Active Stress during Compression Testing of Various Foods Measured Using a Multiple-point Sheet Sensor

Kaoru KOHYAMA,1,† Tomoko SASAKI,1 and Haruka DAN1,2

1National Food Research Institute, 2-1-12 Kannondai, Tsukuba, Ibaraki 305-8642, Japan
2RETS Division, Nitta Corporation, 8-2-1 Ginza, Chuo-ku, Tokyo 104-0061, Japan

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Using a multiple-point sheet sensor (MSS), load and contact area were directly measured for compression of four different foods. The MSS provided temporal and spatial changes in stress applied on the sample surface during the testing. The sum of load value detected by the MSS corresponded to the load measured by a universal testing machine during the compression. The contact area between a flat probe and food surface varied with the variety of foods even though under a small strain, and increased as compression strain increased. The active stress, that is, the load divided by the contact area, was different from conventional stress, that is, the load divided by the initial cross-sectional area. The value of active stress provided a better explanation of textural characteristics of food, because texture is often sensed under a large deformation and mixed assessment of mechanical and geometrical properties.

Key words: texture; large deformation; compression testing; multiple-point sheet sensor; stress distribution

Textural characteristics are classified as mechanical, geometrical, and other properties of food.1) Texture is known to be a very important factor determining the attributes of food2) and it mostly contributes to palatability of many foodstuffs along with flavor.3,4) Texture evaluation is therefore required for quality control in the food industry and for the research and development of new food products. In general, mechanical tests of food materials measure the stress at different compression strains by an instrument such as an Instron universal testing machine.5) To obtain texture-consistent values from mechanical tests, compression tests under a large strain condition are preferable to small deformation tests, because we compress food over the breaking point until almost 100% strain during chewing food.6) Load is easily detected with a testing apparatus at any strain, but measurement of true stress applied to the sample is difficult because the cross-sectional area of the sample changes as sample deformation becomes large.5,7) In many cases, the stress value is conventionally calculated as the detected force divided by the initial cross-sectional area of samples, but this is not correct under a large strain.5,7,8)

In 1997, we introduced a multiple-point sheet sensor (MSS) to detect stress distribution during mechanical tests for heterogeneous foods.9,10) Each pressure sensing cell of the MSS detects the stress value of a point, therefore the MSS system shows the stress distribution of a surface of sample food, and directly measure the two main components of texture, mechanical and geometrical properties,1,2) as humans sense by many stress-sensing points on the skin surface.10)

In this study, the MSS system was used to evaluate the stress distribution during a compression test under large deformations by an Instron machine to show the contact area between a food sample and a flat probe of the machine. From the sum of load and the contact area over all the sensing cells detecting any stress, we derived the “active stress” value as a ratio of the total load applied to food samples divided by the contact area at each time during the compression test.

Since the classical study by Matz,1) who categorized foods into liquids, gels, fibrous foods, etc., classification of various foods by textural characteristics has been done.12-15) In Japan, Sone12) analyzed foods on the basis of their textural properties as liquid foods, gel-like foods, fibroform foods, cellular-form foods, edible oils and fats, and powdered foods. Lately, Toda and Wada13) categorized solid foods into gel-type foods, sponge-like foods, and porous foods with the physical properties determined by sensory evaluation and using a texturometer. Takahashi and Nakazawa14) classified solid foods by force patterns applied to an artificial first molar tooth in the first chew; chewing force pattern 1) with one
peak such as rice cake and bread, 2) with two smooth peaks such as cheese and gels, 3) with two steep peaks such as raw carrot and pickled radish (Takuan), and 4) with many peaks such as rice cracker and peanuts. Their class 1 seems to correspond to sponge-like foods by Toda and Wada,13) the classes 2 and 3 to the gel-type, and class 4 to the porous foods. We think that the class 1 is sponge-type foods, the class 2 is gels, and the 3 and 4 are wet-crisp and dry-crisp foods stated by Szczesniak.15) Our previous study on force-time curves with molars of 14 healthy adults6) showed that the bite force patterns during the first chew were common though the values of absolute bite force and chewing time depended on individuals. Texture did not seem to reflect the absolute force applied to the oral cavity, but it was related to patterns in temporal and spatial changes of the stress.

We chose four test foods for the present experiments, white bread, agar gel (Yokan), cracker, and raw carrot as in our previous study.10) Those foods were widely ranged in texture, and classified into different groups by the force patterns observed in the first chew with molars.6,16) White bread was a sponge-type food, which was a soft and compressible material, but was not cut off in one bite, therefore it showed one smooth peak in the masticatory curve. Agar gel was the representative of gel-type foods, which was soft, homogeneous, easy to rupture, and displayed two smooth peaks in the chewing force pattern. Cracker was a dry-crisp food, which was hard, brittle, highly heterogeneous sample, so that the masticatory pattern became as jagged as the force-time curve obtained by an instrumental test. Raw carrot belonged to wet-crisp foods as do other raw vegetables and fruits, was hard and often fractured at the middle range of strain, so the chewing curve gave two steep peaks. As all real foods including gels were not homogeneous, silicone rubber, used in a previous study,10) was also tested as a control with minimum mechanical properties are reported elsewhere.6)

As a homogeneous control, silicone rubber (Shin-Etsu Chemical Co., Ltd., Tokyo) with thickness of 2 mm was also tested.10)

**Mechanical test.** A compression test of each sample was done using an Instron universal testing machine (Model 5564, Canton, MA, USA) between two flat probes (2580 mm²) at room temperature.6) Multiple-point-sensing of stress was done with an ISCAN system (Ver. 4.2, Nitta Corp., Osaka) with a sheet sensor ISCAN50R (saturated pressure of 3.5 MPa) or ISCAN50H (0.7 MPa) after calibration was used as reported.6) Each cylindrical specimen on the sheet sensor was placed between the flat probes of the Instron apparatus and compressed at a constant speed of 1 mm/sec. The test was replicated more than 7 times for each sample.

The strain was defined as the ratio of deformation to the initial height of samples. From the load and contact area detected by the MSS system, the active stress was calculated as the load divided by the contact area.

**Results**

Using 1936 pressure sensing points on a multiple-point sheet sensor with two different pressure ranges, we displayed the stress distribution on a sample surface during compression testing with a flat probe. Figure 1 shows typical stress distribution patterns at various strains for agar gel, white bread, cracker, and raw carrot, respectively. The values of sum of force detected by all the sensing cells were high in cracker and carrot, and the lowest in bread. The stress value applied to each sensing cell was also high in cracker and carrot, while low in bread and agar gel. The four samples had distinctive spatial distribution patterns of stress. The pattern was the most scattered for cracker, the next for carrot, and the least for the gel. At a low strain, the stress was detected by a smaller number of sensing cells, the number of the stress-detecting cells, however, was increasing within the area under the sample placed for all the samples. Stress detecting area for carrot after breaking about 40% strain was not a circle shape any longer. Agar gel, cracker, and bread kept the circle shape until under large compressive strains, however, the sample area was the largest in agar gel.

Figure 2 shows the load value at every 10% compressive strain from the mechanical test. A high initial slope of the load curves was expected for hard samples (the carrot and cracker), however the former alone showed the high load value. As same as our previous report,6) the cracker broke at a small strain (mean fracture load 7.9 N at 8.7% strain) and then the load decreased. The load value at 10% strain for cracker was little higher than the loads for agar gel and bread, and much lower than that for carrot. The

**Materials and Methods**

**Samples.** White bread (Sun Royal, Yamazaki Baking Co., Ltd., Tokyo), fresh raw carrot, and agar gel (Hon-Neri Yokan, Yamazaki Baking Co., Ltd., Tokyo) were sliced 10 mm thick and then hollowed out by a ring cutter with a diameter of 25 mm. Crackers with a diameter of 25 mm were kindly supplied from Yamazaki Baking Co., Ltd. The initial thickness and diameter of each sample was measured with calipers (CD-15, Mitutoyo, Kawasaki, Japan). Their mechanical properties are reported elsewhere.6)
Fig. 1. Stress Distribution of Cylindrical Samples at Every 10% Compression Strain.

From left to right, examples of agar gel, white bread, cracker, and raw carrot. Agar gel and bread were measured with an ISCAN50H sensor and cracker and carrot using an ISCAN50R. Each dot presents one sensing cell of 1.27 $\times$ 1.27 mm of the sheet sensors, and the green square surrounding each frame is all the sensing area of the sensor (56 $\times$ 56 mm). Stress scales are 0.00–0.10 MPa for agar gel, 0.00–0.50 MPa for bread, and 0.00–1.00 MPa for cracker and carrot, they are drawn in the right side of each figure of 10% strain.
raw curves for cracker were jagged with many fracture points, but mean values for every 10% increase in strain were smoothed. When raw carrot was axially compressed, the load curve has a peak at 40% due to fracture at around 40–45% strain. It was not clear in this plot, but the gel had a peak in load at 50% because of the fracture between 50 and 60% strains as reported before.\(^6\)

The value of contact area at each strain was directly measured by the MSS from the mechanical test. As the original sectional area differed with samples,\(^6\) we standardized the contact area. The relative values of the experimentally obtained contact area to the initial cross-sectional area are shown in Fig. 3. Except for the agar gel, the values of experimentally derived contact area were smaller than the initial areas of the cross-section. For the gel, the ratio of contact area increased from 1 to more than 5 gradually, according to deformation of the sample. For carrot, the value was about 0.7 at 10% strain, but it became more than 1 soon, once decreased a little after breaking at 60%, and then increased again. For cracker, the ratio was the least (0.06) at 10% strain, and increased gradually as the strain increased. It reached 1 at about 70% strain. For bread, the value increased a little from 0.23 to 0.29 till 50% strain. The ratio then increased little by little, but it kept lower than 1 until 90% strain.

Figure 4 shows the active stress curves. As the contact area was neither constant nor equal to the initial value for all the samples, the active stress had different patterns from the load patterns (Fig. 2). The load values applied to the samples became the highest at a very high compression strain for all the samples tested. The maximum point for the active stress moved to 40% strain for carrot and to around 50% for agar gel. Cracker broke at a smaller strain than 10%, the mean and standard error values of fracture strain and active stress were also plotted in the Fig. 4 (mean stress 0.30 MPa at 8.7% strain drawn in solid trian-
The active stress once decreased after fracture for cracker, carrot, and agar gel, while it was continuously elevated for not-broken bread.

Figure 5 shows the coefficient of variation (CV) of stress detected in 264 sensing cells over the initial sizes of each specimen. As the CV is the ratio of the standard deviation to the mean, it represents the spatial distribution of stress, relating to structural heterogeneity. Cracker had an extremely high CV value and bread was the second at a small strain. Generally, the order of the standard error of for each CV value was cracker > bread > carrot > agar gel, and the highest value in the standard error was shown in cracker at 10% strain. Though the two samples showed descending curves, cracker decreased the variance more steeply. For carrot, after breaking at around 40% strain, the value increased once and then decreased again. Agar gel showed the least variances (about 20%) between 40 and 90% strains, but the values were doubly higher than that for the homogeneous control, silicone rubber.

**Discussion**

To obtain values of mechanical properties corresponding to texture, a simple compression test up to very high strain was done. In a conventional way, the stress was derived as the load divided by the initial surface area of samples. The conventional stress curves are not shown in this paper, but curve shapes were similar to the load curves (Fig. 2) as an initial area is used for calculation of the stress. We could measure the true stress called as “active stress” in this paper using many pressure-detecting sensors in simple compression tests. We mainly discuss the active stress obtained from the multiple-point sensing in comparison with the conventional ones.

Compression tests of food often fail to explain textural characteristics, which is described through tactile senses by fingers or oral apparatuses. We suppose that multiple-point sensing of stress during compression tests can resolve at least two problems in conventional mechanical tests. The first one is averaged load applied to a probe of an instrument due to one load sensor. Almost all food including gels were not homogeneous in term of mechanical stress as shown in Figs. 1 and 5. The patterns in spatial distribution were characteristic of structural properties of samples, and may be conveniently used for explaining sample texture. For example, a piece of cracker fractured partially, on a position at several % strain and the stress applied to the position suddenly decreased to zero at the next moment, but stress appeared elsewhere on the plane in the next moment. The sum of load over the sample sometimes resulted in continuous increase despite small cracking. On several occasions, we experienced such a phenomenon for crackers. In such cases we had mis-detected the breaking point with a single load sensor. The other problem is increased differences between true contact area and the original surface area under a high compressive strain. By increasing the number of sensors and reducing the area for a single sensing point, we can directly measure the contact area at any strain.

Theoretically, at a small deformation, the cross-sectional area between the interface of probe and sample is equal to the initial area of the samples, though the value increases as strain increases. However, this observation shows that it depended on sample properties. Obviously, a homogeneous sample such as food gels and silicone fitted the theoretical value at the first, while the others not (Fig. 3). Agar gel was the most nearly ideal material among the four, since the active stress value was close to the ratio of the load to initial cross sectional area at a small deformation. When the sample was non-parallelly cut into a cylinder with the upper and lower sections, the initial contact area became inaccurate, as mentioned by Bourne. The area ratio of experimentally obtained contact area to the theoretical one becomes less than 1, associating the non-linear force-deformation curve at small compression strains in such a case even though the samples were homogeneous. The value of area ratio at 10% strain for carrot shown in Fig. 3 involves this error. In contrast, especially with porous materials such as bread and cracker, the contact area derived by a number of pressure-sensing cells, which detected any stress, was much smaller than the ideal initial area, even if the sample was correctly cut (Fig. 3).

The sample volume at each strain level can be experimentally estimated as the product of the contact area and height. When the compressive strain was smaller than 70%, the volume of agar gel was close to the original one, which was calculated as the initial sectional area by height. It is consistent that gels have structural flows without volume reduction when they are compressed. The network structure of the gel holds a large amount of water. It would be highly damaged at higher compressive strain than 70% and therefore it released the water, which did not contribute to the mechanical resistance. The volume value for carrot was always smaller than the gel, however, it remained about 0.8 of the original volume until 40% strain, then the value went down. Water is likely to be separated from the cells of carrot a little at small strain ranges and in greatly after breaking of the cell walls. Cracker and bread gave much smaller volume values, especially the latter was no higher than 0.2 throughout the tests. It is due to their cellular structure with low densities.

Bread is a cellular foam, the same as a sponge and polymeric foams which contain many air cells. Bread crumbs were open-celled foam as reported, and Ishida et al. recently observed small air holes...
cut specimens with flat surface and a defined size. In and brittle nature of such samples makes difficult to prepare of specimens; the hard truncated by densification with highly zig-zag waves. (Linear elasticity, a plateau of brittle crashing, and are elongated at low stresses followed by a long collapse plateau, truncated by a regime of densification in which the stress rises steeply. As the cell-wall material of crumbs is easy to bend, the bread sample was free from resistance at small deformations and soon reached a long plateau region of buckling. When the bread was pressed, stress was detected at a part of the interface of an instrumental probe. Even though there was a cell-wall material touching the sheet sensor, as air exists inside, the sample gave very small resistance below the detecting limit of the sensor. Since the ratio of air cells is high in white bread, the value of the contact area remained low until 50% strain (Fig. 3). Those observations are consistent that Poisson's ratio of the sponge-like material is close to zero, and that there is no structural flow of cell-wall materials associated with the compression of samples. When the deformation reached 90% of the initial thickness, space for the existing air was completely abolished, resulting in the contact area exceeding the initial cross-sectional area. At this region, densification finally began.

In contrast, cracker may make a close-cell structure surrounding air pores, the linear elasticity of which is controlled by cell-wall bending and cell-face stretching. When a piece of cracker is compressed, a part of the uneven surface, where there are mounds, resists the compression force, as the cell wall is enough hard. As cracker is brittle, the cell structure broke at small strains before the probe touched all over the cross-section of the sample. The stress detected by one sensing cell was quite high due to the stress concentration, however, once the structure was broken, the stress value at the position decreased to zero at the next moment and stress appeared at other positions. We observed such scattering patterns in the course of the output of the MSS while biting by human teeth and compression with a wedge-shaped probe. As the density of the cracker is also low, like bread crumbs, inner air cells helped to prevent flow of the cell-wall materials even though the structure was breaking and kept the contact area small. Both the sum of load and contact area increased gradually with numbers of jags, however, the active stress did not greatly increase until the pore structures of the inside perfectly collapsed at around 70% strain. The compressive stress-strain curve was the same as elastic-brittle foams, which have short linear elasticity, a plateau of brittle crashing, and are truncated by densification with highly zig-zag waves.

A problem in mechanical tests for dry crisp foods is the difficulty in preparation of specimens; the hard and brittle nature of such samples makes difficult to cut specimens with flat surface and a defined size. In many cases, puncture tests using a thin bar or wedge-shaped probe have been done, however, to derive a stress value is difficult because the precise contact area is unknown for such a probe, and to evaluate after-fracture phenomena is impossible since the broken pieces are scattered away under the probe in those methods. Texture is obviously assessed manually or orally after breaking of the food. We are required to compare different foods with wide ranges of textures. Using the active stress, we can analyze compression process with flat probes until a very large strain after breaking of samples and compare textural characteristics of various solid foods including porous samples and ones with uneven surface as well as gels.

In terms of the active stress value, raw carrot displayed the highest stress at fracture point at about 40% strain (Fig. 4). Conventional estimation of stress contrary gave a much higher stress at a large strain as shown in Fig. 2. After the fracture, the broken tissue expanded as shown in Fig. 1. The active stress presented more the reality than the conventional one.

Touching and pressing those samples with fingers, we feel that raw carrot and cracker are hard, gel is softer, and bread is the softest. The active stress value before the fracture point well corresponds to the human manual feelings. Although it is sometimes difficult with fingers, we can break those samples by biting or chewing. We sense that the mechanical resistance for fracture is the highest in carrot, and next in cracker, the lowest in agar gel, but it is difficult to break bread in one chew. The active stress and strain at the breaking point also explain those oral assessments.

We can also demonstrate the heterogeneity of sample surface with the CV value shown in Fig. 5. In homogeneous silicone, the CV value was about 10%. As the stress concentrated to the center part of a cylindrical sample, a higher stress value was observed inside than outside. The stress distribution existed in any food sample; agar gel was the lowest, carrot was the second, and bread and cracker with foam structures were highly scattered. As the surfaces of the crackers were not flat, the CV value and also the standard error were the most significant for a cracker at a small deformation. The two porous samples decreased the CV value as crushing cell structures. Thus, degree of stress distribution observed with the many stress sensors was useful to indicate spatial heterogeneity of samples, causing textural characteristics.

Conclusion

We directly measured load and contact area using a multiple-point sheet sensor (MSS) system during compression tests for various food samples. The...
active stress, defined as the ratio of load to contact area, was a good measure for human tactile senses before and after breaking. The stress distribution over the initial cross-sectional area also explained sample homogeneity. The MSS could show both mechanical and structural properties of samples under wide ranges of deformation. This was a powerful new concept to describe the texture of inhomogeneous foods.

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**References**


