Ergonomic design of beverage can lift tabs based on numerical evaluations of fingertip discomfort

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Ergonomic Design of Beverage Cans Based on Numerical Evaluations of Discomfort in Fingertip When Lifting up the Tab

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Abstract

This paper introduced the finite element analyses to evaluate numerically and objectively the feelings in the fingertip when opening aluminum beverage cans in order to design the shape of the tab. At first, experiments of indenting vertically the fingertip pulp by a probe and tabs of the aluminum beverage can ends have been done to observe force responses and feelings in the fingertip. It is found that a typical force-displacement curve may be simplified as a combination of three curves with different gradients. We feel a touch at Curve 1 of the force-displacement curve, then feel a pressure and our pulse at Curve 2, finally feel discomfort followed by a pain in the fingertip at Curve 3. Moreover, the finite element analyses have been performed to simulate the tab indenting the fingertip vertically to confirm that the simulation results agree well with the experimental observations. Finally, numerical simulations of finger pulling up the tab of the can end has also been performed and discomfort in the fingertip has been presented by the maximum value of the contact stress of the finger model. Comparisons of three kinds of tab ring shape designs showed that the tab that may have a larger contact area with finger is better.

Keyword: Human Fingertip Indentation Experiments, Numerical Evaluation of Pain, Finite Element Analyses, Aluminum Beverage Cans.

1. Introduction

Structural optimization methods based on the finite element analysis have been applied to search the optimum shape and dimensions of the aluminum beverage cans & bottles (Han et al., 2004, 2005; Yamazaki et al., 2007). With the quality of human life being improved, it is becoming necessary to design containers universally based on ergonomics evaluation that considers psychological, physiological, and anatomical affects. Ergonomics designs can be found in many literatures (Kolich and Taboun, 2004; Hendrick, 2000). The physical, cognitive and emotional comfort of the consumers should be considered to create an optimal human-product interaction. However, we need objective, measurable laboratory standards, which can be linked to subjective perceptions of comfort. Only in this way predictions can be made whether a particular design will be felt comfortable or not by the consumer.

Easy-open cans with SOT (Stay-On-Tab) ends (Fig. 1) have been developed more than twenty years before, and the functional problems such as the sealability and the end openability have been almost solved (Nishiyama, 2002). Human-friendly, ease-of-use and comfort are being expected in the development of containers to enhance the quality of human life (Ueno, 2003). The finger-accessibility is used to evaluate whether it is easy to insert fingertip into the gap between the ring and finger deboss of the can end, and whether it is painful or uncomfortable when pulling up the tab ring. The easier the finger can be inserted and the ring can be pulled up, the better the finger-accessibility is evaluated. To improve the finger-accessibility, various methods have been developed. For example, deepening the finger deboss, curving up the ring, or applying scores to the panel under the tab so that the tab may float up a little when the can is filled with beverages and pressured (Yoshida and Yoshizawa, 1996). All of these methods are trying to enlarge the gap between the ring and the finger deboss to make fingertip go into the gap easily and consequently to improve the finger-accessibility. Since there are limitations of these methods, such as a clearance restriction between the tab and the top edge of the seaming wall, the geometrical shapes of the tab ring are required to be investigated.

On the other hand, the fingertip is the most sensitive and important part of human body to obtain information by touching an objective and to control manipulation. Experimental results show that the fingertip is almost incompressible for a point indentor, with the highest change in volume occurring at the largest depth of indentation (Srinivasan et al., 1992). A study of Serina et. al. (1997) has reported that few statistically significant Pearson correlations were found among the relationships of pulp parameters (such as, pulp displacement and stiffness) with fingertip dimensions, gender, and subject age. Finite element analyses have been performed to predict surface deformations of the fingertip (Srinivasan and Dandekar, 1996), and a geometry and a structural model of the fingertip pulp supported by experimental data have been developed to predict the force-displacement and force-contact area responses of the human fingertip during contact with a flat, rigid surface (Serina et al., 1998).

Experiments of presenting stimuli with spherically curved surfaces to the fingertip pulps of human subjects have been performed, and it is observed that an increase in curvature (with no change in contact force) results in a sharper and higher response profile as well as an increase in perceived contact force (Goodwin and Johansson, 1992). Perception of surface pressure applied to the fingers has been investigated experimentally, and the pressure level at which human subjects perceived a pain was measured as the pain pressure threshold (Brennum et al., 1989; Fransson-Hall and Kilbom, 1993; Johansson et al., 1999). Statistical analysis results showed that the pain pressure threshold of males is higher than that of females in average. Moreover, the finite element method was applied to simulate the configuration change of the human fingertip when grasping the aluminum beverage bottle for hot vending and then to evaluate the tactile sensation of heat numerically (Han et al., 2006). However, no works can be found on observing the relation between the pain and the force-displacement curves when a load is applied to the fingertip pulp.

This paper introduces the finite element analysis into the ergonomics design of aluminum beverage can end to evaluate numerically perceptions of discomfort. At first, using a tension-compression tester, experiments of a probe and tabs of beverage can ends indenting vertically the finger pulp are performed. The deformation of the configuration of the fingertip and the pain experienced are studied. Simulations on tabs indenting vertically the fingertip are then performed using the finite element code, and are compared to the experimental observations. The process of index finger pulling up the tab of SOT ends is also simulated by the nonlinear finite element analyses, and the sensation of discomfort in the fingertip is evaluated numerically by the maximum value of the contact normal stress. Three kinds of tab models with different ring designs are analyzed numerically and the finger-accessibility are compared.

2. Experiments on Indenting Human Finger Pulp

2.1 Testing Methods

A commercial tension-compression tester (Shimadzu Corporation, AG-50KNG) is used for the experiments on indenting finger pulp so that dynamic real-time measurements to track the finger pulp thickness changes and force changes over a very short period may be possible. As shown in Fig. 2(a), the index finger is laid on the table of the tester and then an indentor of probe or tab is moved down at a constant velocity v to indent the finger pulp at the center in width direction and at a distance L from the fingertip in longitudinal direction. A computer records automatically the force applied to the finger and the displacement of the indentor every 0.05 second. To avoid any injury to the subjects, an upper limit of the force $P_{\max}$ or an upper limit of the displacement $H_{\max}$ of the indentor is set in advance. When the force reaches the upper limit $P_{\max}$ or the displacement reaches $H_{\max}$, the indentor has been kept stopping for 60 seconds and then been unloaded to its initial position. The subject was allowed to relax until the fingertip regained its undeformed shape for the next indentation. An aluminum probe with a hemisphere tip 3.68 mm in diameter (Fig. 2(b)) and two kinds of tabs with the convex ring or flat ring (Fig.2(c)), are used as the indentors. The tabs are fixed in a cylindrical resin so that they can be fixed to the tester to indent vertically the index fingertip pulp of human subjects. Human subjects are selected from key persons (include female and male) of this study, and the mean age of subjects is 38 year-old, age range is 28-56 year-old. The initial width and thickness T_0 of the finger pulp at various distances L from the tip were measured for each subject prior to the experiment with the finger being free from any external loads (Fig.2(d)).

2.2 Fingertip Indentation by the Probe

In order to determine the deforming property of the finger pulp and to experience the feeling of pain, experiments of the finger pulp indentation at $L = 7 - 8$ mm by the probe have been performed. Figure 3 shows the force changes with time and the displacement of the probe at velocities of $v = 4$ mm/min (Subject DM) as an example of measurement results. The force-time relation plotted in Fig. 3(a) shows that when keeping the probe unmoving after it reaches the upper limit $H_{\max}$, the indentation depths in the finger doesn't change while the force decreases with time going by. It is so called stress relaxation due to the viscoelastic property of human finger. A typical force-displacement curve, as shown in Fig.3(b), may be simplified as a combination of Curve 1, Curve 2 and Curve 3 as shown in Fig.3(c). Let us suppose Point A is the intersection of Curve 1 and Curve 2, and Point B is the intersection of Curve 2 and Curve 3. Moreover, the direction of transverse axis becomes backward if it presents the fingertip thickness T_f that is calculated as $T_f = T_0 - H$, where H is the indentation depth, i.e., the displacement of the indentor. It is observed that the finger thickness decreases almost linearly at the low forces, after passing intersection Point A, the thickness decrease rate becomes lower, and after Point B the thickness decreases almost linearly again but the decrease rate becomes further lower. It is considered that when the deformation of soft tissue comes near to its limit, the force required to deform the soft tissue becomes higher and higher. The experimental results agree with those in literatures (Serina, 1997).

Concerning the influence of the personal differences and the indenting velocity of the probe, the experimental results of HS1 (Subject 1, in 30s, Female), HS2 (30s, Male) and HS3 (50s, Male) are compared in Fig.4, when v = 1 mm/min, 4 mm/min. Comparison result shows that the gradient of Curve 3 in the force-displacement plot doesn’t change much even though the finger dimensions are different person by person. The experimental results agree with those in literatures (Serina, 1997). Figure 4 also shows that the gradient of Curve 3 in the force-displacement plot doesn’t change much even the indenting velocity changes. However, the slower the velocity is, the later Curve 2 rises. It is because that if the velocity is lower, the indenting time becomes longer, hence, the resistance in the fingertip becomes smaller due to the stress relaxation in the soft tissue.

All subjects are asked to report the feeling in fingertips during the indentation. The common feeling change is as follows; we feel a touch at Curve 1 of the force-displacement curve, then feel a pressure and our pulse at Curve 2, finally feel discomfort followed by a pain in the fingertip at Curve 3. The discomfort and pain in the finger increases as the force or the indentation depth increases. If the total load is the same, the narrower the contact area is, the deeper the indentation depth becomes, i.e. the thinner the fingertip becomes, hence, the greater the discomfort and pain is felt. In the numerical analysis of finger-accessibility of the tab described later, only Curve 3 is necessary to be taken into account because we focus on only the feeling of discomfort and pain in the fingertip when pulling up the tab to open the beverage can. Therefore, it is judged that the fingertip model can be simplified as an elastic model of a constant value of Young’s modulus.

2.3 Fingertip Indentation by Tabs

Since the space under the tab ring is narrow, the finger cannot be inserted much. Experiments on the tab indenting vertically the finger pulp at L = 2 mm, 5 mm have been performed. Two kinds of tabs with different tab ring designs, as illustrated in Fig.5, the convex ring and flat ring are tested. Force-time-displacement curves obtained when the velocity of the tab is v = 2 mm/min, 4 mm/min and 6 mm/min shown the same tendency as in the case of the probe with a hemispherical tip.

Figure 6(a) shows the influence of the indenting position in the finger when indenting velocity v = 6 mm/min (Subject CM). It is observed that Curve 2 in the force-displacement curve rises earlier when L = 2 mm as compared with the case of L = 5 mm because the fingertip is thinner at L = 2 mm. Figure 6(b) shows the influence of the tab ring shape when indenting velocity v = 2 mm/min (Subject DM). It is found that the deformation of finger pulp indented by the flat tab is relatively small as compared with the case indented by the convex tab if the indenting force is the same.

3. Finite Element Analyses

3.1 Human Fingertip Model

Figure 7 shows the schematic diagram of the distal part of human fingertip (Netter, 2004). The fingertip is simplified as an elastic model with two kinds of mechanical properties, the bone and the soft tissue. Figure 8 shows the vertical cross-section, transverse cross-section and the whole model of the three-dimensional finite element model of the finger. The mechanical properties of bone and soft tissue of index fingertip model are assumed as:

Young's modulus E = 17 GPa, 5 MPa, Poisson's ratio ν = 0.3, 0.45, respectively (Wu et al., 2002; Fung, 1981.). The model is descritized into eight-node solid elements. Since bone hardly deforms during pulling up the tab, only one layer of elements is defined as bone in order to save the computational cost.

3.2 Simulation of the Tab Indenting the Fingertip

In order to confirm the effectiveness of the finite element model of the fingertip for numerical analyses of finger-accessibility, simulations of the tab indenting vertically the finger pulp at L = 2 mm (Fig. 9) have been performed and compared with the experimental results. The length of the finger model is shortened and the bone elements are neglected to save computational cost. The freedoms of the nodes adjacent to the bone are fixed. The tab ring is assumed as a rigid body in the finger indenting simulation. The finite element code, MSC.MARC is utilized to perform the numerical analyses.

Experimental results and numerical analysis results are compared in Figure 10. The upper axis shows the thickness of the finger model at the indentation position obtained by numerical analysis, and the thickness is noted as T_a when the deformation depth in the finger model is 1.25 mm. The lower axis shows the finger thickness measured in the experiments. Since the initial finger thickness of Subject DM at L = 2 mm is 8.19 mm, the force-displacement curves in Fig.6(b) can be translated to the force-thickness curves. Comparing the analysis results to the experiment results, it is clear that the rear part of the force-thickness curves agree very well with each other. Therefore, it can be concluded that the finite element model of the finger is available for the finger-accessibility analysis to evaluate numerically discomfort in the fingertip. Figure 11 also shows that deformation in the finger model compressed by the flat tab model is relatively small as compared with the convex tab model when the load is the same, which agrees with the experimental observations.

4. Numerical Analysis of Finger-accessibility

4.1 Analysis Model

Figure 12 shows the standard opening method of the beverage can with SOT end (Reynolds Metals Company, 1984). There are four steps, the first step is to pull up the tab ring by the index finger while pressing the tab nose by the thumb, the second step is to pull the tab completely forward and the third step is to push the tab back down. It is ready for drinking when the tab stays on the can as shown in the last step. In the first step, pressing the tab nose by the thumb can make the tab ring rise up a little naturally and can prevent the tab ring slipping down along the surface of the index finger pulp so that the finger can be easily inserted into the space under the tab ring. Although there are various methods to open the beverage can by consumers, this paper focus on this standard opening method. To evaluate the touch feeling of the pain (or discomfort) in the finger when pulling up the tab ring, the finite element analysis model is developed as shown in Fig. 13. Assuming the deformations of tabs and the finger models are symmetry to the central vertical plane, numerical analyses on 1/2 finite element model is performed. All freedoms of the nodes on the circular edge of the rivet part of the tab are fixed. The edge nodes of the bone elements on the tip of the finger model are enforced to move 0.5 mm forward and then move upper forward to simulate the process of fingertip pulling up the tab. The maximum value of the contact normal stress of the finger model when pulling up the tab is used to present the pain (discomfort) in the finger. The smaller the contact stress is, the less pain (discomfort) the finger experiences and the better the finger-accessibility of the tab is evaluated.

The material model used for the aluminum tab is assumed as an elasto-plastic von Mises material with isotropic hardening. The Young's modulus E = 70 GPa, Poisson's ratio ν = 0.33 and yielding stress σ = 260 MPa are assumed. The tab model is descritized into four-node shell elements with 0.33 mm thickness.

4.2 Comparison of the Finger-Accessibility of Tab Ring Designs

In order to investigate the effect of the geometric shape of the tab ring, three kinds of shape designs, i.e., the convex ring (Model 1), the flat ring (Model 2) and the concave ring (Model 3), are modeled as shown in Fig.14. The tab ring of Model 3 is designed to match the shape of finger pulp. The length of the symmetric central lines and the symmetric central cross-sections of three tab models are the same.

Figure 14 shows the deformation of the fingertip pulp and the contact normal stress distribution of finger model when the tab models are pulled up 2.5 mm. It is obvious that the stress concentration occurred at the part in contact with the central part of the convex ring. When the displacement of the ring center (H_1) becomes 2.5 mm, finger can be inserted more and the tab can be re-held for an easy open. The difficulty is evaluated by the can openability rather than the finger-accessibility when H_1 is larger than 2.5 mm, so the simulation results before H_1 becomes 2.5 mm are observed. The maximum value of the contact normal stress, the contact areas, and the maximum value of the equivalent elastic strain of the finger are compared in Fig.15 for three kinds of tab models when H_1 = 2.5 mm. In the case of the tab with a concave ring, the contact area between the finger and ring is the largest and the maximum value of the contact normal stress and equivalent strain are the smallest. It is considered that if a larger area shares the load that required for pulling up the tab, the contact normal stress and equivalent strain may become lower. Hence, the pain in the finger may decrease more. Therefore, it is concluded that the finger-accessibility of the tab that may have a larger contact area with finger is better. The finger-accessibility of the tab with a concave ring is better than that of the tab with a flat ring or a convex ring.

5.Conclusions

Experiments of indenting vertically the fingertip pulp by a probe and the tab of can ends have been done to observe force responses and to study feelings in the fingertip. The FEA has been performed to simulate the tab indenting the fingertip vertically for developing the finite element model of the fingertip. Moreover, a numerical simulation of finger lifting up the tab of can end has also been performed, and discomfort in the fingertip has been evaluated numerically to present the finger-accessibility of the tab. The comparison of three tab shape designs showed that the finger-accessibility of the tab that may have a larger contact area with finger is better.

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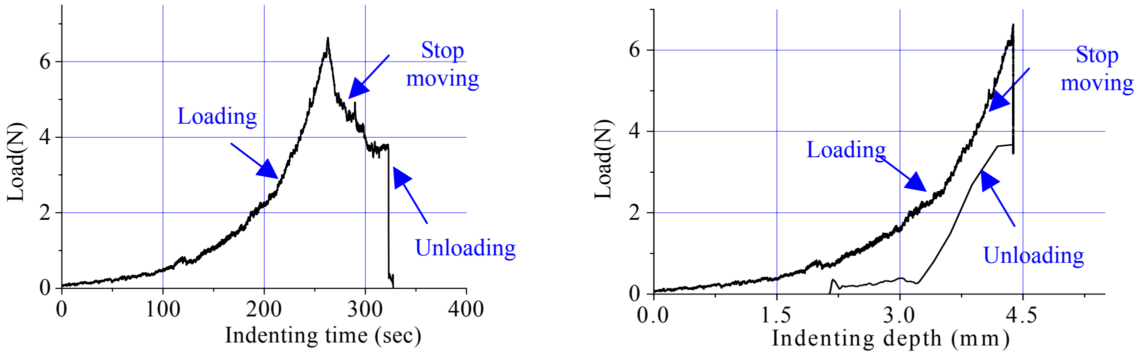
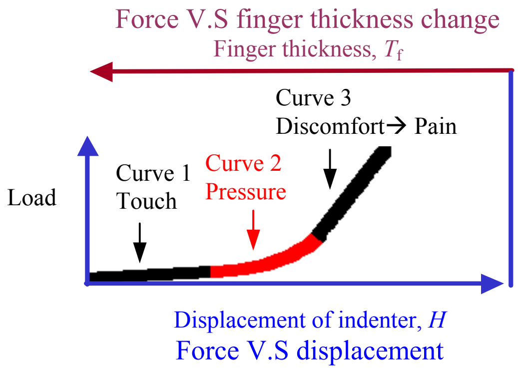
Fig. 1 A Stay-On-Tab end.

(a) Fingertip and tab (b) A probe (c) Convex tab and flat tab (d) Center cross-section of finger

Fig.2 Experimental setup.

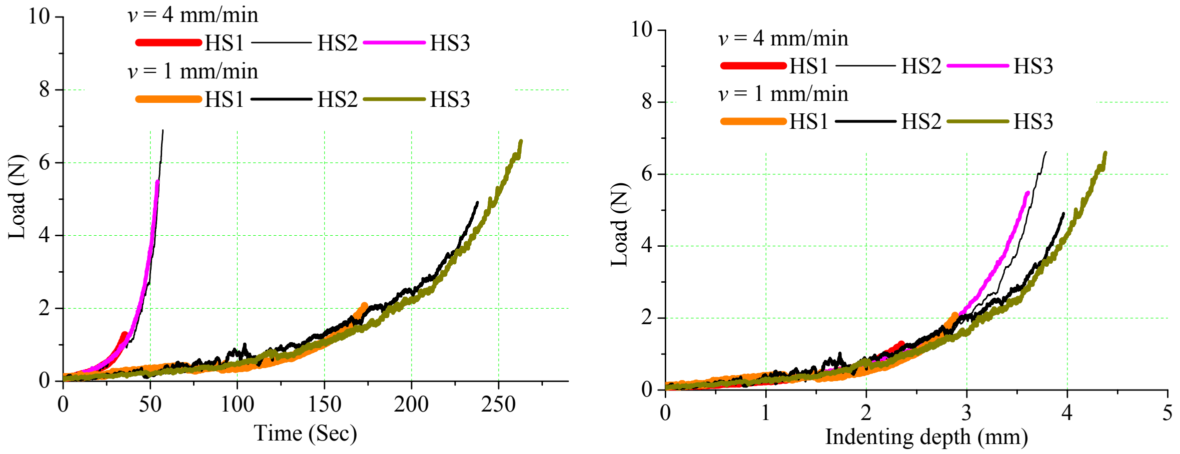


(a) Load-time curves (b) Load-displacement curves



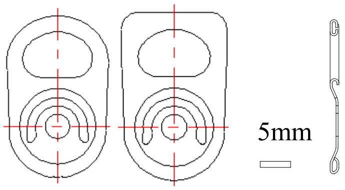
(c) Diagram of feelings in fingertip

Fig.3 Typical fingertip pulp compression results by the probe.



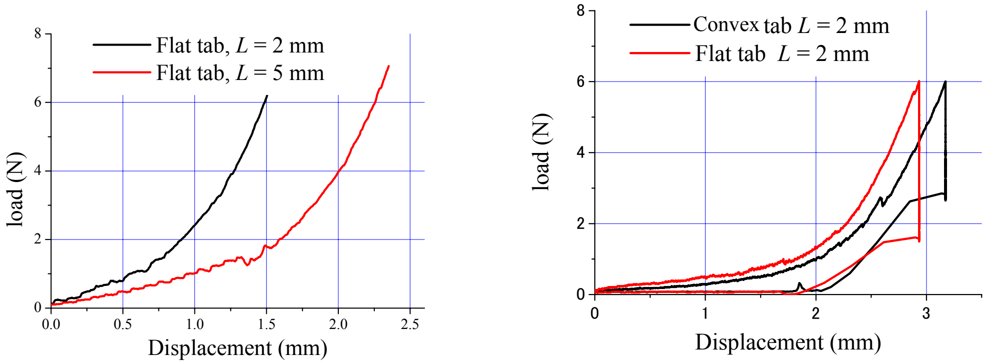
(a) Relation between indenting time and load. (b) Relation between indenting depth and load.

Fig.4 Observations of personal differences.



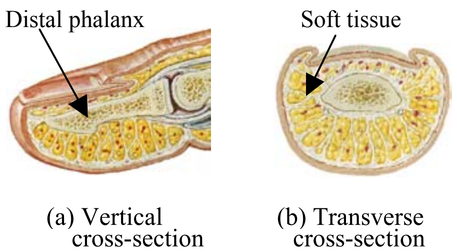
(a) Top view (b) Side view

Fig. 5 Convex and flat tabs.



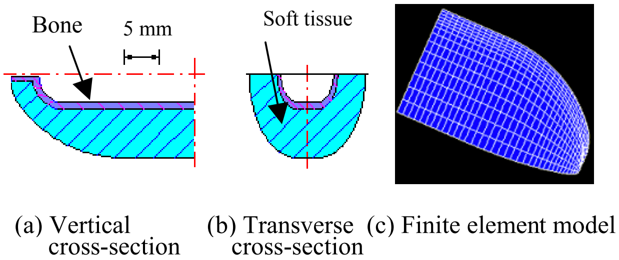
(a) Effect of pulp position (b) Effect of tab shapes

Fig.6 Fingertip pulp compression results by tab load.



(a) Vertical cross-section (b) Transverse cross-section

Fig. 7 Schematic diagram of finger.



(a) Vertical cross-section (b) Transverse cross-section (c) Finite element model

Fig. 8 Model of distal part of index finger.

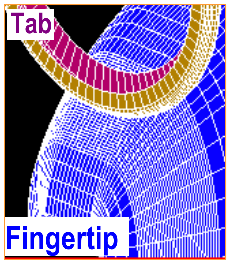
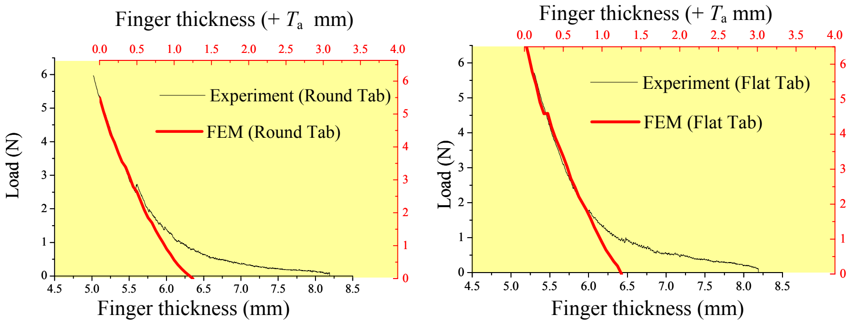


Fig.9 Analysis model



(a) Round tab (b) Flat tab

Fig.10 Comparison between analysis results and experimental ones.

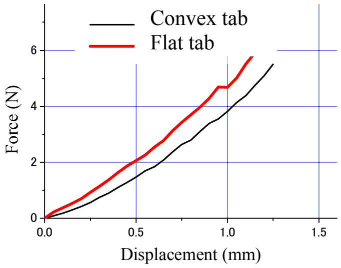


Fig.11 Simulation results.

(a) Step 1 (b) Step 2 (c) Step 3 (d) Step 4

Fig.12 SOT end opening procedures.

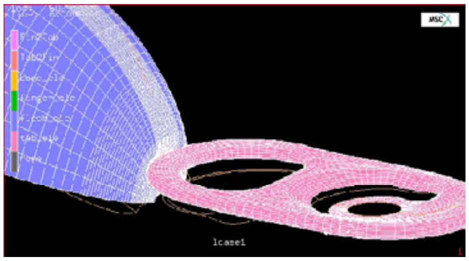
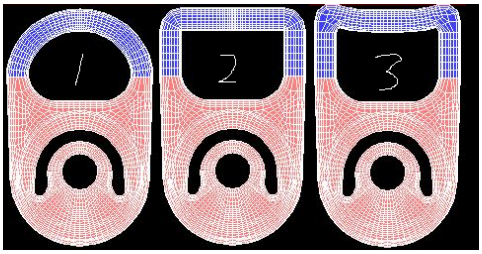
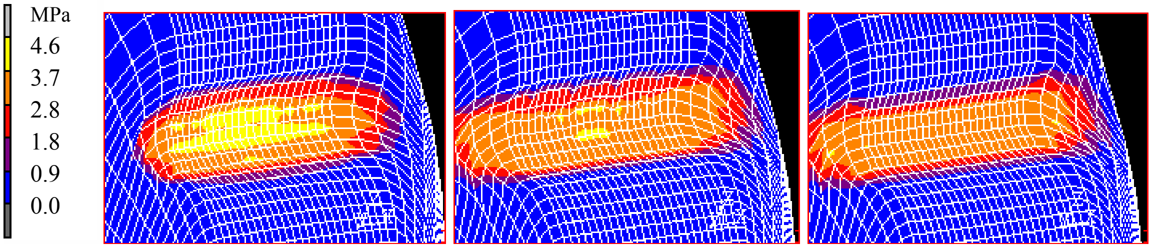


Fig.13 Finite element analysis model.



(a) Model 1 (b) Model 2 (c) Model 3

Fig.14 Finite element models of tabs.



(a) Model 1 (b) Model 2 (c) Model 3

Fig. 15 Contact normal stress distributions of finger models.

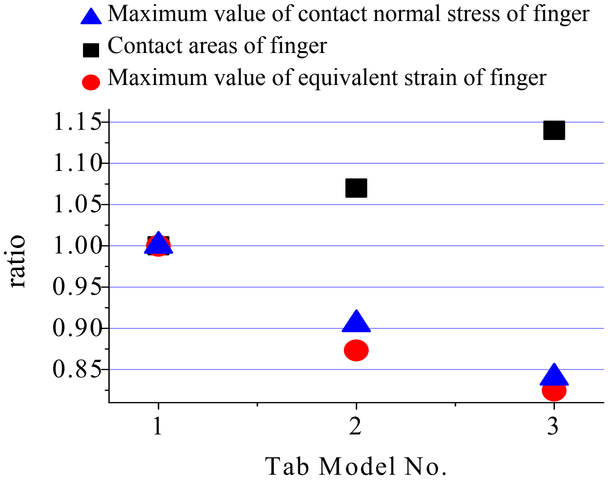


Fig.16 Comparison of three tab models.