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## Laser micro-drilling of multi-layered artificial skin

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### Abstract

A multi-layered artificial skin is mainly consisted of three layers of silicone elastomer, print paper, and resin plate. Sealing of facial defects with the multi-layered artificial skin causes perspired water from the surface of missing parts, which results in insanitary conditions to the skin surface. Therefore, the laser micro-drilling using nanosecond and picosecond pulsed laser was investigated to provide the breathability for multi-layered artificial skin without human eye's recognition of drilled holes, which can satisfy both the breathability and aesthetic problems. The visibility of drilled hole was affected by the pitch distance of drilled holes, and its visibility decreased with increasing the pitch distance. A small color difference measured using a colorimeter led to the low visibility, and laser micro-drilling with small color difference is effective to obtain the breathable multi-layered artificial skin with low visibility of drilled holes, which can improve the breathability for the multi-layered artificial skin.

*Keywords:* micro processing; drilling; multi-layered artificial skin

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### 1. Introduction

Facial prosthesis treatment, which can repair missing parts of the face around caused tumors and traumatic injuries, has been attracted attention in the field of rehabilitation medical. Recently, a multi-layered artificial skin, which is mainly consisted of three layers of silicone elastomer, print paper and resin plate, was newly developed [1]. It was proposed by introducing the concept of personal digital shade guide

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and pseudo-angle layer as facial prosthesis in order to recover an aesthetic surface [2, 3]. However, sealing of facial defects with the multi-layered artificial skin causes perspired water from the surface of missing parts, which results in insanitary conditions to the skin surface below the multi-layered artificial skin. Therefore, air permeability is a desirable property of facial prosthesis, and micro-drilling method with high breathability and aesthetic quality is required for a multi-layered artificial skin, which can be applied to facial prosthesis treatment. In this study, laser micro-drilling of multi-layered artificial skin was experimentally investigated to provide the breathability for multi-layered artificial skin without human eye's recognition of drilled holes, which can satisfy both the breathability and aesthetic problems. Moreover, laser micro-drilled surface of multi-layered artificial skin was aesthetically evaluated to characterize the appearance of laser drilled hole by a calorimeter and a color discrimination threshold experiment.

## 2. Investigation of Aesthetic Quality with UV Nanosecond Pulsed Laser

### 2.1. Experimental procedures

Figure 1 shows a schematic diagram of the experimental setup. A Q-switched Nd:YAG laser pumped by a flash lamp was used as the laser source, and fourth harmonic of 266 nm was used at constant pulse repetition rate of 20 Hz in this experiment. The intensity distribution and shape of the laser beam from the oscillator were unsuitable for the micro-processing experiment. Thus, in order to improve its intensity distribution and shape, the laser beam was expanded by a factor of 4. Then, the shape of the expanded laser beam was formed using a circular mask. The diameter of the circular mask was calculated and selected in accordance with the wavelength of the laser beam to adjust the spot size of 50  $\mu\text{m}$  on the specimen surface using a focusing lens of 100 mm focal length as shown in Fig.1 (a). Figure 1 (b) shows a schematic illustration of multi-layered artificial skin, which is consisted of three structural layers. The tonal and textural appearances of the patient's skin are reproduced and matched with print paper by using the concept of individual shade guide [1]. Multi-layered artificial skin is worn on the patient's facial surface by turns of resin plate (Polycarbonate) as a scaffold material, print paper as a digital print layer, and silicone elastomer as an artificial cornified layer. Laser beam of 5 ns and 100  $\mu\text{m}$  was irradiated on multi-layered artificial skin in air.

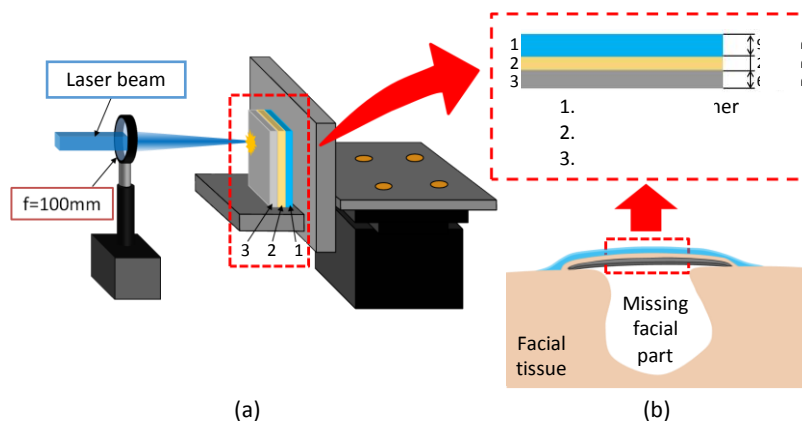


Fig. 1. Schematic illustration of laser drilling experiment; (a) laser irradiation setup; (b) structure of multi-layered artificial skin

## 2.2. Effect of laser irradiation direction on aesthetic quality

Appearance of laser drilled hole on silicone elastomer affects aesthetic quality, which was investigated by changing the laser irradiation direction. Figure 2 shows photographs of laser drilled holes on silicone elastomer side by 1000 shots of 266 nm irradiated from silicone elastomer side and resin plate side. In the case of silicone elastomer side irradiation, a large heat affected area was observed as black circles around laser drilled holes. On the other hand, their black areas were unclearly observed on silicon elastomer surface of multi-layered artificial skin in the case of resin plate side irradiation. When the laser beam was irradiated from silicone elastomer side, laser induced plasma continued during laser irradiation time. Its long heat input of the laser induced plasma into silicone elastomer and printed paper around the drilled hole resulted in the generation of a large heat affected zone. In contrast, proper laser irradiation time from resin plate side could minimize the time of heat input caused by the laser induced plasma, and heat affected zone around the drilled hole could be reduced. Therefore, the laser irradiation from resin plate side is effective in achieving good aesthetic quality of the laser drilled hole, and the irradiation direction was fixed from resin plate side in the following experiments.

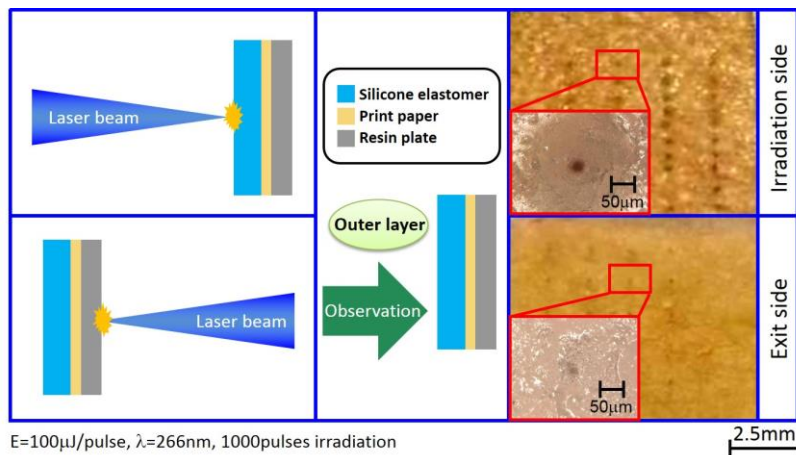


Fig. 2. Appearance of laser drilled holes on silicone elastomer side by 266 nm

## 2.3. Effect of pitch distance of drilled holes on visibility and color difference

Specimens were prepared as shown in Fig.3 (a), and laser irradiation experiments from resin plate side were carried out by various pitch distances of drilled holes in order to discuss the visibility of laser drilled hole. Color difference of laser drilled specimen was evaluated by a colorimeter (TES corporation, TES-135 plus) as shown in Fig.3 (b).

Figure 4 shows photographs of the drilled holes on silicone elastomer side, when laser beam of 266 nm and 100 μJ was irradiated from resin plate side by 1000 shots. Pitch distance of drilled holes  $P_n$  was varied, and total number of drilled hole is constant to 532 at each pitch distance of drilled holes. Diameters of processed areas by hole pitch  $P_n = 0.4$  mm, 0.6 mm and 0.8 mm were 10 mm, 15 mm and 20 mm, respectively. Laser drilled holes were arranged in a rectangular lattice shape with each hole pitch. As shown in the figure, marks of drilled hole become remarkable with decreasing the pitch distance of drilled holes, and they are inconspicuous at a large pitch distance of drilled holes.

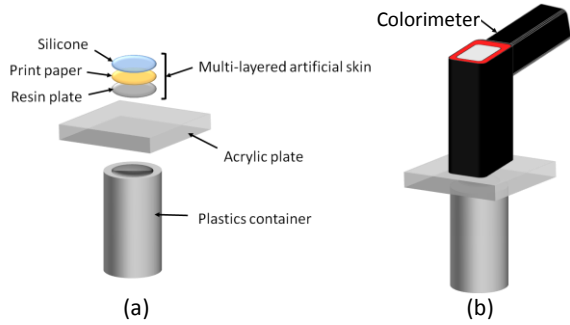


Fig. 3. Schematic illustration of specimen and color analyzer; (a) setup of specimen; (b) measuring method of color difference

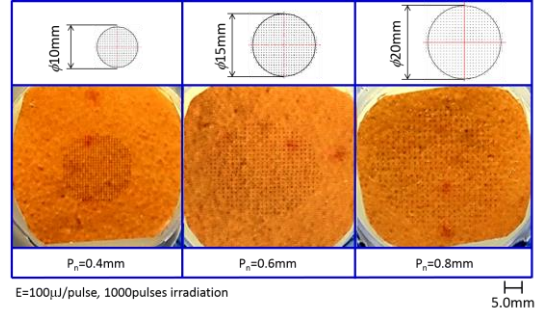


Fig. 4. Photographs of drilled holes on silicone elastomer surface as exit side by various hole pitches

In order to clarify the effect of pitch distance on the visibility of laser drilled hole, color discrimination were investigated at each hole pitch by using color difference  $\Delta E$ , which were measured as shown in Fig. 5. In general, color discrimination is defined as the recognition of color difference between plural color chromaticity and tone. [4]. In laser drilling process, discolored regions of drilled hole lead to decreasing the brightness and the saturation, and it is considered that processing conditions change the color difference of processed specimen. Therefore, the color difference  $\Delta E$  before and after drilling process was calculated by using brightness difference  $\Delta L^*$  and chromaticity difference  $\Delta a^*$ ,  $\Delta b^*$  in Equation (1).

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

The measuring time and diameter of measured area are 2 s and 10 mm, respectively. The average of 5 measurement values was recorded as the color difference  $\Delta E$ . As shown in Fig.5, the color difference decreased with increasing the hole pitch, in other words, larger hole pitch leads to similar color condition to non-process specimen.

In order to evaluate the visibility of drilled hole, color discrimination threshold test was carried out as shown in Fig. 6. Observers watched the specimens with drilled holes for 5 s after removing the partition plate, and this observation was repeated at every 0.1 m observation distance from 3.0 m. When observers recognized the drilled hole at a certain observation distance, its distance was recorded as the color discrimination threshold.

Figure 7 shows the evaluation results of color discrimination threshold test for processed specimen with various pitch distance of drilled holes by ten observers described as initials. Although there are individual differences in evaluation results, all observers indicated that color discrimination threshold decreased with increasing the pitch distance between drilled holes. These results agree well with measurement results of color difference as shown in Fig. 5. Since a large color difference between a specimen with and without drilled hole resulted in high visibility of drilled hole, laser micro-drilling method with a small color difference is effective in reducing the visibility and improving aesthetic quality of drilled hole. In normal, human would keep a certain distance from others to feel comfortable situation due to psychological effects [5], and it is reported that good interpersonal distances of comfortability and conversation are more than 1.5 m and 1.0 m, respectively [6]. Therefore, it can be expected that multi-layered artificial skin with laser drilled holes can be applied to facial prosthesis treatment, although the laser drilled holes could not overcome human eye's recognition less than 1.5 m.

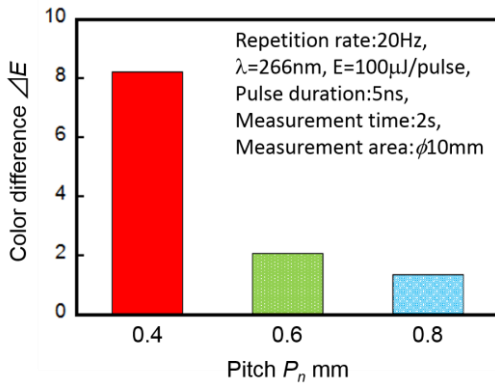


Fig. 5. Color difference of processed specimen with various pitch distances and non-processed specimen

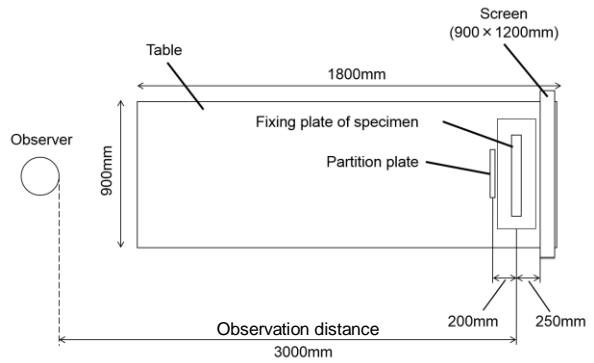


Fig. 6. Schematic diagram of color discrimination threshold test for processed specimen at the farthest distance of 3.0 m

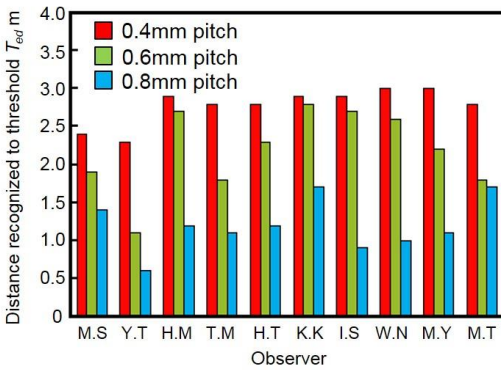


Fig. 7. Evaluation results of color discrimination threshold test for processed specimen with various pitch distances between drilled holes

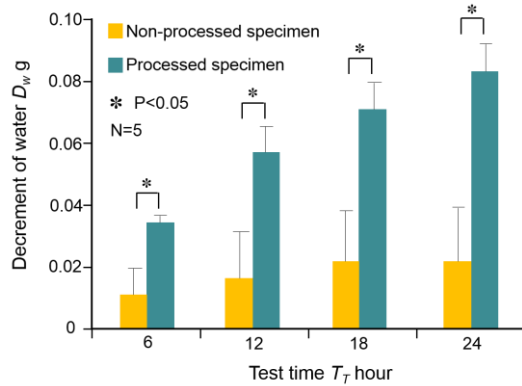


Fig. 8. Decrement of water with non-processed and processed specimen for various test time from 6 hours to 24 hours

#### 2.4. Breathability of multi-layered artificial skin with laser drilled holes

In order to discuss the breathability of multi-layered artificial skin with laser drilled holes, test specimens were prepared, when the pitch distance of drilled holes and the diameter of processed area were 0.4 mm and 10 mm, respectively. Distilled water was put in bottles, which were covered by multi-layered artificial skins with and without drilled holes. Weights of these test specimens were measured every 6 hours up to 24 hours in an incubator at 37 degree Celsius. Average weight difference of 5 test specimens was recorded as decrement of water as shown in Fig. 8. Decrement of water of test specimen with drilled holes was larger than that without holes ( $P < 0.05$ , Mann-Whitney U test), and its decrement of water increased with increasing the test time. Therefore, it was clarified that fabrication of laser micro-drilled hole for the multi-layered artificial skin could improve the breathability.

### 3. High-throughput Micro-drilling with IR Picosecond Pulsed Laser with High Pulse Repetition Rate

#### 3.1. Experimental setup

The possibility to satisfy both high processing efficiency and good aesthetic quality was investigated by picosecond pulsed laser in order to create breathability holes for multi-layered artificial skin. Laser beam of 12.5 ps and 1064 nm was irradiated from resin plate side by a Galvano scanner with  $f\theta$  lens of 100 mm focal length, and focal point was fixed on the surface of resin plate.

#### 3.2. Dividing method of number of shots

As mentioned before, laser induced plasma affects the visibility of drilled hole, and laser irradiation at a fixed point with high pulse repetition rate might result in heat accumulation [7, 8]. Therefore, dividing method of number of shots was proposed to prepare a certain off-time, and discolored region around the drilled hole was evaluated. Figure 9 shows the relationship between number of shots at each processing point and time. At first, at hole number 1, laser irradiation of shots number  $N_1$  is carried out with pulse repetition rate  $R_p$  at one cycle (Process  $h_{11}$ ). The laser irradiation time is defined as  $t_s$ , and Equation (2) is derived as number of shots  $N_1$  at one processing point in one cycle. After laser beam moves from hole number 1 to 2 with time  $t_{travel}$ , laser irradiation was carried out again at hole number 2 with the same irradiation time  $t_s$  and pulse repetition rate  $R_p$  (Process  $h_{12}$ ). After series of this laser irradiation process were repeated until hole number  $n$  (Process  $h_{1n}$ ), hole number returns again to the initial hole number 1 with time  $t'_{travel}$ . This cycle was defined as one cycle, and the number of cycles was expressed as  $C_m$ . Here, the rest time except for laser irradiation time at one processing time  $t_s$  can be considered as off-time  $t_o$ , which is expressed as Equation (3). Equation (4) indicates that the total number of shots  $N_T$  can be obtained by repeating the processing with number of shots  $N_1$   $m$  times (the number of cycle  $C_m$ ) to create a penetration hole at each processing point.

$$N_1 = R_p \cdot t_s \quad (2)$$

$$t_o = (n-1)(t_{travel} + t_s) \quad (3)$$

$$N_T = N_1 \cdot C_m \quad (4)$$

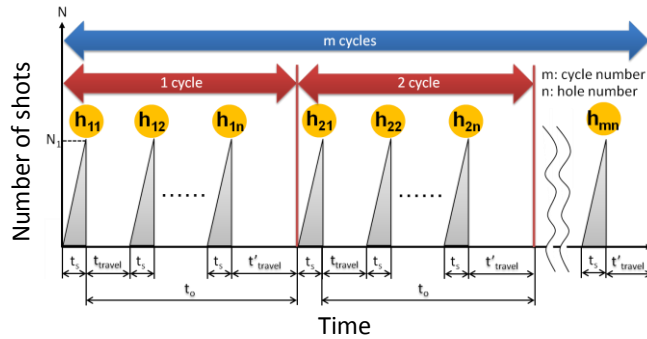


Fig. 9. Relationship between number of shots at each processing point and time

Under the same total number of shots  $N_T$  to obtain the penetration hole, when the number of shots  $N_1$  at one processing point is small, the number of cycles  $C_m$  becomes large. Therefore, off-time  $t_o$  increases with decreasing  $N_1$  as the number of shots in one cycle under the same total number of shots. One penetration hole is created by repeating  $m$  times of process with the number of shots  $N_1$ , and  $n$  penetration holes are formed after  $m$  cycles. When the time  $t_{travel}$  of movement between holes is less than the pulse interval time  $1/R_p$ , the time loss could be minimized.

### 3.3. Experimental results and discussion

Figure 10 shows photographs of the drilled holes on silicone elastomer surface, when the total number of shots and off-times were constant to 40,000 pulses and 110 ms, respectively. Laser beam of  $50 \mu\text{J}$  was irradiated from the resin plate side at pulse repetition rate of 100 kHz. As shown in the figure, smaller number of shots  $N_1$  in one cycle and large number of cycles lead to decreasing the discolored region around the drilled hole.

Figure 11 is the measurement results of discolored region around drilled hole with various numbers of shots per one cycle under the condition (constant total number of 40,000 shots and off-time of 110 ms), when laser beam of  $50 \mu\text{J}$  was irradiated from the resin plate side at pulse repetition rate of 100 kHz. A small number of shots  $N_1$  in one cycle is effective in the reduction of discolored region around the drilled hole, and a proper off-time could avoid a large heat accumulation at high pulse repetition rate conditions.

A proper dividing the total number of shots could reduce the discolored region caused by the temperature rise of specimen due to the heat accumulation at high pulse repetition rate conditions, and efficient processing with small heat affected zone could be expected.

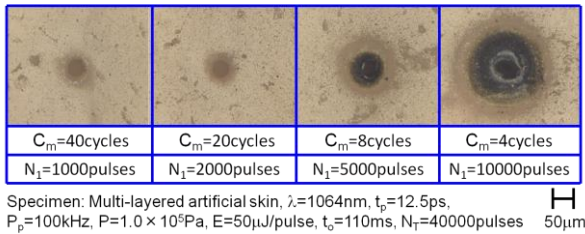


Fig. 10. Photographs of drilled hole at exit side by various numbers of shots

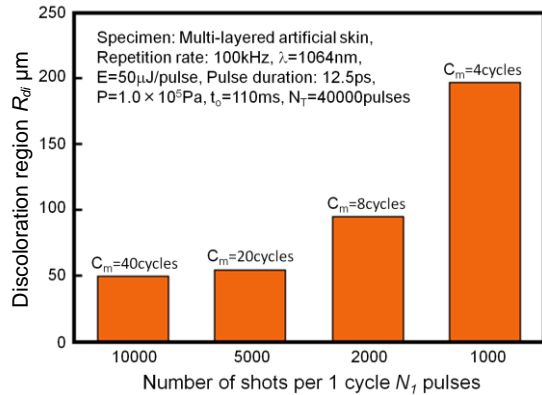


Fig. 11. Discoloration region around drilled hole with various numbers of shots per one cycle

## 4. Conclusions

In this study, the laser micro-drilling using nanosecond and picosecond pulsed laser was experimentally investigated to provide the breathability for multi-layered artificial skin. Main conclusion obtained in this study are as follows:

- (1) Heat affected zone caused by the laser irradiation on multi-layered artificial skin could be reduced by the laser irradiation from the resin plate side compared with that from the silicone elastomer side.

- (2) Fabrication of laser micro-drilled hole for the multi-layered artificial skin could improve the breathability.
- (3) The visibility of drilled hole on the multi-layered artificial skin was affected by the pitch distance of holes, and its visibility decreased with increasing the pitch distance between laser drilled holes.
- (4) The pitch distance of drilled holes had an influence on the color difference measured using a colorimeter, when the multi-layered artificial skin with drilled holes was compared with that without a drilled hole.
- (5) Color discrimination threshold experiments revealed that the visibility decreased with increasing the pitch distance between laser micro-drilled holes. In other words, the small color difference measured using a colorimeter led to the low visibility, and laser micro-drilling with small color difference is effective to obtain the breathable multi-layered artificial skin with low visibility.
- (6) A proper dividing the total number of shots could reduce the discolored region caused by the heat accumulation, and efficient processing with small heat affected zone could be expected even at high pulse repetition rate conditions.

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