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Measurement of Microscopic Young's Modulus of Crispy Foods

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Abstract. This study addresses a measurement method of microscopic Young's modulus of crispy foods. It is significant for examining food texture to measure substantial mechanical property of the foods independent of its structure. There are few studies on measurement of Young's modulus on a micro-scale level although many macroscopic studies were reported. We propose a new method to estimate microscopic Young's modulus of crispy foods. The method consists of a micro-scale compression test and the individual finite element analysis. The estimated Young's modulus is about 300-1500MPa on the microscopic level that is much more than 10 times larger than the macroscopic values.

Keywords: Food texture, Microstructure, Finite element analysis, Young's modulus, Crispy food

1. Introduction

Food texture is one of the most important factors to evaluate the food. We enjoy variety of food textures in mastication of foods. It is especially significant for snack foods to have pleasurable food textures as much as they dominate their commercial values. Food textures are closely related to mechanical properties of the foods such as Young's modulus and material strength. Many previous researches examined relationships between deformation and crash of foods on the macroscopic level [1]-[6].

When Young's modulus of snack food is estimated by the macroscopic compression test, the food is assumed to be uniform. However, a whole piece of the snack food has irregularly-shaped structure and non-uniform material properties on the microscopic level. These factors are mixed on the macroscopic level. For examining food texture exactly, geometrical structure and material properties should be measured independently, which will lead to develop a new fabricated food with a novel food texture. However, traditional compression tests cannot distinguish the two factors definitely. This study proposes a new method to measure substantial Young's modulus of snack foods on the microscopic level.

2. Materials and Methods

Most of snack foods are hard but fragile. They suddenly break down with critically small deformation when the load is over a certain value. These mechanical properties give crispy food texture. To observe the load-deformation behaviour of these brittle solids, it is necessary to measure micro-scale of load and displacement under a compression test. We developed a new testing machine as shown in Fig. 1. The indenter module is composed of a linear actuator (Piezo-electric nano-positioner) for compressing a test piece of a snack food and a laser displacement gauge for measuring displacement in the compression test. The testing machine measures milli-newton scale of compression load and nano-meter scale of displacement. However, the only microscopic compression test cannot provide microscopic Young's modulus because the load-deformation behaviour results from two factors, material property of the food and its structure.

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To estimate Young’s modulus independent of the inner structure, we propose a new method. Figure 2 shows the procedures to estimate Young's modulus. Our proposed method uses a micro-focus X-ray CT for obtaining the exact 3-D structure of test piece and combines the result with the load-deformation data measured on microscopic level.

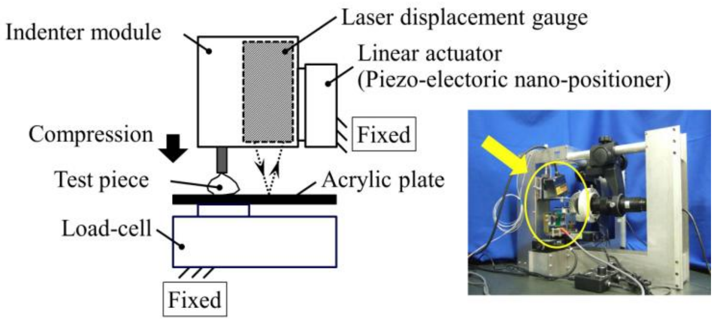


Fig. 1: Testing machine for micro-scale compression test

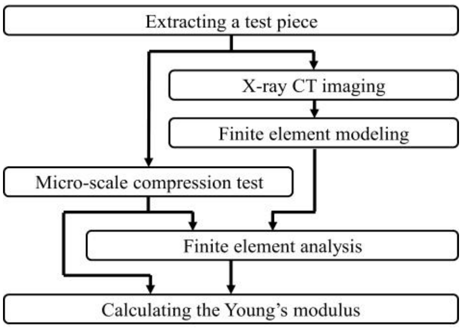


Fig. 2: Estimation procedures of Young's modulus

The procedures for estimation of microscopic Young's modulus are as follows.

#Step 1. Making a test piece

Three kinds of snack foods in the market were used for the measurement in this study. They are about 5-10 mm width and 80-100 mm length as shown in Fig. 3. Small pieces with 1 to 3 mm size were plucked out of the snack foods. These pieces are fixed on an acrylic plate with resin adhesive for the compression test as shown in Fig. 3.

#Step 2. X-ray CT imaging

The test pieces were scanned by a micro X-ray CT (ScanXmate-L080HT, ComScanTecno Co., Ltd.) with 512×512 pixels. Figure 4 is an example CT image of a test piece. A white intricate shape on the rectangle base is the snack food in the figure. One pixel has 15 μm length in the CT image and slice thickness is adjusted to the length.

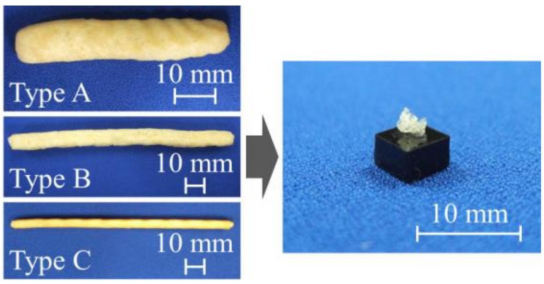


Fig. 3: Three types of snack foods and an example of compression test piece

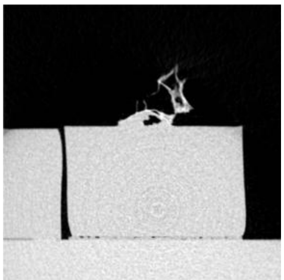


Fig. 4: CT image of test piece

#Step 3. Extracting solid parts

Some snack foods contain liquid oil in them. The oil parts give no effect on stress analysis because of liquid property. We must exclude the oil areas and extract only the snack foods from X-ray CT images for exact estimation of Young's modulus. It is not easy to separate oil parts from solid dough area because they appear as grey areas in the CT image. We applied a threshold processing method for the separation. Figure 5 shows the process. First, we set a threshold that is almost the lowest CT value of the oil and dough area. The oil and dough area are extracted by the threshold as shown in Fig. 5(b) from the original image as in Fig. 5(a). The image as in Fig. 5(b) includes clusters of oil and thin frames of snack dough. Second, we apply an erosion process to the image. The erosion process has a reduction effect of the edge pixels. Since almost all the dough frames are thin with about five pixels, they disappear after three or four times of the erosion process. Oil areas are also reduced, but remain in the image as small clusters as shown in Fig. 5(c). Third, we apply a dilation process that has expansion effect on the edges. The oil clusters are left as in Fig. 5(d). It is easy to find difference between the original image as in Fig. 5(a) and the only oil image as in Fig. 5(d). Finally we obtain the only solid dough areas as shown in Fig. 5(e).

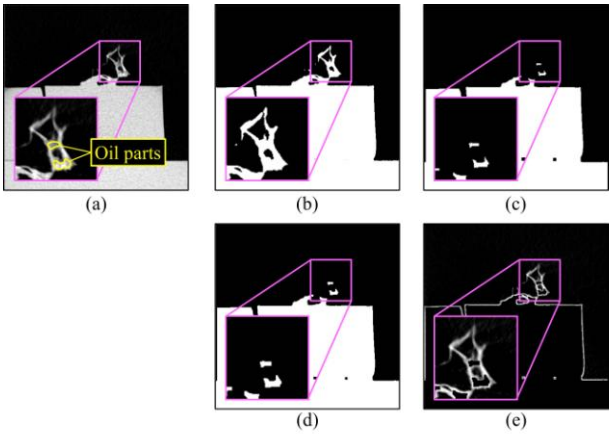


Fig. 5: Separation process of food material from oil parts

#Step 4. Finite element modeling

The individual finite element model with small same voxels is made from the X-ray CT images after #Step 3. The each voxel is a cube with 15 μm side length. The example model is shown in Fig. 6. The total number of elements is about 350,000 and the number of nodal points about 450,000.

#Step 5 Micro-scale compression test

Compression tests of snack foods were performed with our developed testing machine. Figure 7 shows an example of the load-deformation relationship from the compression test. It is reasonable to assume that dough of the snack foods shows linear elasticity in the initial stage.

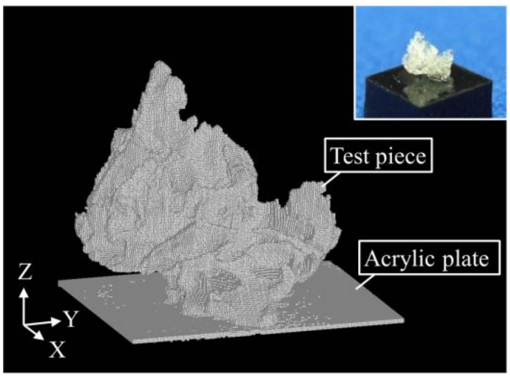


Fig. 6: Finite element model

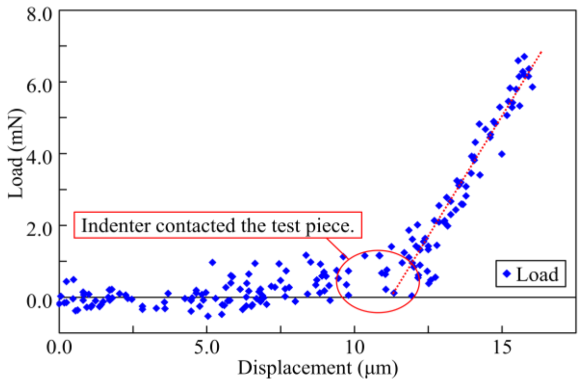


Fig. 7: Example of load-deformation relationship

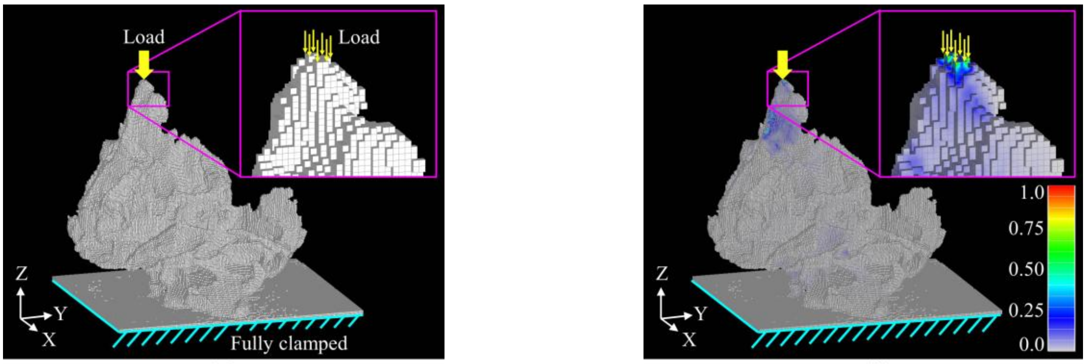
#Step 6 Estimation of the Young's modulus

The microscopic compression test and the individual stress analysis give a microscopic Young's modulus because they hold elastic relationship. Equation (1) shows the relationship.

$$E_a \Delta d_a = E_c \Delta d_c \quad (1)$$

Where E_a is the assumed Young's modulus in the finite element analysis, Δd_a is displacement obtained in the analysis, E_c is the real Young's modulus, Δd_c is the displacement obtained by the micro-scale compression test. The real Young's modulus E_c can be estimated since Δd_a, Δd_c and E_a are known.

For performing the stress analysis, we give load and boundary conditions to the finite element model of the test piece. The model is fixed on the bottom surface. Several uniform loads corresponding the indentation point in the compression test are applied to the nodal points on the top surface as in Fig. 8(a). The sum of the loads is equal to the load of the micro-scale compression test. Young's modulus of the snack food part was given 1.55 GPa as E_a and the Poisson's ratio was 0.35. The acrylic part was given 2.8 GPa and the Poisson's ratio 0.39. The result of stress analysis is shown in Fig. 8(b). From the stress analysis, analytical displacement Δd_a is obtained.



(a) (b)

Fig. 8: Mechanical condition and finite element analysis
(The colour-bar denotes normalized equivalent stress)

3. Results

Three types of snack foods in Japanese market were used for this study. 13-18 test pieces were plucked out of one individual snack piece along the longitudinal axis. Compression tests were performed under the condition of 1 μm/s with 100 μm stroke. Finite element analyses were executed by MD-Nastran2011. Figure 9 shows the results of estimated Young's modulus by the procedures as in Fig. 2. Each snack food has variations of Young's modulus along the longitudinal axis. Type A and B have larger values of Young's modulus than that of type C though the cross sectional density looks a converse relation.

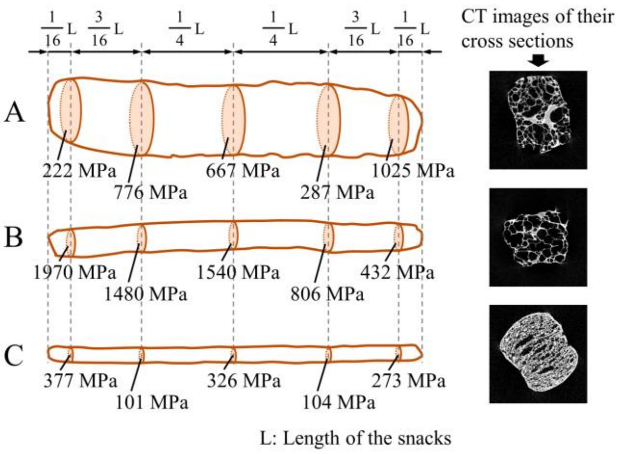


Fig. 9: Estimated results of Young's modulus

4. Discussion

Type A of snack food is thick in diameter compared to type B and C. Type A and B have similar inside structures with very sheer walls and easily breakable in mastication. On the contrary, type C is thin and dense compared to type A and B. It is harder to break it than type A and B. However, the estimated Young's modulus has smaller than those of type A and B. It suggests that food texture depends on both microscopic mechanical property and its structure.

Macroscopic Young's moduli were also estimated by conventional compression tests. Table 1 shows the comparison of microscopic Young's moduli and macroscopic ones for the three kinds of snacks. Type A, B and C are estimated as 5.0 MPa, 7.4 MPa and 13 MPa respectively. These values are much smaller than microscopic ones. This result is similar to relationship between apparent Young's modulus of cellular foam and Young's modulus of dense solids made with artificial material [7]. Moreover, there is no linear relationship between them. It means that the macroscopic Young's modulus greatly depends on its structure. These facts have been revealed by implementation of microscopic measurement of Young's modulus for the first time.

In this paper, we focused on measurement of microscopic Young's modulus of snack foods. The microscopic material strength is also an important factor for food texture because it related to fracture behaviour of the foods. The proposed method is applicable to estimation of microscopic material strength. However, the present compression machine does not have an enough stroke to break a test piece. It needs a 500 μm stroke at least. It needs an enhancement of the stroke as the present machine has 100 μm stroke at most. It will also need a nonlinear stress analysis for the estimation of the microscopic material strength because deformation at the fracture is large for the microscopic level. We are now developing the estimation method of microscopic material strength.

Table 1: Microscopic and macroscopic Young's modulus

Young's modulus	Type A	Type B	Type C
Microscopic (MPa)	619	1250	238
Macroscopic (MPa)	5.0	7.4	13

5. Conclusion

This study discussed microscopic Young's modulus of snack foods. The results present that macroscopic mechanical property (apparent Young's modulus) greatly depends on its microscopic mechanical property as well as their structure. The proposed method provides us basic data for development of a new crispy food.

6. Acknowledgement

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