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REVIEW ARTICLE

# Effect of pre-drying and par-frying conditions on the crispness of French fries

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**Abstract** An experimental design was used to study the effect of pre-drying (to 10, 15 and 20% weight loss) and par-frying conditions (160, 170 and 180 °C) on the crispness of French fries. Par-frying time was adjusted with a software program to obtain equal moisture content and internal texture for all samples. Crispness was evaluated with a sensory panel. Furthermore, samples were analysed with a texture analyser and with confocal scanning laser microscopy (CSLM). Par-frying at 180 °C resulted in a crispier product than at 160 and 170 °C. Pre-drying to 20% weight loss lead to blisters and reduced crispness in comparison with pre-drying to 10 and 15% weight loss. Instrumental texture measurements showed a good correlation with sensory crispness. Large differences in cell structure, such as blisters, could be observed with CSLM. CSLM was useful to explain results from the instrumental and sensory texture evaluation.

**Keywords** French fries · Frying · Crispness · Sensory analysis · Texture analyser · Confocal scanning laser microscopy

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## Introduction

French fries are appreciated throughout the world because of their pleasant taste and texture [1]. The general process for French fries production is blanching–drying–frying and each step is important for the final product quality [2]. Furthermore, the process requires permanent adjustment according to the raw material characteristics and the interrelations among the process steps [3]. Blanching in hot water is used mainly to inactivate enzymes, to improve texture, and to obtain a bright, uniform colour [4]. Pre-drying prior to the frying step improves texture and reduces oil uptake [5]. Oil absorption is reduced in two ways. Firstly, the proportion of open pores is decreased during pre-drying due to shrinkage [6]. After frying, oil is taken up in the open pores from which water has evaporated [7]. Decreasing the volume of open pores will reduce oil uptake. Secondly, pre-drying is responsible for part of the moisture loss, and, therefore, the frying time can be shortened [5]. Generally, frying is a two-step procedure: par-frying and finish-frying. During par-frying, a part of the water is evaporated and crust formation starts. After par-frying, the product is frozen, packaged and distributed. Finish-frying takes place in a restaurant or at home shortly before consumption and results in the final product with the desired flavour and texture.

Frying is an operation, in which mass and heat transfer take place simultaneously [8]. During frying, characteristics of the product change considerably. Heat is transferred from the oil to the product, and water is evaporated from the product surface in the form of steam bubbles. In the beginning, this is only free water, but a boundary of evaporating water moves inwards as the surface dries out [3]. The temperature at the boundary does not exceed 103 °C [9]. A crust is formed, increasing the resistance to water vapour transport and causing an increase in pressure in the surface area [10].

The product only shrinks in the first stage of the frying process (by 5–10%); afterwards, the size stabilises, while the crust thickness and the porosity increase on further frying [5]. Oil uptake into the product occurs mainly after frying, when the product is removed from the oil, by both condensation and capillary mechanisms [11].

The texture of French fries consists of two parts: a crispy outer crust and a soft, mealy interior [12]. The interior of French fries consists of cooked and slightly dehydrated cells [13], and the texture is similar to cooked potatoes. Microscopic analysis of potato strips, fried in dyed oil, showed that the oil is located in the crust region only [14]. The crust has a thickness of about 1 mm, depending on the frying time and temperature. In a structural sense, the crust can be considered a semi-rigid sponge, filled with oil, and about 80% of the crust's volume is made up of void space [15]. Pedreschi and Aguilera [16] used confocal scanning laser microscopy (CSLM) to show that oil in the crust was like an "egg-box" surrounding intact dehydrated potato cells but not penetrating into them.

Crispness is an important quality attribute of French fries and depends, to a large extent, on the crust properties. Crispness is usually determined with a sensory panel, but this is a time-consuming procedure. Texture analysers are generally used as an instrumental alternative to predict crispness in an objective way. Several physical parameters derived from a force–deformation curve showed a good correlation with sensory crispness [17, 18]. These include distance at maximum force, initial slope, maximum force divided by distance and the area below the force–deformation curve. A better relationship between structure and texture was, however, found by studying the jaggedness of the force–deformation curve [19]. The jaggedness of the curve corresponded with the many breaking events that occur by puncturing a crispy material. Veronica et al. [20] reported that the linear distance and the number of peaks in a force–deformation curve during fracture showed a good correlation with sensory perceived crispness for extruded snack foods.

The moisture content has a significant effect on crispness [17, 21]. Also, the internal texture of the product can affect the textural properties of the crust [22]. These aspects have, however, often been neglected when determining the crispness of French fries. A higher value for crispness was found in French fries with increased drying time [23] and increased frying time [24]. It was, however, not clear whether this could be attributed to the varied condition or to a difference in moisture content. Therefore, in the present research, the effect of pre-drying and par-frying conditions on crispness of French fries was studied independent of the moisture content and internal texture. To achieve this, the frying time was adjusted in such a way that the moisture content and internal texture were equal for all samples. Crispness was evaluated in three different ways: sensory with a panel, instrumentally with a texture analyser and microscopically with CSLM.

## Materials and methods

### Sample preparation

Laboratory-scale equipment at Aviko b.v. (Steenderen, The Netherlands) was used for sample preparation [25]. Potatoes from one batch (cv. Agria, 21.9% dry matter) were used throughout the study to minimise variation in raw material. For each experiment, 3 kg of potatoes were peeled for 25 s at 16 bar with a steam peeler and cut into strips (11 mm × 11 mm) with a mechanical cutting device. Subsequently, the strips were blanched in 50 L of blanching water from the factory according to standard blanching conditions. In this way, starch was gelatinised and excess reducing sugars were leached out. After blanching, the strips were dipped in a 0.5% solution of sodium pyrophosphate in blanching water (40 s at 70 °C) in order to obtain a bright and uniform colour. Table 1 shows the experimental design that was used to determine the effects of pre-drying (10, 15 and 20%) and par-frying (160, 170 and 180 °C). A full factorial design was set-up in triplicate, and the experiments were carried out in randomised order. Pre-drying was carried out in hot air (70 °C). The extent of pre-drying was expressed as the percentage of weight loss:

$$M_{\text{after pre-drying}} = M_{\text{before pre-drying}} \times((1-\text{drying percentage})/100) \qquad (1)$$

The frying time was chosen in such a way that all samples had the same final moisture content and internal texture. This was calculated using a software program developed at Aviko b.v., which was based on extensive previous research [26]. In fact, this means that the effect of different time–temperature combinations of par-frying was studied, instead of different par-frying temperatures. Partially hydrogenated palm oil was used for par-frying in a product to oil ratio of 1:13. After par-frying, oil was allowed to drain off for 30 s before cooling. The strips were consecutively cooled for 15 min (till 20 °C), chilled for 15 min (till 2 °C) and frozen in 20 min (till −20 °C). For all analyses, only straight strips with a length of 5–10 cm were used.

### Sensory evaluation

A panel of three experts with many years of experience (>7 years) in testing French fries evaluated the samples. Three samples and a reference (both 300 g) were finish-fried simultaneously for 3 min at 180 °C. After finish-frying, the

**Table 1** Process conditions in the experimental design

| Design | Experiment | Pre-drying Weight loss (%) | Par-frying Temperature (°C) | Par-frying Time (s) |
|---|---|---|---|---|
| 1 | 10 | 10 | 160 | 134 |
| 2 | 21 | 10 | 160 | 134 |
| 3 | 26 | 10 | 160 | 134 |
| 4 | 11 | 10 | 170 | 111 |
| 5 | 22 | 10 | 170 | 111 |
| 6 | 27 | 10 | 170 | 111 |
| 7 | 9 | 10 | 180 | 95 |
| 8 | 16 | 10 | 180 | 95 |
| 9 | 8 | 10 | 180 | 95 |
| 10 | 12 | 15 | 160 | 125 |
| 11 | 3 | 15 | 160 | 125 |
| 12 | 20 | 15 | 160 | 125 |
| 13 | 1 | 15 | 170 | 104 |
| 14 | 18 | 15 | 170 | 104 |
| 15 | 4 | 15 | 170 | 104 |
| 16 | 23 | 15 | 180 | 88 |
| 17 | 24 | 15 | 180 | 88 |
| 18 | 2 | 15 | 180 | 88 |
| 19 | 25 | 20 | 160 | 116 |
| 20 | 17 | 20 | 160 | 116 |
| 21 | 19 | 20 | 160 | 116 |
| 22 | 15 | 20 | 170 | 96 |
| 23 | 6 | 20 | 170 | 96 |
| 24 | 7 | 20 | 170 | 96 |
| 25 | 13 | 20 | 180 | 81 |
| 26 | 5 | 20 | 180 | 81 |
| 27 | 14 | 20 | 180 | 81 |

samples were allowed to cool down for 3 min to reach an acceptable temperature for consumption and offered to the assessors. They judged the samples in randomised order on crispness, blisters, colour and two attributes, homogeneity and doneness, for internal texture. The panel used a structured scale from 4 to 8 for the evaluation according to the company's sensory quality control procedure (Aviko b.v., Steenderen, The Netherlands). The use of half and quarter points was permitted. A score of 8 means better than the reference, a score of 7 means equal to the reference, a score of 6 means minor defect, a score of 5 means large defect and a score of 4 means very large defect. Together, they agreed on one score per attribute and sample. The samples were evaluated in two consecutive days, and there was at least 15 min between each cluster of samples.

## Texture analysis

A texture analyser (TA-XT Plus, Stable Micro Systems Ltd., Surrey, UK) was used for instrumental analysis of the French fries samples. A standardised protocol was followed for each analysis. Samples were finish-fried individually for 3 min at 180 °C, followed by draining of oil for 30 s. Texture analysis was performed exactly 3 min after the sample was removed from the fryer. The French fry was fractured longitudinally with a wedge-shaped probe (30° cutting angle, 15 mm width) at a speed of 40 mm/s. This simulated a bite with the front teeth [27]. Ten replicates were carried out of each sample.

A force–distance diagram was constructed from the resistance that the probe encountered during fracture. As the amount of recorded data points directly influences the parameters deducted from the diagram, a high acquisition rate of 65,000 Hz was used. Fracture of the crust occurred within 150 s after the probe touched the sample surface. Therefore, only this part of the force distance diagram was used for further analysis. The number of peaks during fracture of the crust was used as a measure for crispness. A threshold value for peak height is used to filter noise, so that the contrast between crispy and non-crispy samples is maximal. Preliminary research on samples of French fries showed that a threshold value of 0.60 N was optimal [28].

## Microscopic analysis

The cell structure in the crust of all samples was observed before finish-frying with a Leica CSLM (type TCS-SP, Leica Microsystems, Rijswijk, The Netherlands), configured with an inverted microscope and an ArKr laser for single-photon excitation. A 488 nm laser line was used for excitation, inducing a fluorescent emission of FITC detected between 500 and 650 nm [29]. Cross-section coupes of about 2 mm were cut from a frozen French fry with a sharp razor blade and stained with a few droplets of a 0.1% solution of fluorescein isothiocyanate in water. The coupes were covered with a moisturised cap until analysis to prevent dehydration. Additionally, a Leica stereomicroscope (type MZ16, Leica Microsystems) was used to make images of the product surface.

## Determination of moisture and oil content

Moisture and oil content were determined in duplicate before and after finish-frying. Finish-frying was carried out for 3 min at 180 °C, and then the oil was allowed to drain off for 30 s. To minimise moisture loss, samples were frozen by immersion in liquid nitrogen for 20 s and stored at − 18 °C until analysis. A standard oven drying method was used to determine the moisture content. About 50 g of sample was cut in pieces ($<0.5$ cm$^3$), and a representative $5 \pm 0.2$ g was weighed and dried to constant weight at 105 °C. Fat content was determined by Soxhlet extraction using the Gerhardt Soxtherm (Dijkstra Vereenigde BV, Lelystad, The Netherlands) following the same sampling procedure as described above. In the Soxtherm, the sample was immersed in boiling petroleum ether for 15 min. Subsequent extraction for 1 h was enough to extract the total fat from the sample, and petroleum ether was removed by evaporation. Samples were placed in an oven at 70 °C for 15 min to remove any residual solvent. Samples were cooled to ambient temperature in a desiccator and weighed to calculate the oil content.

### Statistical analysis

All statistical analyses were performed using SPSS 10.0.7. Sensory and instrumental data were evaluated using two-way ANOVA. The ANOVA model looks like this: $y_{ijk} = \mu + \alpha_i + \beta_j + y_{ij} + \varepsilon_{ijk}$, in which $y_{ijk}$ is the output variable, $\alpha_i$ represents pre-drying, $\beta_j$ represents par-frying, $y_{ij}$ represents the interaction term (pre-drying × pre-frying), and $\varepsilon_{ijk}$ represents the error term. $Z$-values $> | 2 |$ were considered as outliers. Difference contrasts were calculated to determine the significance level of the settings for pre-drying and par-frying ($\alpha = 0.05$). Pearson correlation was used to calculate the correlations between sensory and instrumental parameters.

## Results

### Statistical analysis

The interaction term of the two-way ANOVA (pre-drying × prefrying) did not contribute significantly to the model ($p > 0.05$), neither for the sensory evaluation nor the instrumental measurements. Therefore, the interaction term was excluded from the model, and the ANOVA was recalculated to increase the significance of the main effects (pre-drying and par-frying). The recalculated ANOVA model looks like this: $y_{ijk} = \mu + \alpha_i + \beta_j + \varepsilon_{ijk}$.

### Sensory evaluation

Table 2 shows the results of the sensory evaluation. Significant effects of pre-drying and par-frying on crispness were found. Samples that were pre-dried until 15% weight loss were significantly crispier than those pre-dried until 20% weight loss. No significant difference was found between pre-drying to 10 and 15% weight loss. Par-frying at 180 °C resulted in a significantly higher crispness in comparison to par-frying at 160 and 170 °C. A strong effect of pre-drying was found on blister formation. Linear regression showed a positive relation between the extent of pre-drying and the degree of blisters ($p < 0.05$, $r^2 = 0.84$). Furthermore, significant effects were found for pre-drying on doneness and for par-frying on colour. Pre-drying until 20% weight loss resulted in a significantly lower value for doneness, compared to pre-drying until 10 and 15% weight loss. Colour showed the tendency to increase with par-frying temperature, but no statistically significant relation was found ($p > 0.05$, $r^2 = 0.18$). Nevertheless, a significantly better colour was obtained for samples that were par-fried at 180 °C than at 160 °C.

### Texture analysis

With texture analysis, significant effects of pre-drying and par-frying were found on the number of peaks. Pre-drying until 10 and 15% weight loss resulted in a significant higher number of peaks (55.1 and 53.8, respectively) than pre-drying until 20% weight loss (50.2). For par-frying at 180 °C, a significantly higher number of peaks (56.2) was found than for par-frying at 160 and 170 °C (52.9 and 51.0, respectively).

### Microscopic analysis

Figure 1 shows a number of typical structures that were observed in the crust of the samples. The structure in Fig. 1A looked like a blister, as a layer of cells was separate from the surface forming an air pocket. This was confirmed by stereomicroscopy. Figure 2A shows the surface of a French fry with blisters and one without, and Fig. 2B represents a close-up of a blister. The open structure of Fig. 1B was generally found in samples that had a high score for crispness in the sensory evaluation. This included samples that were pre-dried until 10 and 15% weight loss but not the samples that were pre-dried until 20% weight loss. The structure did, however, not occur more often in one of the time–temperature combinations of par-frying. Most of the samples, in which the structure of Fig. 1D was observed, with round cells on the surface, had been pre-dried to 10% weight loss. The structure of Fig. 1C, flat cells in a compact structure, could not

**Table 2** Results of sensory evaluation of French fries samples[a]

| | Crispness | Blisters | Colour | Homogeneity | Doneness |
|---|---|---|---|---|---|
| Pre-drying | | | | | |
| 10% | 6.61 ab | 7.36 a | 7.33 a | 6.67 a | 5.94 a |
| 15% | 6.88 a | 6.67 b | 7.29 a | 6.75 a | 6.00 a |
| 20% | 6.39 b | 5.36 c | 7.25 a | 6.78 a | 5.47 b |
| Par-frying | | | | | |
| 160 °C | 6.58 b | 6.58 a | 7.08 b | 6.69 a | 5.94 a |
| 170 °C | 6.48 b | 6.46 a | 7.31 ab | 6.60 a | 5.71 a |
| 180 °C | 6.96 a | 6.41 a | 7.47 a | 6.94 a | 5.86 a |

[a] Different letters within pre-drying and par-frying are significantly different ($p < 0.05$). A 4–8 line scale was used. For explanation of sensory ratings, see the Methods and materials section.

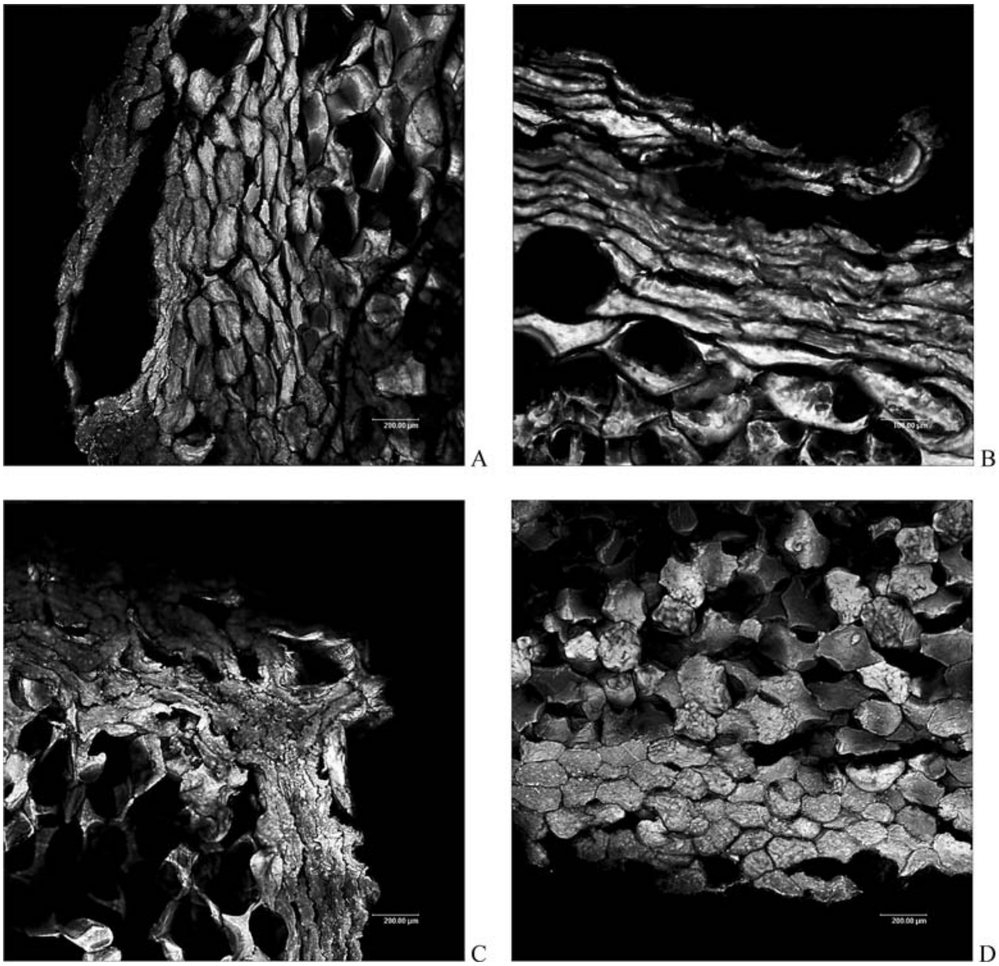

**Fig. 1** CSLM images of typical structures observed in the French fries samples of experiment 21 **A**, 17 **B**, 26 **C** and 2 **D**: **A** was observed in experiments 19, 20 and 25 as well; **B** was observed in experiments 4, 7, 12 and 14 as well; **C** was observed in experiments 6, 18 and 22 as well; **D** was observed in experiments 1, 4 and 15 as well

be attributed to a specific pre-drying or par-frying condition. Generally, samples, of which Fig. 1C and D are representatives, had a lower score for crispness.

### Moisture and oil content

The moisture and oil contents, determined before and after finish-frying, are shown in Table 3. No significant effects on moisture content were found. There were, however, effects of both pre-drying and par-frying on oil content. Pre-drying until 20% weight loss resulted in significantly less oil uptake than until 10 and 15% weight loss. The effect was even more apparent when the oil content was expressed on the basis of dry matter. Similar results were obtained after finish-frying. The oil content was significantly higher after par-frying at 180 °C than at 170 °C. The oil content of samples that were par-fried at 160 °C was in between the other temperatures. Expressing the oil content on the basis of dry matter gave similar results. After finish-frying, the same trend was observed. The highest oil content was found for samples that were par-fried at 180 °C and the lowest value for samples that were par-fried at 170 °C. The difference was, however, not significant after finish-frying.

## Discussion

Significant effects of the extent of pre-drying and of different time–temperature combinations of par-frying on crispness were demonstrated. These effects were independent of the moisture content, as no significant differences in moisture content could be found among the samples ($p > 0.05$). A correlation between sensory and instrumental analysis of crispness was obtained ($p < 0.05$, $r = 0.76$). Both sensory evaluation and texture analysis showed that the highest value for crispness resulted from par-frying at 180 °C. In microscopic analysis, however, the typical cell structure associated with a crispy crust did not occur more often in samples that were par-fried at 180 °C than those that were par-fried at 160 and 170 °C. The enhanced crispness may be explained by the temperature difference between surface and core. The core temperature remains at 103 °C because of the presence of water [3, 13]. A higher frying temperature, therefore,

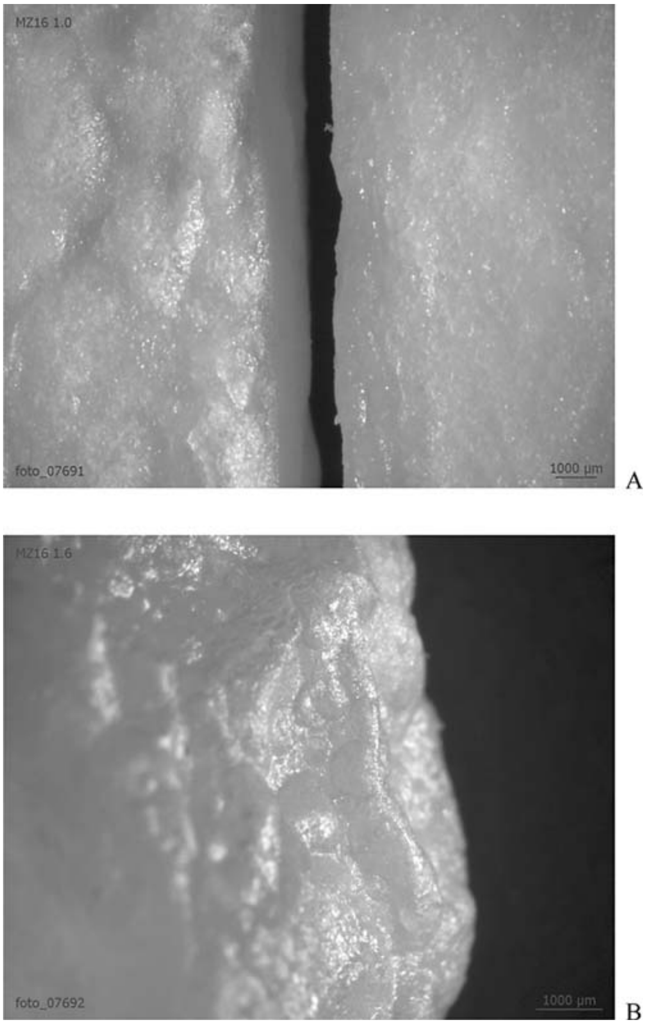

**Fig. 2** Stereomicroscope images of the surface of a French fry with and without blisters (**A**, respectively left and right), and a close-up of a blister **B**

results in a larger temperature difference and a thicker crust. In the present study, it is, however, likely that the frying time compensated this effect to some extent. This would explain why no difference was found between par-frying at 160 and 170 °C. Another explanation for the effect of par-frying at 180 °C is that the pressure build-up of evaporating water in the crust region is larger at this temperature. The cells will be pushed away more vigorously as water vapour forces its way outside, and this will result in a more porous crust structure. Previously, it was shown that porosity of French fries increases with frying temperature [30]. This would also explain the higher uptake of oil that was found after par-frying at 180 °C. Because of a higher porosity, a higher amount of oil can be absorbed in the product after removal from the fryer.

Pre-drying until 20% weight loss resulted in the lowest value for crispness in the sensory evaluation and for the number of peaks in the texture analysis. No differences were found between pre-drying to 10 and 15%, although microscopic analysis showed that the structure of “round” cells at the surface occurred mostly at pre-drying to 10% weight loss. Samples that were pre-dried to 10% weight loss were par-fried for a longer time than samples that were pre-dried to 15% weight loss in order to obtain equal final moisture contents (see Table 1). Apparently, this compensated each other with respect to crispness.

The longer par-frying time resulted in a slightly higher oil uptake, but this was equalised after finish-frying. Krokida et al. [23] observed a strong positive effect of pre-drying time on crispness. This effect can, however, be attributed to differences in moisture content to a large extent. Remarkably, they did not report any negative effects of prolonged pre-drying. Gupta et al. [8], on the other hand, stated that intensive pre-drying has a negative effect on the texture of French fries. This was found in the present study as well because sensory analysis and microscopic observations revealed that blisters were formed on the product surface after pre-drying until 20% weight loss. It seems, therefore, that there is an optimum in the extent of pre-drying. Pre-drying can be used to partially replace par-frying by removing loosely bound water. As the par-frying time is shortened, the oil uptake will be reduced. However, on prolonged pre-drying, the outer cell layers will dry out and skin formation will occur. This has been observed previously in experiments in which potatoes were dried in hot air [31, 32]. During subsequent par-frying,

**Table 3** Moisture and oil content of French fries samples before and after finish-frying[a]

| | Moisture content (%) | | Oil content (%) | | Oil content (g/g ds) | |
|---|---|---|---|---|---|---|
| | Before finish-frying | After finish-frying | Before finish-frying | After finish-frying | Before finish-frying | After finish-frying |
| Pre-drying | | | | | | |
| 10% | 66.8 a | 52.1 a | 4.53 a | 9.54 a | 0.136 a | 0.200 a |
| 15% | 66.1 a | 52.8 a | 4.30 a | 9.68 a | 0.127 b | 0.205 a |
| 20% | 67.4 a | 53.4 a | 3.89 b | 8.94 b | 0.120 c | 0.192 b |
| Par-frying | | | | | | |
| 160 °C | 67.1 a | 52.4 a | 4.24 ab | 9.41 a | 0.128 ab | 0.198 a |
| 170 °C | 67.0 a | 52.5 a | 4.13 b | 9.25 a | 0.125 b | 0.196 a |
| 180 °C | 66.2 a | 53.4 a | 4.40 a | 9.60 a | 0.130 a | 0.206 a |

[a] Different letters within pre-drying and par-frying are significantly different ($p < 0.05$).

a layer of dried cells will be separated from the cells underneath at several areas forming blisters. Moreover, this layer hinders oil absorption, as the oil content before and after finish-frying of samples pre-dried to 20% weight loss was considerably lower than the other samples and the reference.

## Conclusion

Par-frying at 180 °C resulted in a more crispy product than par-frying at 160 and 170 °C. Pre-drying to a weight loss of 20% lead to blister formation having a negative influence on crispness. No difference in crispness was found between pre-drying to 10 and 15% weight loss; a longer par-frying time compensated a lower extent of pre-drying. The number of peaks during fracture correlated well with sensory crispness. Large differences in cell structure, such as blisters, could be observed with CSLM, but it was not possible to show differences in crispness. Nevertheless, CSLM gave insight in the cell structure and this was useful to explain results from the sensory evaluation and instrumental texture analysis.

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