Application Note

Food

Multifaceted Evaluation of Frozen Tempura Batter Coating Focusing on Food Texture

Kayo Migita, Natsumi Koike, Akinori Kogure, Toshihiro Aoshima

Food

Abstract

In this article, a multifaceted evaluation of the batter coating of frozen tempura was carried out using four instruments, a texture analyzer, X-ray CT, laser microscope, and scanning electron microscope (SEM), in order to clarify the differences in the physical properties and structure associated with food texture. In addition to quantifying "moistness" and "crispness" using the texture analyzer, the thickness of the batter coating was measured with the X-ray CT, surface height measurements and color image observation were carried out with the laser microscope, and microregions were observed and analyzed with the SEM, confirming that there are differences in the internal structure, surface shape, and distribution of the oil content of each texture. Since information on completely different aspects can be acquired with each instrument, a comprehensive evaluation of the complex factors that produce the food texture is possible by using a combination of instruments.

1. Introduction

The "deliciousness" of foods consists of multiple factors, including taste, smell, and visual appeal. However, texture, sometimes called "mouthfeel," is also one extremely important factor. Mouthfeel refers to the physical sensations experienced when food is placed in the mouth or chewed, and is expressed by various onomatopoeic words such as "crisp" and "chewy." Among these, the packaging of some foods uses onomatopoeic terms to emphasize the appeal of their distinctive textures, and this has become an important "selling point" for consumers when deciding which product to select.

In the development of food products, the method of evaluating texture has become a key point. Sensory methods have long been used, but because sensory evaluations depend on the human senses, they are easily influenced by differences between individuals conducting the evaluation and their physical condition. Thus, the difficulty in ensuring repeatability is an issue. As an additional issue, technical training for the panelists who conduct evaluations also requires time and labor. To compensate for these problems, evaluation methods based on measurement of physical properties with instruments may be used. This approach eliminates the human error that had been a problem with sensory evaluations, enabling objective evaluations.

Food texture is also complexly influenced by the interactions of various factors, such as the ingredients contained in the food, their amounts, and the cooking method. Since differences in these factors may appear in the structure and surface condition of foods, observation and measurement of the internal structure and surface condition of foods make it possible to analyze and understand the factors that contribute to texture, allowing more efficient food product development from the physical viewpoint.

This article introduces an example of an analysis of the differences in texture that occur due to differences in the heating method from the aspects of evaluation of physical properties and structural and surface observation, using frozen tempura as the test sample.

2. Experiment

In this experiment, four instruments were used for evaluation of mechanical properties and structural and surface observation. Table 1 shows the names of the instruments, the purpose of the experiment, and the corresponding sections in this article.

The test samples used here were commercially-available frozen tempura, which features "moistness" when prepared by microwave oven cooking and "crispness" after microwave oven + oven cooking. The "Moist" type is prepared by heating for 1 min in a microwave oven, and the "Crisp" type is prepared by additional heating in an oven after microwave heating. Since the heating time in the oven is adjusted depending on the sample size required by each instrument, the specific sample preparation procedure and the flow of the tests will be described in the sections concerning each instrument.

Table 1 Instruments Used

General name of instrument	Purpose	Section
Texture analyzer	Quantification of texture	2.2
X-ray CT	Cross-sectional observation and coating thickness evaluation	2.3.1
Laser microscope	Measurement of roughness/color image observation of batter surface	2.3.2
SEM	Oil distribution/shape observation of batter surface	2.3.3

2.1 Sensory Evaluation

Table 2 shows the results of the sensory evaluation. Sensory evaluation of moistness and crispness was conducted by 15 assessors using a 100-point scoring scale based on a scoring method. The results for sample ① (Moist) showed a high score for moistness and low score for crispness, while sample ② (Crisp) showed an intermediate score for moistness and a high score for crispness.

Table 2 Results of Sensory Evaluation

Sample	Moistness (100 = perfect score)		Crispness (100 = perfect score)	
	Average [Points]	Coefficient of variation	Average [Points]	Coefficient of variation
① Moist	75.6	9.90	12.7	9.02
② Crisp	42.9	21.14	73.9	15.68

2.2. Evaluation of Physical Properties

The texture of the samples was quantified using a Shimadzu EZTest™ texture analyzer (Fig. 1). It is possible to conduct texture tests of foods of various types and shapes by changing the jig, plunger, and test method to be used. In this experiment, hardness was measured by a piercing test. The test samples were tempura of Japanese winter squash (kabocha). One type of sample was prepared by microwave heating, and the other was prepared by microwave heating with additional heating in an oven, after which the batter coatings were cut from the respective samples (Fig. 2). The coatings were cut to a size of 20 mm × 20 mm and fixed with the jig, then pierced at a speed of 1 mm/s with φ3 mm plunger until the plunger fully penetrated the sample. The number of tests was n = 10. Fig. 3 shows the condition of the test. As the results of the measurements of the ① Moist and ② Crisp samples, Fig. 4 shows the test force-strain curves, and Table 3 shows the hardness and the strain when hardness was detected.

Fig. 1 Appearance of EZTest Texture Analyzer

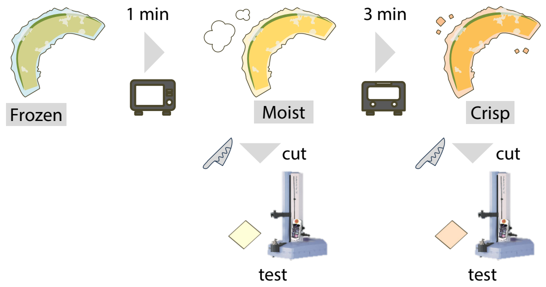

Fig. 2 Sample Preparation/Test Procedure (Texture Analyzer)

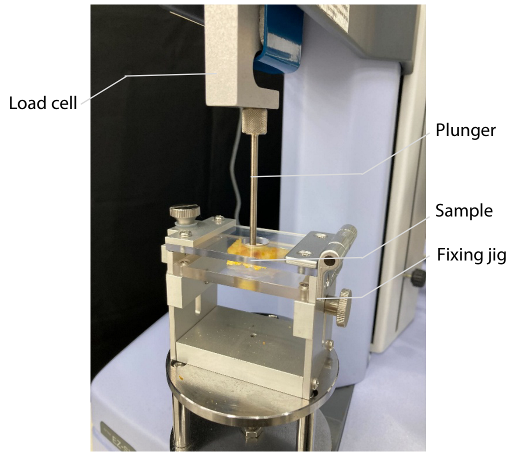

Fig. 3 Condition of Test

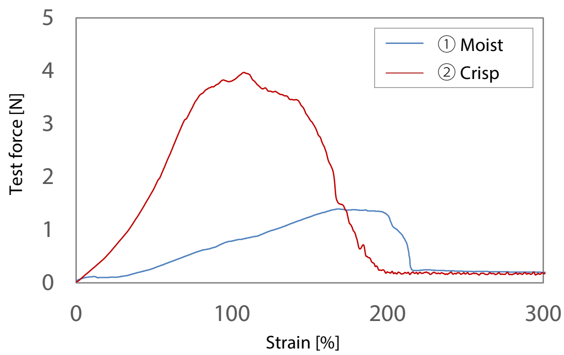

Fig. 4 Test Force-Strain Curves (Comparison by Representative Values)

Table 3 Test Results (n = 10)

Sample	Hardness_test force		Hardness_strain	
	Average [N]	Coefficient of variation	Average [N]	Coefficient of variation
① Moist	0.88	0.31	227.44	0.31
② Crisp	3.84	0.46	80.63	0.48

The hardness of the tempura batter coating was shown by the difference in the maximum test forces when a load was applied with the plunger, whereas crispness was shown by the difference in the strain at the point where the maximum test force (i.e., hardness) was detected. Since ① Moist showed a small maximum test force and large strain, it is difficult to tear, which is in good agreement with the sensory evaluation of moistness. In contrast, the hardness of ② Crisp was 4.3 times higher than that of ① Moist, while its strain was only 1/3 that of ①, and the Crisp sample displayed good bite and crispness. Moreover, fine roughness can be seen in the graph of the "Crisp" batter. This is due to the fine breakup of the batter coating, and a crisp texture that can be felt in the mouth is detected.

2.3. Structural Observation

In comparison with the texture analyzer, which can quantify food textures, the X-ray CT, laser microscope, and SEM are instruments that acquire information concerning the internal structure and surface, and are not suitable for quantifying texture as such. However, the indexes of the internal structure, surface shape, and oil distribution of the coating obtained by these instruments reinforce the results of the numerical evaluation by the texture analyzer, and offer clues for explaining why the mouthfeel of a food is “Moist” or “Crisp.”

In this experiment, the three instruments used for sample observation have different observation principles, magnifications, and resolutions; therefore, it is necessary to select the appropriate instrument depending on the purpose and object of observation. Table 4 shows the approximate resolution of the instruments and the targets in this experiment.

Table 4 Comparison of Instruments Used in Structural Observation

Product name	XSeeker 8000	OLS5500	SS-2000
Type	X-ray CT	Laser microscope	Scanning electron microscope (SEM)
Main feature	3-dimensional internal observation	Measurement of surface roughness	Detailed observation Element distribution
Observation principle	X-rays are irradiated, and the X-rays transmitted through the sample are detected.	Laser beam is irradiated, and the surface height is detected from the confocal image.	Electron beam is irradiated, and the electron signals generated by the sample are detected.
Resolution	0.1 mm	Horizontal 0.12 µm Vertical 0.01 µm	3.5 nm (30 keV, In-Chamber R-BSE, low-vacuum mode)
Observed region in this experiment	φ100 × H80 mm	8.5 × 8.5 mm	4.7 × 4.7 mm 0.4 × 0.4 mm
Observation target in this experiment	Coating thickness	Roughness of coating surface	Coating surface shape Oil distribution

2.3.1 Coating Thickness Evaluation by X-Ray CT

Since X-ray CT allows nondestructive observation of the 3-dimensional internal structure of samples, it can follow changes over time in the same sample. In this experiment, a kabocha tempura sample was first photographed in the “Moist” condition after heating for 1 min in a microwave oven, and the same tempura was then rephotographed in the “Crisp” condition after additional heating for 3 min in an oven (Fig. 5).

The instrument used in this experiment was an XSeeker™ 8000 bench-top X-ray computed tomography (CT) system (Fig. 6). As advantages, this device allows easy setting of the scanning conditions and short-time, and high-throughput scanning. Table 5 shows the scanning conditions in this experiment. Both the “Moist” and “Crisp” samples were photographed using the “Resin / Fine” mode.

Fig. 5 Sample Preparation/Observation Procedure (X-Ray CT)

Fig. 6 Appearance of XSeeker 8000 Bench-Top X-Ray CT System

Table 5 X-Ray CT Scanning Conditions

Setting conditions	Resin / Fine
X-ray output	160 kV
Scanning time	5 min
Voxel size	0.1 mm

Since this instrument scans the entire tempura sample at one time, macroscopic comparison of the two datasets is possible (Fig. 7). When the images of the same location were enlarged and compared, the points where oil had accumulated in the “Moist” sample appeared as voids in the “Crisp” sample, and points where part of the batter coating had peeled off could also be observed (Fig. 8). Furthermore, from Fig. 9, it can be understood that the coating has a two-layer structure. The gray outer layer is considered to consist mainly of oil, while the main component of the white inner layer is flour. Comparing the “Moist” and “Crisp” samples in Fig. 9, the thickness of the “Crisp” coating was thinner, and a large number of voids could be seen. Therefore, a wall thickness geometry analysis was carried out using VGSTUDIO MAX (option) to quantitatively evaluate the coating thickness of the entire tempura sample. When the tempura ingredient (kabocha) and the batter coating were separated based on the CT values, and only the coating was analyzed, the obtained VR images and histogram revealed that the coating of the “Crisp” type displayed an overall tendency to be thin (Fig. 10).

Based on these results, differences in the batter coating thickness and oil accumulation depending on the cooking method could be seen, suggesting the possibility that these factors also influence differences in food texture.

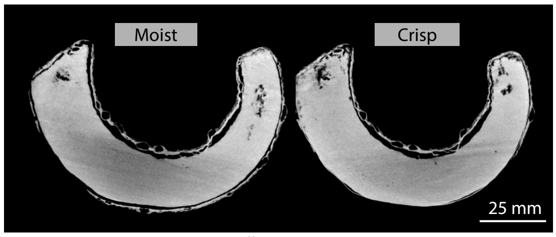

Fig. 7 Overall CT Cross Sections

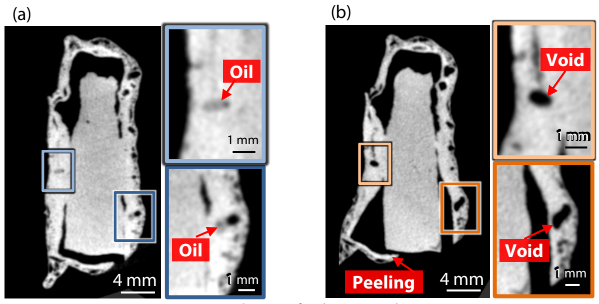

Fig. 8 Condition of Oil Accumulation
(a) Moist, (b) Crisp

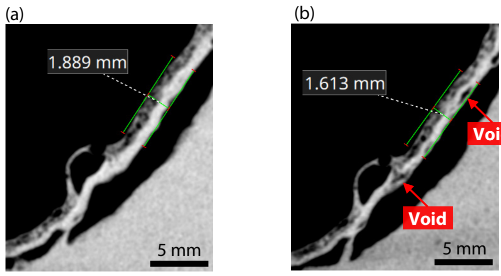

Fig. 9 Thickness and Voids of Batter Coating
(a) Moist, (b) Crisp

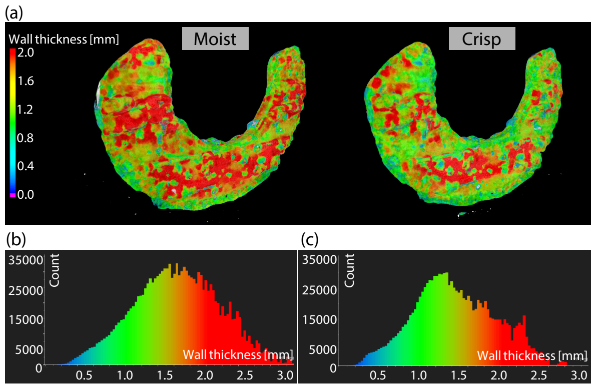

Fig. 10 Wall Thickness Analysis of Batter Coating
(a) Color map (VR), (b) Histogram (Moist), (c) Histogram (Crisp)

2.3.2 Evaluation of Coating Surface Roughness by Laser Microscope

The laser microscope was used in high-magnification measurements of the roughness of the sample surface and color observation (color images). It is possible to grasp the differences in the batter coatings of the "Moist" and "Crisp" types from changes in roughness and also changes in color. Fig. 11 shows the appearance of the OLS5500 laser microscope used here. In this instrument, optical resolution is enhanced by using a single-wavelength 405 nm laser beam, and topographical information can be acquired by reflective confocal laser microscopy. Color images of the same field can also be obtained by using a white LED.

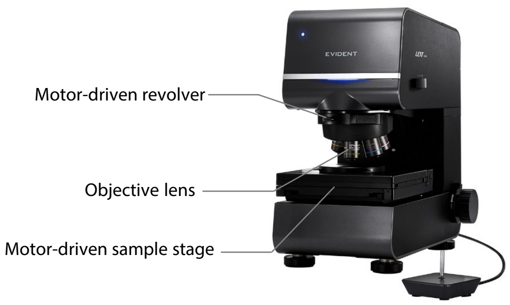

Fig. 11 OLS5500 Laser Microscope for 3D Measurement

In this experiment, the samples were prepared by the following procedure in order to observe the same areas of the "Moist" and "Crisp" samples. First, the entire kabocha tempura was heated for 1 min in the microwave oven, after which part of the sample was cut off and observed on the stage (Fig. 12). Following this, the observed sample was heated in the oven and placed on the stage again, and the "Crisp" sample was observed (Fig. 13).

To observe the shape of a wide area of the sample, an alignment ("tile-stitching") function was used. The image acquisition condition was the ultra-high speed mode using a 20x objective lens.

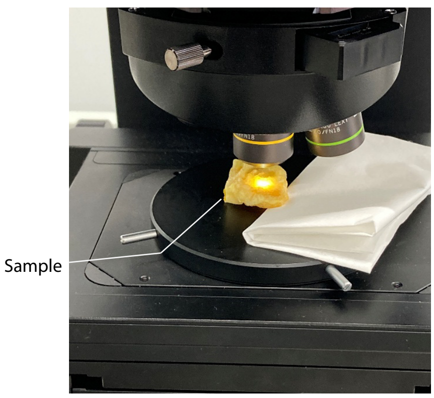

Fig. 12 Condition of Observation

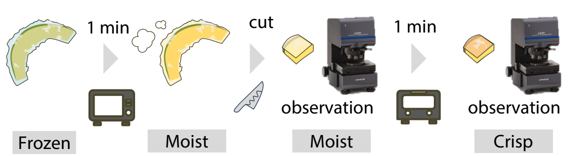

Fig. 13 Sample Preparation/Observation Procedure (Laser Microscope)

Fig. 14 shows color images of the "Moist" and "Crisp" tempura samples acquired with the laser microscope. Areas with little oil were observed as yellow, while those with a large amount of oil were observed as black. In the "Moist" tempura, more than half of the field of view is black, showing that the batter coating contains a larger amount of oil than in the "Crisp" tempura.

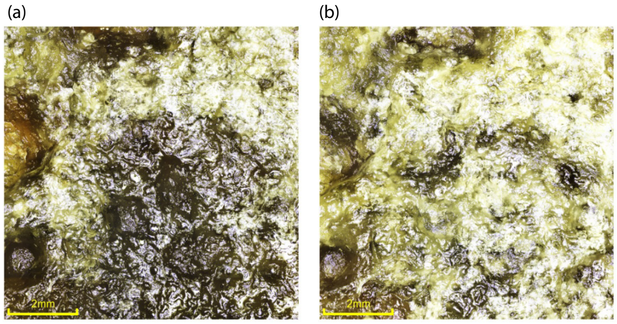

Fig. 14 Color Images
(a) Moist, (b) Crisp

Next, Fig. 15 shows the height images. The positions corresponding to the areas where a large amount of black coloration was observed in Fig. 14 (a) are indicated by the yellow boxes. Based on the fact that contrast of the "Crisp" tempura has become brighter, it can be understood that the entire surrounding area has become convex. The arithmetical mean height Sa of the surface of the "Moist" sample is 164.7 µm, while the Sa of the "Crisp" sample is 199.6 µm, indicating that the oven heating process not only reduced the oily content, but also increased the overall roughness of the sample. As a comparison of the heights of the two coatings at the same position, Fig. 16 shows the height graphs of the A-A' and B-B' sections in Fig. 15. The difference in the absolute values in the areas enclosed in the yellow boxes shows that the height has increased from around 100 µm to approximately 500 µm.

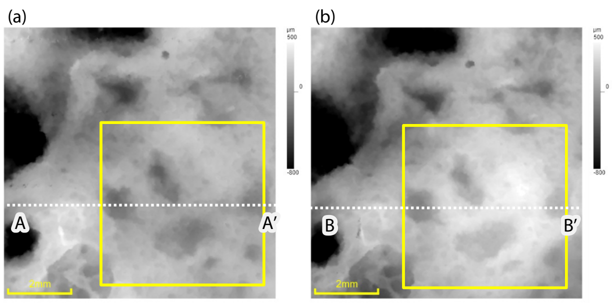

Fig. 15 Height Images
(a) Moist, (b) Crisp

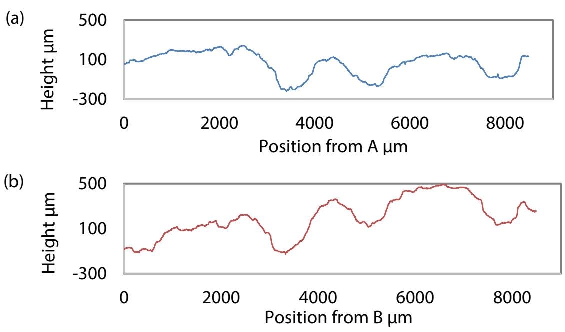

Fig. 16 Height Graphs
(a) Moist: A-A' section in Fig. 15,
(b) Crisp: B-B' section in Fig. 15

Based on the above points, from the observation in the laser microscope, differences in the appearance of the oil at the coating surface and in the surface roughness and height can be seen in the coatings of the "Moist" and "Crisp" tempura. These results show that oven heating not only removes the oil from the tempura, but also changes the coating height, as though the batter rises. These changes are thought to contribute to the "light" texture of the coating.

2.3.3 Evaluation of Coating Surface Oil and Shape by SEM

Scanning electron microscopy (SEM) makes it possible to observe the surface shape and component contrast of samples by detecting secondary electrons and backscattered electrons from the sample surface when it is irradiated with an electron beam, and analyze elemental information by investigating characteristic X-rays. The instrument used in this experiment was the SUPERSCAN™ SS-2000 shown in Fig. 17. This instrument supports observation under low-vacuum conditions (7 to 500 Pa (MultiVac N_2, H_2O)), and is also suitable for observation of food samples containing moisture and oils.

In this experiment, the samples were prepared by the following procedure in order to compare the SEM morphologies of the same parts of the "Moist" and "Crisp" samples. First, the kabocha tempura was heated for 1 min in a microwave oven, and part of the coating of the "Moist" sample was set on the aluminum SEM sample stage and observed. Following this, a "Crisp" sample was prepared by moving the entire sample and stage as-is to the oven and reheating for 1.5 min, and the sample was then observed again (Fig. 18, Fig. 19). This procedure made it possible to directly compare the changes in the sample morphology in the same area. Table 6 shows the main observation conditions.

Fig. 17 Appearance of SUPERSCAN™ SS-2000 Scanning Electron Microscope

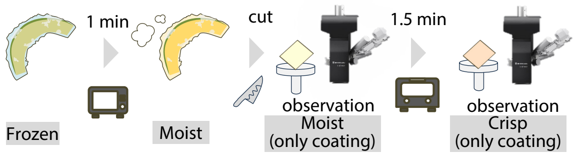

Fig. 18 Sample Preparation/Observation Procedure (SEM)

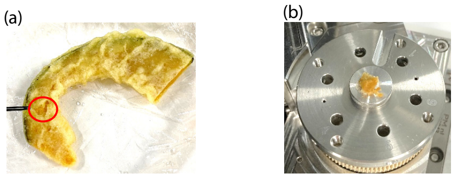

Fig. 19 Example of Sample
(a) Coating sample extraction position (red circle),
(b) Setting condition on sample stage

Table 6 Observation Conditions

	Low magnification	High magnification
Magnification	25 x	300 x
Size of field	4.7 mm	0.4 mm
Accelerating voltage	15 keV	
Incident beam current	1 nA	
Pressure	10 Pa, H_2O	

Fig. 20 to Fig. 22 show the results of SEM observation. Although no large changes in the overall shape could be observed in the low-magnification images (Fig. 20), clear differences could be confirmed by comparing the high-magnification images (Fig. 21) showing enlarged views of the areas in the yellow squares in Fig. 20. In the high-magnification secondary electron images in the upper row in Fig. 21, local changes in the surface topology could be observed, as the "Crisp" sample displayed granular convex structures that were not seen on the surface of the "Moist" sample. Furthermore, in the backscattered electron images in the lower row of Fig. 21, the oil-rich regions that had been visible on the "Moist" sample were observed as depressions in the "Crisp" sample, and the oil-rich regions in those spots had disappeared. In addition, when the elemental distribution of the "Crisp" sample was observed, carbon (C) was distributed over the entire area, and particularly in regions with large contents of oil, the oxygen (O) signal was reduced and the intensity of carbon was strong (Fig. 22).

From the above, it was suggested that oil droplets several tens of micrometers on the coating surface of the "Moist" sample was driven off by heating, and on the other hand, the increase in the fine roughness of the batter coating surface is expected to contribute to a "Crisp" texture.

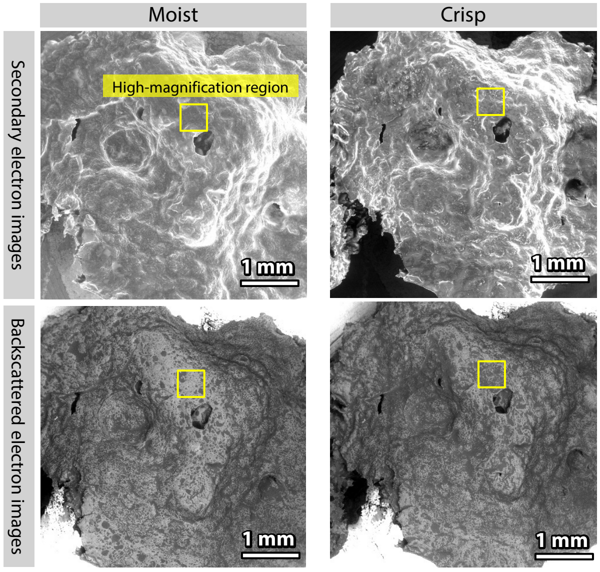

Fig. 20 Low-Magnification Images of 4.7 mm Field of View

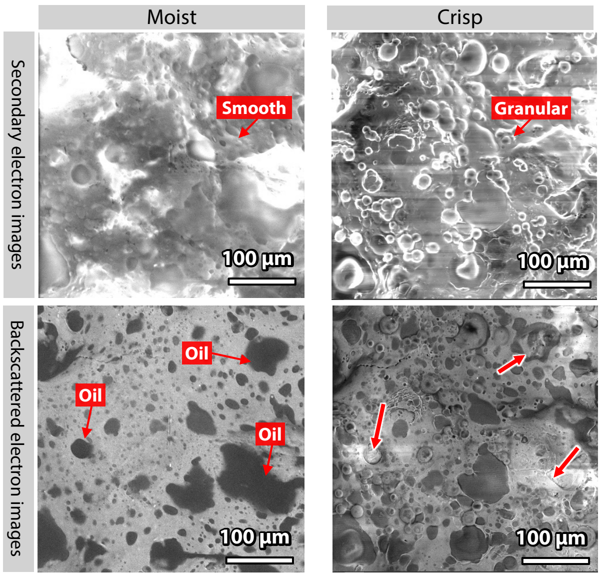

Fig. 21 High-Magnification Images of 0.4 mm Field of View
(Yellow Squares in Fig. 20)

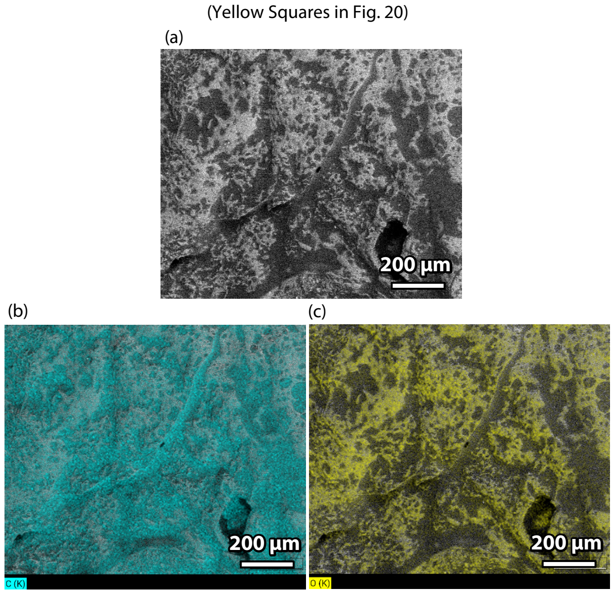

Fig. 22 Element Distribution by EDS (Crisp Sample)
(a) Backscattered Electron Image,
(b) Element Distribution (Carbon), (c) Element Distribution (Oxygen)

Table 7 List of Results

Evaluation method/ instrument	Indexes	Sample used	Results	
			"Moist" sample	"Crisp" sample
Sensory evaluation	• Moistness • Crispness	Entire tempura sample	• High moistness score	• High crispness score
Texture analyzer EZTest	• Maximum test force • Strain	Only coating	• Low hardness value • Large strain value at maximum test force	• High hardness value • Small strain value at maximum test force
X-ray CT XSeeker 8000	• Coating thickness • Observation of internal structure	Entire tempura sample	• Thick batter coating • Oil-rich regions	• Thin batter coating • Disappearance of oil
Laser microscope OLS5500	• Observation of color images • Height of surface roughness	Part of tempura sample	• Black coloration • Small arithmetical mean height Sa	• Yellow coloration • Large arithmetical mean height Sa
SEM SS-2000	• Oil distribution • Surface shape	Only coating	• Oil-rich regions • Smooth surface	• Disappearance of oil • Granular surface roughness

3. List of Results

Table 7 shows all the evaluation results of this experiment. Multiple instruments were used to evaluate tempura samples with different textures based on the indexes of the respective devices. As a result, it was possible to identify differences in the physical properties, structure, and appearance of the samples.

4. Discussion

Differences in the numerical values of the food texture obtained with a texture analyzer and by sensory evaluation were observed in the two aspects of "Structure" and "Oil content" through the results of observations utilizing X-ray CT, laser microscopy, and SEM.

In the structural aspect, the X-ray CT results confirmed that the batter coating of the "Crisp" type becomes thinner. Accompanying this decrease in the coating thickness, the internal structure became denser, suggesting the possibility that this contributes to an increase in the hardness of the coating as a whole. In observation by laser microscopy and SEM, it was found that local protrusions and granular convex structures appeared on the surface of the "Crisp" sample. Due to the formation of these protrusions and convex structures on the surface, it is thought that the distribution of the force acting on the coating surface during chewing becomes uneven, and local differences in the force in flat parts and convex parts tend to occur more easily. Based on these findings, in order to achieve a crisp mouthfeel, in addition to a simple increase in hardness, local structural changes, including changes in the surface shape, are also considered important. This kind of structure is thought to promote fracture of the batter coating, as one factor that contributes to a crisp mouthfeel.

Next, from the perspective of the oil content, the results of observation with the three types of instruments, namely, X-ray CT, the laser microscope, and SEM, confirmed that the oily fraction which was observed in the "Moist" tempura decreases or disappears in the "Crisp" type. As the oil content is a factor that contributes to a moist mouthfeel of the coating, it is thought that not only structural changes, but also differences in the oil content, are involved in the formation of differences in food texture.

Based on these points, it is thought that the macro- and microscopic structural changes and changes in the oil content act in a complex manner to cause the differences in texture shown by the sensory evaluation and texture analyzer.

5. Conclusion

A sensory evaluation and evaluation of physical properties using a texture analyzer, and structural observations from the macro to the micro level using an X-ray CT, laser microscope, and SEM were conducted for frozen tempura with different food textures depending on the heating conditions. The impression of the food texture, or "mouthfeel," obtained in the sensory evaluation was quantified in the form of physical property values by using the texture analyzer, and the factors that formed the grounds for those numerical values were then evaluated based on the results of various types of observation. As a result, it was suggested that differences in food texture correspond to changes in the food structure and oil content.

In this experiment, different samples were examined with four types of instruments. However, if physical property tests can be carried out with the samples as-is after observation of the same areas, a more direct and high accuracy analysis is considered to be possible. Moreover, in this experiment, the food texture was changed by using different heating methods, but in cases where the ingredients (flour, oil) or the deep-frying method is changed, there is a possibility that different factors from those in this study may contribute to the texture. As demonstrated in this experiment, although "food texture" is often grasped sensorily, as suggested by the term "mouthfeel," this property can be visualized scientifically in terms of the structure and physical properties of the food and the condition of the oil content by combining multifaceted evaluations using multiple instruments. This technique is expected to become an effective approach for reproducing and controlling the target texture in food product development and quality design.

01-00987-EN First Edition: Jul. 2026

SHIMADZU
Shimadzu Corporation
www.shimadzu.com/an/

Please fill out the survey

Related Products
Some products may be updated to newer models.

XSeeker™ 8000
Benchtop X-Ray CT System

EZ Test
Compact Tabletop Tester

EZ Test Texture Analyzer
Texture Analyzer

Related Solutions

Food and Beverages

Texture

Price Inquiry

Product Inquiry

Technical Service / Support Inquiry

Other Inquiry