association of Official Analytical Chemists. (2000). *Official methods of analysis.* (17th ed.). Gaithersburg, MD: AOAC.

Blahovec, J., Vacek, J., & Patocka, K. (1999). Texture of fried potato tissue as affected by pre-blanching in some salt solutions. *Journal of Texture Studies, 30,* 493–507.

Chen, J., Karlsson, C., & Povey, M. (2005). Acoustic envelope detector for crispness assessment of biscuits. *Journal of Texture Studies, 36,* 139–156.

Duizer, L. (2001). A review of acoustic research for studying the sensory perception of crisp, crunchy and crackly textures. *Trends in Food Science and Technology, 12,* 17–24.

ISO. (1988). *Sensory analysis. General guidance for design of test rooms.* Standard no. 8589. Geneve, Switzerland.

Kita, A. (2002). The influence of potato chemical composition on crisp texture. *Food Chemistry, 76,* 173–179.

Kita, A., Lisinska, G., & Golubowska, G. (2007). The effects of oils and frying temperatures on the texture and fat content of potato chips. *Food Chemistry, 102,* 1–5.

Lefort, J. F., Durance, T. D., & Upadhyaya, M. K. (2003). Effects of tuber storage and cultivar on the quality of vacuum microwave-dried potato chips. *Journal of Food Science, 68,* 690–696.

Luyten, H., Plijter, J. J., & van Vliet, T. (2004). Crispy/crunchy crusts of cellular solid foods: a literature review with discussion. *Journal of Texture Studies, 35,* 445–492.

Pedreschi, F., & Moyano, P. (2005). Effect of pre-drying on texture and oil uptake of potato chips. *LWT - Food Science and Technology, 38,* 599–604.

Pedreschi, F., Moyano, P., Santis, N., & Pedreschi, R. (2007). Physical properties of pre-treated potato chips. *Journal of Food Engineering, 79,* 1471–1482.

Rojo, F. J., & Vincent, J. F. V. (2008). Fracture properties of potato chips. *International Journal of Food Science and Technology, 43*(4), 752–760.

Segnini, S., Dejmek, P., & Öste, R. (1999a). Relationship between instrumental and sensory analysis of texture and color of potato chips. *Journal of Texture Studies, 30,* 677–690.

Segnini, S., Dejmek, P., & Öste, R. (1999b). Reproducible texture analysis of potato chips. *Journal of Food Science, 64*(1), 309–312.

Srisawas, W., & Jindal, V. K. (2003). Acoustic testing of snack food crispness using neural networks. *Journal of Texture Studies, 34,* 401–420.

Szczesniak, A. S., Brandt, M. A., & Friedman, H. H. (1963). Development of standard rating scales for mechanical parameters of texture and correlation between the objective and the sensory methods of texture evaluation. *Journal of Food Science, 28,* 397–403.

Van Vliet, T., Visser, J. E., & Luyten, H. (2007). On the mechanism by which oil uptake decreases crispy/crunchy behaviour of fried products. *Food Research International, 40,* 1122–1128.

Varela, P., Chen, J., Fiszman, S. M., & Povey, M. (2006). Crispness assessment of roasted almonds by an integrated approach to texture description: texture, acoustics, sensory and structure. *Journal of Chemometrics, 20,* 311–320.

Vickers, Z. M. (1987). Sensory, acoustical and force-determination measurements of potato chips crispness. *Journal of Food Science, 52,* 138–140.

Vincent, J. F. V. (1998). The quantification of crispness. *Journal of the Science of Food and Agriculture, 78,* 162–168.
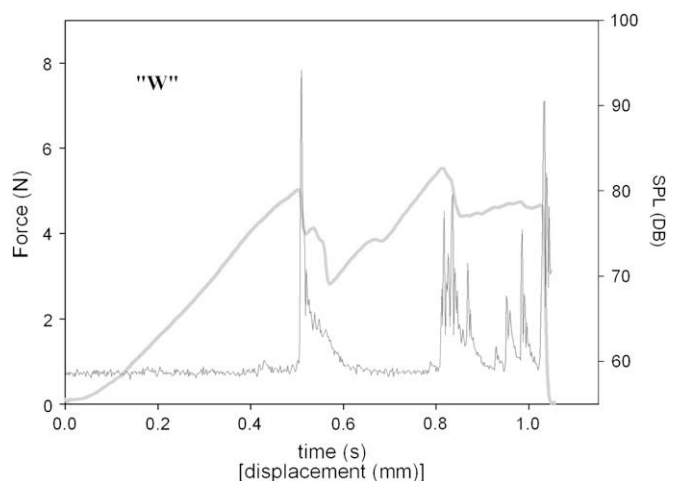

Fig. 4. Force (grey line) and Sound Pressure Level (SPL, black line) versus probe displacement. Potato chip "W".