Application to Artificial Skin of Double Cone Tube Made of Acrylic Resin Formed by Micro Stereolithography

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A functional double cone tube (DCT) array with gas trapping and high durability is developed in the application of artificial skin. A stereo-lithography system is employed to fabricate DCT made of acrylic resin. In an aqueous solution, a certain amount of gas can be trapped in the tube due to capillary force balance. Under applying an external load, internal stress is effectively released at the interface between top and base cones. In the tactile sensing investigation, softness and tackiness senses as an artificial skin are felt.

Keywords: Artificial skin, Micro stereo-lithography, Acrylic resin, Double cone tube (DCT), Gas storage, Stress distribution

1. Introduction

Recently, tactile sensing has been recognized as one important technical category in the IoT (internet of things) and functional robot industries [1-3]. As well known, the intelligent and functional electronic devices such as smart mobile phone system with touch panel have become a more important tool in our usual lives. In future, it is expected to develop a functional panel, which enables touchy-feely operation. Meanwhile, biometrics have been focused in order to fabricate an effective and usable structure. In this regard, the various studies concerning relationships between micro topological structure and human tactile sense have been focused.

The purpose of this study is to develop a micro three dimensional (3D) structure with tactile characters of the human and to characterize its functionality and durability. In the experiment, a double cone tube (DCT) structure is employed and evaluated at the point of interface control among liquid, gas and solid. As the tactile sensing test, a DCT array is formed and employed to contact with human fingers.

2. Experimental

2.1. Fabrication of double cone tube

A micro stereo-lithography as shown in Fig. 1 was employed to form a DCT made of acrylic resin (Ciba Speciality Chemicals inc.). The process flow and conditions are summarized in Table 1. Figure 2 shows a schematic design of typical DCT, which is composed with top and base cones (top diameter: 0.5 mm, base diameter: 5.0mm and total height: 2.1 mm). The DCT structure was fabricated on a Si(100) substrate.

![Fig. 1. Micro stereo-lithography for DCT fabrication.](image-url)
The Si substrates are cleaned up with organic solvents such as acetone (Nacalai tesque Co. Ltd.), methanol (Nacalai tesque Co. Ltd.) and DI-water each for 5 min. The acrylic resin liquid was exposed to He-Cd laser of 325 nm wavelength in a certain volume of the chamber. After operating the laser scanning in 3D region, the sample into the IPA (Isopropyl Alcohol) (Nacalai tesque Co. Ltd.) for 5 min in order to rinse the sample surface.

2.2. Gas storage test
In order to evaluate a gas trap property, the DCT sample was immersed into the some liquids, such as, deionized (DI) water, synthetic sweat (acid: 44008785, alkaline: 44008775, Hayashi Co. Ltd.) and methanol. The gas trap phenomena can be recorded by using a video camera.

2.3. Surface energy and liquid spreading analysis
The contact angle measurement was employed for analysis of surface energy. The contact angle $\theta$ on the materials in this experiment was measured by a contact angle meter. The wetting energy $W_a$ can be obtained by the following Young-Duplet equation.

$$W_a = \gamma (1 + \cos \theta) \quad \text{mJ/m}^2 \quad (1)$$

The surface energy of $\gamma$ is defined as a sum of dispersion $\gamma^d$ and polar $\gamma^p$ factors as following equation.

$$\gamma = \gamma^d + \gamma^p \quad \text{mJ/m}^2 \quad (2)$$

Moreover the wetting energy between the surface and test liquid are represented as an interaction between these materials as follows.

$$W_a = 2 \sqrt{\gamma_1^d \gamma_2^d + 2 \sqrt{\gamma_1^p \gamma_2^p}} \quad \text{mJ/m}^2 \quad (3)$$

Surface energy $\gamma$ can be determined by these equations. The surface energies were summarized in a surface energy factor map as shown in Fig. 3a. In this figure, the distance between each component position represents the square root of the interface energy $\sqrt{\gamma_{12}}$.

![Fig. 2. Design of DCT structure.](image)

![Fig. 4. Schematic of surface energies component map.](image)

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Table 1. Fabrication processes of DCT.

| Process         | Experimental conditions |
|-----------------|-------------------------|
| Organic clean   |                         |
| Acetone         | 5 min                   |
| Methanol        | 5 min                   |
| DI-water        | 5 min                   |
| Formation       |                         |
| Material        | Acrylic resin           |
| He-Cd Laser ($\lambda$=325nm) | Power:14 $\mu$W Time:45 min |
| Development     |                         |
| Vacuum drying   | 10 min                  |
| IPA(Isopropyl alcohol) | 5 min                  |
| Vacuum drying   | 10 min                  |
The interface energy is represented as follows.

\[
(\sqrt{\gamma_{12}})^2 = (\sqrt{\gamma_{1}^d - \gamma_{1}^d})^2 + (\sqrt{\gamma_{1}^p - \gamma_{2}^p})^2 \tag{4}
\]

Moreover, spreading coefficient \( S \) mJ/m\(^2\) is well-known as an evaluation method of interface energy balance [4].

\[
-S = \gamma_{12} - \gamma_{13} - \gamma_{23} \quad \text{mJ/m}^2 \tag{5}
\]

The values of \( \gamma_{12} \), \( \gamma_{13} \), \( \gamma_{23} \) represent the interface energy as shown in Fig. 3b. We can discuss the liquid instruction based on the spreading coefficient \( S \) as follows.

- \( S < 0 \): Poor interface energy balance (Liquid intrusion should occur)
- \( S > 0 \): Good interface energy balance (Liquid intrusion should not occur)

In this regard, the spreading coefficient \( S \) mJ/m\(^2\) was represented as a circular model as shown in Fig. 4. If the circle, liquid intrusion should occur \( (S < 0) \). The detail of circle model is described in the literature [5].

2.4. Laplace pressure and liquid intrusion analysis

In order to analyze the gas trapping phenomena in DCT, the Laplace pressure is employed. In general, the Laplace pressure \( \Delta P \) in micro tube is given by the following equation.

\[
\Delta P = P_2 - P_1 = \frac{2\gamma}{r} \quad \text{Pa} \tag{6}
\]

where the symbols \( P_1 \) and \( P_2 \) represent pressure in environmental liquid and inert gas of DCT, respectively. The symbols \( \gamma \) and \( r \) denote surface energy of the liquid and radius of DCT, respectively.

2.5. Deformation and durability test

In order to evaluate the deformation and durability of DCT, a certain external force was applied at the top of DCT. As a loading system, a micro manipulator (UGO-239, Surugaseiki Co. Ltd.) was employed. Two kinds of DCT samples, a base cone fixing or not, were prepared. An epoxy resin adhesive was used for fixing of the base of DCT. The maximum distance by indenting the manipulating tip was set at 640mm. The deformation and destruction of DCT sample were observed by an optical microscopy. The deformation analysis was also conducted by 3D finite element method. In Table 2, the simulation parameter was summarized.

2.6. Tactile sensing measurement test

In order to evaluate the tactile sensing property, a 4x4 array composed by 16 pieces of DCT. By contacting DCT array by human finger, tactile sensing test was carried out as shown in Fig. 5. In general, it is regarded the tactile sense is difficult to quantify. Some researchers employed so-called SD method [6,7]. However, in order to simplify, we propose a new method of tactile sensory evaluation with the pentagon-shaped graph. This original evaluation in this study was proposed to indicate a tactile sense visibly. Figure 6 shows a chart for recording and pentagon-shaped graph for visualizing the tactile sensing data. As the evaluation, the following five kinds of characteristic properties are defined [8].

- spiky: keen sense like indenting by a sharp needle
- hardness: rebound pressure sense
- sensitivity: recognition of contacting position
- temperature: warmness sensing
- adhesion: adsorption of tactile skin to a sample

Table 2. Material parameters for FEM simulation.

| Properties         | Materials  |
|--------------------|------------|
|                    | Acrylic resin | Si (100) |
| Young’s modulus    | 3.14 GPa   | 130 GPa  |
| Poisson ratio      | 0.35       | 0.28     |
| Density            | 1180 kg/m\(^3\) | 2328 kg/m\(^3\) |

Fig. 5. Tactile sensing test by contacting a human finger with DCT array.

Fig. 6. Pairs adjectives of sensory evaluation.
3. Results and discussion

3.1. DCT structure by stereo-lithography

Figure 7 shows the photograph of the DCT used in this experiment. The sizes in DCT are mostly same to the design. The maximum size deviation at the top cone in DCT is 30μm. The multi-layer lines can be observed in the side wall of DCT.

3.2. Gas storage test

In order to observe the gas trap property, the DCT was immersed in some liquids, as summarized in Table 3. In these cases, the gas trap at an inert region of the DCT can be confirmed in various liquids clearly. (The arrowhead indicates the top position at the liquid/gas interface.) In methanol environment, a micro bubble was grown at the apex of top cone. These results indicate the decrease of Laplace pressure $\Delta P$, defined in Eq.6, due to surface energy of environmental liquid.

3.3. Surface energy and spreading analysis

The possibility of gas storage in DCT can be discussed by surface energy balance and spreading analysis. Surface energies of the sample materials are summarized in Table 4. The dispersion component of acrylic resin is relatively large as compared with polar component. Figure 8 shows the component map of sample surfaces. The circular models represent the combination with acrylic resin and air (origin point in the figure). It is clearly observed that the component points of both DI-water and synthetic sweat position in the outer region of the circles. However, the point of methanol is set in the inner region of the circle. From this result, it can be discussed that the intrusion of both DI-water and synthetic sweat into the interface of acrylic resin/gas is less likely to occur due to the good interface energy balance.
On the contrary, it can be supposed that the methanol can spread at gas/acrylic resin interface, which indicates the methanol can intrude into the inner region of DCT.

3.4. Laplace pressure and liquid intrusion analysis

As the other important factor on liquid intrusion into DCT, Laplace pressure should be taken into consideration. As shown in Eq.6 and Fig.9, Laplace pressure \( \Delta P \) decreases as the increase of capillary tube radius. Therefore, the Laplace pressure becomes weak from the top to bottom of the DCT, as shown in Fig.10. In this regard, the cone shape is effective to prevent the liquid propagation into the inner region of DCT, which indicate the capability of gas storage in liquid environment.

3.5. Deformation and durability test

In the artificial skin operation, surface deformation under the indenting pressure should be taken into consideration. As increasing the indenting distance, a slight deformation can be confirmed at the top/bottom junction of DCT as shown in Table 5. No deformation of the top cone in DCT is confirmed because the stress can be released due to the junction deformation. In the case of the DCT with fixing of the bottom cone by epoxy adhesive, a certain crack propagates to fracture the top cone from the bottom one. However, in the case of the softened substrate, it can be considered the durability of the external load is relatively high, because of no crack formation. By the deformation and stress simulations, the deformation results of DCT can be analyzed as shown in Fig. 11. In Figs.11a and 11b, the deformation and simulation value of the both left and right sides of the top/bottom junction are shown, respectively. As increasing the indentation distance by the micro needle, the both of left and right side deformation increases linearly, which are similar to the simulation results. It is clearly discussed that the internal stress concentrates at the junction of top/bottom interfaces.

Fig. 9. Capillary model of DCT in liquid environment.

Fig. 10. Laplace pressure in DCT as a function of tube radius.

Table 5. Deformation test of DCT by indenting a micro needle.
3.6. Tactile sensing measurement test

Figure 12 shows pentagon-shaped graph of the results of characteristic testing. From these results, the following consideration can be obtained. The DCT array surface was felt more likely “sensitivity” “adhesion” and “temperature”. It can be considered that these results indicate “more comfortable” in contact with the human fingers. In the literature, the correct cognitive ability of the human reduced when the pattern size is under 1 mm, and the human could not recognize when the shape size was below 0.2 mm [9]. The typical pitch of the fingerprint ridge of human is about 0.5 mm which acts effectively for the human sensing procedure. In general, the human’s sweat, sebum and water became external factors between a human finger and an artificial skin. The phenomena relate closely to the human sense concurrently.

4. Conclusion

In the application of artificial skin, DCT array is formed by the stereo-lithography. The DCT made of acrylic resin is evaluated at the points of the gas trap at the inner region of DCT and deformation due to external loads. Surface energy balance and Laplace pressure are employed to analyze the gas trap phenomena. The tactile sensing test is employed to evaluate the DCT array as an artificial skin. The DCT array surface indicates “more comfortable” in contact with the human fingers.

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