Textural Characterization and Kinetics of Potato Strips During Frying

F. PEDRESCHI, J.M. AGUILERA, AND L. PYLE

ABSTRACT: A single puncture test (SPT) system was designed to determine textural changes in potato strips in situ during frying at 160, 175, and 190 °C. Puncture force changed drastically with time and depth in the strip during frying. Force-distance curves were expressed as representative textural parameters as CF (core force), RF (rupture force), and S (springiness). Normalized parameters CF* and S* for core force and springiness were used in modeling textural changes in the core during initial tissue softening and later crust development process, respectively. High frying temperatures accelerated the process, and the finished fried potato strip was a composite structure made of a hard crust and a soft core.

Key Words: puncture test, frying, French fries, crust, texture, kinetics

Introduction

FRYING IS A WIDELY USED COOKING METHOD THAT CREATES unique textures and flavors in foods. As a result, fried foods exhibit a crispy and oily outer layer or “crust” and a mealy interior or “core” whose microstructures have been formed during the frying process. Deep-fat frying of potatoes has great commercial importance. For example, the multimillion-dollar snack industry exhibits an 8% per year growth rate, and French-fry processing in the United States utilizes more than 30% of the potato crop (Saguy and Pintus 1995).

Crust formation in French fries is the result of changes in the original structure of the potato tissue after exposure to hot oil (about 170 to 180 °C), namely, softening of the middle lamella between cells, starch gelatinization inside cells, and dehydration. These changes are responsible also for the amount and location of the absorbed oil (Baumann and Escher 1995). Aguilera and Gloria (2000) determined that almost 70% to 80% of the oil absorbed by commercial frozen parfried potatoes was oil wetting the surface at the end of frying. Pedreschi and others (1999), using confocal laser scanning microscopy, demonstrated that oil in the crust was like an “egg-box” surrounding intact dehydrated potato cells but not penetrating into them. Important properties of the surface of potatoes related to oil absorption and final product characteristics such as the area-scale fractal complexity (Asfc) and the smooth-rough crossover (SRC) change drastically during frying (Pedreschi and others 2000).

A fried potato piece is a composite structure formed by a crisp crust and an internal mealy core. The core does not sense directly the effect of the hot oil but gets cooked by conductive heating from the internal interface of the crust, which stays at about 100 °C. Cell separation is the principal physical attribute of a mealy potato, and firmness is often related to starch swelling and gelatinization as well as to the stability of the pectic substances in the cell wall and the middle lamellae (Anderson and others 1994). Starch content is the main determining factor in potato texture, while pectic materials have an effect opposite to that of the starch on texture. Starch tends to cause rounding of cells and separation, whereas pectic material tends to prevent cell separation and produce cohesiveness. The net result of all these changes is gelled starch and a softer tissue in which the cells are easily separated (Anderson and others 1994).

A recommended assay to study the texture of French fries is the puncture test, which measures the force required to insert a probe into a food (Bourne 1982). Solids distribution, oil spots/pockets, and crust frying patterns (for example, whether the fries are cooked over a layer of hot oil, partially or fully submerged) contribute to the variability in the texture of fried potatoes. In spite of its variability, the puncture test gives excellent discrimination between the mechanical properties of the crust and can be used for products of different sizes and shapes because it is less sensitive to the cross-sectional geometry of the product (Texture Technologies Corp. 1995).

Textural properties of fried products are usually determined after removal from the fryer, when unsteady conditions of moisture content and temperature exist inside the product (Rubnov and Saguy 1997; Aguilar and others 1997; Du Pont and others 1992; Texture Technologies Corp. 1995). In situ mechanical testing of potato strips during frying allows the study of the kinetics of textural development in potato tissue with minimal intrusion. The main objectives of this study were: (i) to characterize textural changes in the crust and core of potato strips in situ during frying at 3 temperatures: 160, 175, and 190 °C; (ii) fit data appropriate kinetic expressions to the data; and (iii) correlate experimental data with the development of the crust and core regions in fried potatoes.

Materials and Methods

Materials

Potatoes (variety Estima) and vegetable oil (Mazzola, pure corn oil, Bestfoods UK Ltd., U.K.) were the raw materials. Strips were cut from the pith parenchymatous region of potato tubers (1 × 1 × 10 cm), rinsed for 1 min in distilled water to eliminate loose material adhering to the surface, and blotted with paper towel.

Frying Conditions

Blotted potato strips were fried for up to 15 min at 3 temperatures: 160, 175, and 190 °C. The oil was preheated for 1 h prior to frying and discarded after 6 h of use (Blumenthal...
Textural Characterization During Frying...

A temperature-controlled heating system was used to reduce temperature fluctuations during frying experiments as much as possible (±1.5 °C). This system consisted of a heater block that heated the pan containing the frying oil, a temperature feedback controller (ADP 15, Mantracourt, Amber Instruments, Chesterfield, U.K.), and a thermocouple was used to measure the temperature of the oil inside the frying pan.

Setup for Puncture Tests

The experimental setup used for the puncture tests is shown in Fig. 1. The system consisted of a sample holder to keep the potato strip inside the frying pan and a metal device containing 6 holes attached to the travelling system of the Texture Analyzer. Thus, a puncture element (2 mm dia metal rod) could be placed successively in each hole (10 mm separation between holes) to test the same strip at different positions and frying times. This setup was called the single puncture test (SPT) system (alternatively, 6 puncture elements can pierce the piece simultaneously; not reported here).

Puncture Tests

Strips from 9 potatoes were tested in triplicate inside the frying pan by the SPT system using a Texture Analyzer TA.XT2 (Texture Technologies Corp., Scarsdale, N.J., U.S.A./Stable Micro Systems, Goldating UK, Scarsdale, N.Y., U.S.A.). Force (F) against distance curves were generated at different frying times maintaining a constant speed of 2 mm/s and a travel distance of 5 mm, approximately half of the thickness of the strip.

Force-Distance Curves

Force against distance curves were determined for 7 frying times in the case of 160 and 175 °C and for 9 frying times in the case of 190 °C. Curves for each time from strips of the same potato were averaged, and the resulting curve was used to define textural parameters (a representative curve of experimental results is shown in Fig. 2). The following parameters were selected and determined using the software program of the Texture Analyzer (Fig. 2):

- Springiness (S): Slope of the initial region of the force-deformation curves where the force increases almost linearly. It reflects the bending of the outer layer of the piece by the puncture element before rupture.
- Rupture force (RF): Force at which the plunger penetrates the outer layer or crust. It may be a peak force when the crust is formed (curve A in Fig. 2) or, when only a leathery layer exists (beginning of frying), correspond to a pronounced change in curvature after the initial linear portion of the force-deformation curve (curve B in Fig. 2).
- Core force (CF): Value of the force when the puncture element has travelled a distance of 5 mm and almost reaches the center of the strip in the mealy core.

Modeling Texture During the Frying Process

Modeling texture during frying used normalized values of CF and S, which were denoted as $\text{CF}^*$ and $\text{S}^*$, respectively (value at any time divided by the value corresponding to the raw potato). $\text{CF}^*$ allowed cooking of the core to be followed during frying experiments as it represents the force near the center of the strip. Based on findings by Rahardjo and Sastry (1993) for softening of potato tissue during heat treatment, texture changes in the core were modeled as a combination of two 1st-order kinetic equations (Eq. 1) consisting of fast and slow phases:

$$\ln \text{CF}^* - \ln \text{CF}_0^* = -k_c t$$

where:

- $\text{CF}^*$: Normalized core force at time $t$
- $\text{CF}_0^*$: Normalized core force at the beginning of each phase
- $t$: Time (min)
- $k_c$: Kinetic constant for core cooking during frying (min$^{-1}$) with $k_{ci}$ and $k_{cii}$ as reaction rate constants for the fast and slow phase, respectively.

On the other hand, $\text{S}^*$ was used to study not only the initial softening of the potato tissue for short times of frying but also the progressive hardening of the crust. The following equation was used to describe the variation of $\text{S}^*$ with frying time:

$$\frac{d\text{S}^*}{dt} = -k_s e^{-k_s t} + k_{th}$$

Eq. 2 after integration yields:

$$\text{S}^* = e^{-k_s t} + k_{th} t$$

Figure 1—Experimental setup for in-situ single puncture tests (SPT) of potato strips during frying

Figure 2—Representative parameters extracted from a typical force against distance curve to study the kinetics of changes in texture in potato strips during frying.
Textural Characterization During Frying . . .

where:

\[ S^* = \text{Normalized springiness} \]

\[ k_s = \text{Kinetic constant for softening of potato tissue during frying (min}\text{-}1) \]

\[ k_h = \text{Kinetic constant for the crust hardening process during frying (min}\text{-}1). \]

The 1st term in Eq. 3 represents the decrease in \( S^* \) due to the initial softening of potato tissue induced at short frying times (potato tissue softening process), while the 2nd term represents the formation of crust (crust hardening process) at longer times. Parameters were estimated by linear and nonlinear regression procedures using SAS (SAS 1994).

Results and Discussion

Setup for Puncture Tests

The SPT system used in this work allowed the in situ study with minimal intrusion of changes in the texture of potato strips during frying. Data were obtained from different positions of the same potato strip, minimizing variations due to the specimen. Although the area tested was relatively small (3.14 mm²) and not representative of all the fried product, the possible variability due to position was handled by multiple replicates. There was no significant difference (p < 0.01) in texture measurements when the puncture element was placed in any of the 6 positions of the puncture system. Also, prior punctures did not have a significant effect on the successive punctures along 1 potato strip as confirmed by ANOVA (P < 0.01) for all texture parameters extracted from curves obtained by either treatment (results not shown). Hence, there was sufficient statistical support to ensure that variations in the force-distance curve with frying time are only due to changes in the structure of the strip as a result of the frying process.

Force-Distance Curves

Figure 3 shows average data for force against penetration distance only for 5 selected frying times, however, kinetic constants were obtained from data for all times. The coefficient of variation for all data varied between 12% and 32%. The shape of the force-distance curves varied drastically with time, reflecting changes in the texture of raw potato strips during frying (Fig. 3), which in turn resulted in variation of the textural parameters CF*, S*, and RF. For times < 6 min, a continuous reduction in: (i) area under the curves (equivalent to work) and (ii) force at 5 mm of probe travel, defined as CF*, indicated the softening of the tissue. This softening of the tissue is due to phenomena such as the solubilization of the middle lamellae and the gelatinization of starch, both occurring at around 60 to 80 °C, typical of a cooking process (Anderson and others 1994). Also, the onset of crust formation, revealed by the 1st appearance of a peak in force around 0.85 mm depth in Fig. 3 (average value for the 3 frying temperatures), occurred after 3 min for 160 and 175 °C.

Table 1—Values of kinetic constants (k) during frying of potato strips at 160, 175, and 190 °C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model</th>
<th>Frying temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>160 °C</td>
</tr>
<tr>
<td>CF*</td>
<td>Eq. 1</td>
<td>( k_{ci} = 0.408 ) (0.013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k_{cii} = 0.086 ) (0.022)</td>
</tr>
<tr>
<td>S*</td>
<td>Eq. 3</td>
<td>( k_s = 0.378 ) (0.030)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( k_h = 0.020 ) (0.002)</td>
</tr>
</tbody>
</table>

1CF* was fit to a model with 2 1st-order phases represented by Eq. 1 and S* to a model represented by Eq. 3. Subscripts ci, cii, s, and h indicate fast and slow phases of cooking of the core during frying, tissue softening, and crust hardening processes during frying, respectively.

2 Values in parenthesis represent the standard deviation of k values.

Figure 3—Force against distance curves for potato strips fried at (A) 160 °C, (B) 175 °C, and (C) 190 °C using the SPT system. Raw potato (—); 1.5 min (—); 2.25 min (—); 3 min (—); 6 min (—); 15 min (—)
and earlier for 190 °C. The distance at which this peak appeared is consistent with the often cited value of about 1 mm for the crust thickness in fried potatoes (Lamberg and others 1990). After 6 min of frying, the continuous increase of the rupture force (peak force in this case) from 1.58 to 2.38 N (average values for the 3 temperatures tested) suggests that the predominant process was the consolidation of the crust structure. This progressive increase in RF may run parallel to dehydration of the external cells of the potato tissue in the strip surface forming the crust. Higher frying temperatures resulted in harder crusts after 15 min of frying (RF values of 1.94, 2.29, and 2.90 N for 160, 175, and 190 °C, respectively). Thus, in all cases, a finished fried potato strip was a composite structure made of a hard crust (RF > 1.9 N) and a soft mealy core (CF < 0.5 N).

**Kinetics of Textural Changes During Frying**

The kinetics of textural changes in potato strips during frying were studied using normalized textural parameters extracted from force against distance curves such as CF* and S* (Fig. 4 and Fig. 5, respectively). CF* was useful to follow the kinetics of cooking of the core during frying because it represents the force at 5 mm of probe travel distance (near the center of the strip in the core region). On the other hand, S* allowed study not only of the softening of the tissue during the 1st min of frying but also of crust development for longer frying times. It reflects the bending (indicative of the deformation capacity) of the outer layer of the piece (leathery or crust structure depending on frying time) by the puncture element before penetration.

**Kinetics of Core Cooking During Frying Using CF***

Cooking or softening of the core during frying represented by CF* was modeled as a combination of two 1st-order kinetic equations representing: (i) an initial phase with a fast rate of cooking and (ii) a terminal slow phase of cooking (Fig. 4). The rate of cooking of the core in the slow phase (represented by \( k_{ci} \)) was more than five times slower than that of the fast phase (represented by \( k_{cf} \)). The core of French fries was almost completely softened after 6 min of frying (the end of the fast phase) as shown by a low penetration force in Fig. 3 that hardly changed with further frying. The extra frying time was required for the appropriate formation of the crust. Higher frying temperatures accelerated cooking of the core as shown by increasing \( k_{ci} \) values in Table 1 (0.408, 0.416, and 0.522 min⁻¹ for 160, 175, and 190 °C, respectively). Loh and Breene (1981) indicated that a 1st-order kinetic model was applicable for cooking of most vegetables, and Anderson and others (1994) suggested that the observed biphasic mechanism during cooking of potatoes may represent 2 simultaneous phenomena: thickening of the cell wall and reduction of the wall matrix viscosity, both occurring with different rate constants.

**Kinetics of Tissue Softening and Crust Development During Frying Using S***

Initial softening at the surface of potato tissue (t < 6 min) and development of the crust (t > 6 min) during frying can be followed simultaneously using Eq. 3, which showed a good fit to S* data at the 3 selected frying temperatures (Fig. 5). The 1st term in Eq. 3 represents an initial decrease in S values during frying due to the softening of the surface layers of potato tissue for short frying times (softening), while the 2nd term represents the development of the crust (hardening) at longer frying times. The overall texture of a French fry at any frying time is characterized by these 2 terms. S increased progressively for times > 6 min and with frying temperature, suggesting a temperature-dependent dehydration and consolidation process in the external cell layers of the strip as the crust progressively developed and hardened (Fig. 5). Higher frying temperatures resulted both in a faster softening of the tissue (\( k_{si} \) values of 0.378, 0.4298, and 0.6684 min⁻¹ for 160, 175, and 190 °C, respectively) and hardening of the crust (\( k_{ci} \) values of 0.020, 0.031 and 0.047 min⁻¹) as shown in Table 1.

**Conclusions**

The experimental setup presented in this work allowed the study in situ and with minimal intrusion of the main textural changes during frying of potato strips. Changes in the shape of the force-distance curves during frying permitted the kinetics of texture development and structural change in potato strips to be followed during frying. In sim-
Textural Characterization During Frying

ple terms, frying shows an initial stage (t < 6 min) in which the whole tissue softens, the core becomes cooked, and crust formation starts, and a later stage in which the crust develops and hardens progressively (t > 6 min). Higher frying temperatures accelerated cooking of the core and hardening of the crust, resulting in French fries with harder crusts. A finished fried potato strip became a composite structure made of a hard crust region and a soft core region. The SPT system can be used to optimize texture formation of French fries and other fried products during frying under different conditions (variety, product shape, preprocessing, and so on).

References


Ms. 20000307

This research was supported by Fondecyt Project 2980058, Nestle Research Center (Ves-chez-les-Blanc, Switzerland) and Nestle-Chile. We thank Alla Program of the CE for partially supporting the visit of Franco Pedreschi to the Univ. of Reading to perform the mechanical analysis and to CYTED Project XI.13.

Authors Pedreschi and Aguilera are with the Dept. of Chemical Engineering and Bioprocesses, Pontificia Universidad Católica de Chile, P.O. Box 306, Santiago 22, Chile. Author Pyle is with the Dept. of Food Science and Technology, Univ. of Reading, P.O. Box 226, Reading, RG6 6AP, UK. Direct correspondence to José M. Aguilera (E-mail: jmaguile@ing.puc.cl).

318 JOURNAL OF FOOD SCIENCE—Vol. 66, No. 2, 2001